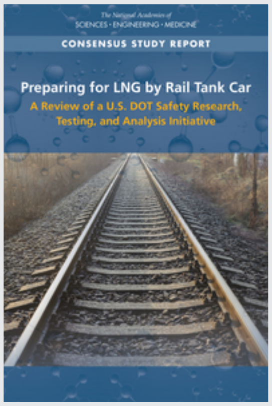

Preparing for LNG by Rail Tank Car: A Review of a U.S. DOT Safety Research, Testing, and Analysis Initiative (2021)

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Preparing for LNG by Rail Tank Car: A Review of a U.S. DOT Safety Research, Testing, and Analysis Initiative

Committee for a Study on the Safe Transportation of Liquefied Natural Gas by Railroad Tank Car

A Consensus Study Report of
The National Academies of
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COMMITTEE FOR A STUDY ON THE SAFE TRANSPORTATION OF LIQUEFIED NATURAL GAS BY RAILROAD TANK CAR

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NOTE: See Appendix B, Disclosure of Unavoidable Conflicts of Interest.

Preface

Natural gas production in the United States has dramatically increased and exceeds the reach—especially in the Northeast—and capacity of the country's gas transmission pipeline system. While pipelines are generally the most efficient means of transporting natural gas, compressed natural gas and liquefied natural gas (LNG) have been transported by marine vessel and truck for several decades. Seeking to deliver natural gas where pipeline access is limited, rail carriers in 2017 petitioned the U.S. Department of Transportation's (DOT's) Pipeline and Hazardous Materials Safety Administration (PHMSA) to transport LNG in bulk by rail tank car across the extensive North American freight railroad network. In 2019, PHMSA proposed a rulemaking to allow bulk transportation of LNG by DOT-113 tank car, issuing its final rule in 2020.

To inform the rulemaking, PHMSA and the Federal Railroad Administration (FRA) established an interagency task force to conduct a multi-task initiative of research, data gathering, testing, modeling, and outreach. Subsequently, the Further Consolidated Appropriations Act of 2020 called on PHMSA to commission a study by the Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine to examine the safety of transporting natural gas by rail. This report is the product of the first phase of a two-part study on the safe transportation of LNG by rail tank car. This study reviews the interagency initiative, which consists of "plans and activities to inform government and industry decisions about the transportation of LNG by rail and consider ways to ensure the continued safety of these shipments over the longer-term." The complete study charge is presented in full and discussed in Chapter 1.

To conduct the study, TRB convened a committee of experts whose fields include railroad engineering, safety, and operations; railway simulation; track and equipment failure analysis; accident investigation; heavy equipment full scale testing; hazardous materials safety regulation; hazardous materials transportation, packaging, and safe handling; LNG behavior; state and local emergency management; and risk analysis. Led by Craig E. Philip (National Academy of Engineering), Research Professor and Director of the Vanderbilt Center for Transportation and Operational Resiliency, the committee members authored the report's conclusions and recommendations through a consensus effort while serving uncompensated in the public interest. Biographical information about the committee members appears at the end of the report.

ACKNOWLEDGMENTS

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

The PHMSA liaison for the study was Michael Klem, who provided contract oversight and handled information requests from the committee. The committee was briefed by or received information from the following PHMSA Office of Hazardous Materials Safety officials: Olivia Apple; Yolanda Braxton; Howard "Skip" Elliott, Administrator; William Quade; William Schoonover; and Robert Starin. The committee was briefed by or received information from the following FRA officials: Francisco González III; Mark Maday; and Phani Raj.

Serving as the study director, Micah D. Himmel managed the study and drafted the report under the guidance of the committee and supervision of Thomas R. Menzies, Jr. Karen Febey managed the report review process. Tyler Kloefkorn assisted with developing parts of the report.

Anusha Jayasinghe provided administrative, logistical, and research support in addition to assisting with preparing the report for publication.

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 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.

The committee thanks the following individuals for their review of this report: Eric Gebhardt, Wabtec Corporation; Bo Barker Jørgensen, Aarhus University; Melvin Kanninen, MFK Consulting Services; John Samuels, Revenue Variable Engineering, LLC; Joseph Shepherd, California Institute of Technology; and Jo Strang, American Short Line and Regional Railroad Association.

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 Chris T. Hendrickson (National Academy of Engineering), Carnegie Mellon University (emeritus), Pittsburgh, Pennsylvania, and Roger McCarthy, McCarthy Engineering, Palo Alto, California. 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

Most natural gas produced and consumed in the United States is transported long-distance through a nationwide network of transmission pipelines, but the country's pipeline capacity is limited in some regions and pipelines are an impractical option for transportation outside North America. For transportation by other modes, natural gas can be cooled to a liquid state to produce a much denser liquefied natural gas (LNG). Bulk shipments of LNG have been transported by water in marine tankers and by highway in tank trucks for decades.

LNG has not been transported to any significant degree by railroad in the United States. Except for some individually approved shipments in portable tanks on flatcars, LNG had not been authorized by federal safety regulations to be transported by rail. However, in response to a 2017 petition from the Association of American Railroads and an April 2019 presidential executive order, the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) and Federal Railroad Administration (FRA) initiated a rulemaking to allow LNG to be transported by rail tank cars designed for cryogenic hazardous commodities. A final rule authorizing the movements was approved in July 2020, but stipulated that the tank cars used to move other types of cryogens would need to be redesigned with a thicker outer tank (9/16 inches versus 7/16 inches) composed of higher-grade carbon steel and the trains transporting these tanks would be subject to requirements for enhanced braking, monitoring train location and tank pressure, and safety and security route planning. The rule calls for modifications of the outer tank to increase puncture resistance in the case of a derailment.

To support development of the final rule and inform subsequent decisions to ensure the safe movement of LNG by rail, PHMSA and FRA jointly established an LNG-by-rail task force (Task Force) during January 2020. The Task Force was given 15 research, testing, and analysis tasks, each intended to help PHMSA and FRA "know, predict, reduce, and prepare for" any significant risks that could arise from LNG's transportation by rail. The tasks related to these four purposes are listed in Table S-1. Concurrently, Congress directed PHMSA to commission a study by the National Academies of Sciences, Engineering, and Medicine (the National Academies) on the safe transportation of LNG by rail tank car.[1] While development of the final rule proceeded at a pace that would the preclude the study from informing it, PHMSA and FRA nevertheless viewed the study mandate as an opportunity for a review of the Task Force's activities by an independent committee of experts in hazardous materials transportation safety.

[1] Further Consolidated Appropriations Act of 2020: Committee Print of the Committee on Appropriations, U.S. House of Representatives, P.L. 116-94, 1231, 2020, https://www.govinfo.gov/content/pkg/CPRT-116HPRT38679/pdf/CPRT-116HPRT38679.pdf.

TABLE S-1 Tasks in the Liquefied Natural Gas (LNG) Task Force Project Plan as Categorized by the Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration

KNOW the Risk	PREDICT the Risk	REDUCE the Risk	PREPARE for the Risk
Empirical Review of International LNG Rail Transportation	Evaluate Punctures and Derailment Simulation Modeling	Electronically Controlled Pneumatic Brakes	Emergency Responder Opinions and Needs
Loading/Unloading Safety Assessment	Worst Case Scenario Model	Train Operational Controls	LNG Educational and Outreach Plan
Quantitative Risk Assessment	Safety/Security Route Risk Assessment	Automated Track Inspection Program	
Full-Scale Impact Testing	Train Energy Dynamics Simulator		
UN-T75 Portable Tank Fire Testing	Modal Conversion Between LNG by Truck and Rail		

PHMSA and FRA negotiated a Statement of Task with the National Academies that consists of two study phases, with each phase producing a report. The full Statement of Task for the two-phase project is provided in Chapter 1. In the first phase, the study committee is charged with reviewing the Task Force's completed, ongoing, and planned tasks. Specifically, the committee is asked to examine the quality, completeness, and relevance of the research, testing, and analysis tasks and to provide advice on how they could be improved, recognizing that the two agencies will need to remain vigilant in monitoring the effectiveness of the requirements in the rule authorizing movement of LNG by rail. This report is the product of this first phase, and is therefore limited to reviewing the plans and progress of the Task Force. While the Task Force's work finished in 2020, some tasks remain pending and therefore may be modified on the basis of the review's findings. Likewise, there may be opportunities to strengthen the analyses of the results of completed tasks to better inform future decision making and research, testing, and analysis activities.

No longer limited to examining the Task Force's research, testing, and analysis activities, the second phase of the project will provide a more in-depth review of the safe transportation of LNG, including an examination of the applicability of existing guidelines for emergency responses to LNG rail incidents and safety assurance measures that address a range of risk factors such as incidents caused by deliberate acts, human factors, or track component defects. The second phase is scheduled to be completed in mid-2022.

STUDY APPROACH

The committee was not tasked with conducting its own analyses, but rather to exercise its expert judgment on the basis of what it learned from PHMSA and FRA briefings and materials describing and documenting the outcomes, plans, and status of the Task Force's work. The documents and briefings explained the methodologies used in conducting the research, analyses, modeling, and testing for each task and how the results are being, or will be, integrated into the safety assurance mission of PHMSA and FRA. In its review, the committee focused on the Statement of Task's emphasis on assessing the initiative's relevance, completeness, and quality to support PHMSA, FRA, and industry decision making going forward to ensure the safety of LNG rail movements and monitor the efficacy of the requirements in the new rule authorizing them.

In treating relevance first, the committee considered how directly each of the 15 tasks aligns with the transportation of LNG by rail tank car. The six tasks that addressed LNG specifically were considered to be the most relevant, and thus grouped and examined together for completeness and quality. The groupings are shown in Figure S-1. An example is the Worst-Case Scenarios Model, which examines how the hazard characteristics of LNG would affect the type and severity of the consequences of a rail incident. Next, in terms of relevance, the committee examined the tasks that concern rail transportation of hazardous materials more generally, an example being the Safety and Security Route Risk Assessment task. Finally, the committee considered the completeness and quality of tasks that concern railroad safety assurance generally, such as the task on the Automated Track Inspection Program (ATIP). It merits noting that this regrouping of the tasks based on their specific relevance to LNG and its safe transportation by rail is not a prioritization of the 15 tasks with respect to their overall significance for understanding and reducing risk, but rather a reflection of the committee's charge to examine the specific risks associated with LNG.

The three groupings provide an organizing framework for the report chapters. The groupings reveal how the results and information from one task are intended to inform others. Figure S-1 maps the connections among the individual tasks to show these interrelationships. The tasks to the left involve gathering empirical data; the tasks in the middle use the collected data to create models; and the tasks to the right use the simulation results in analyses.

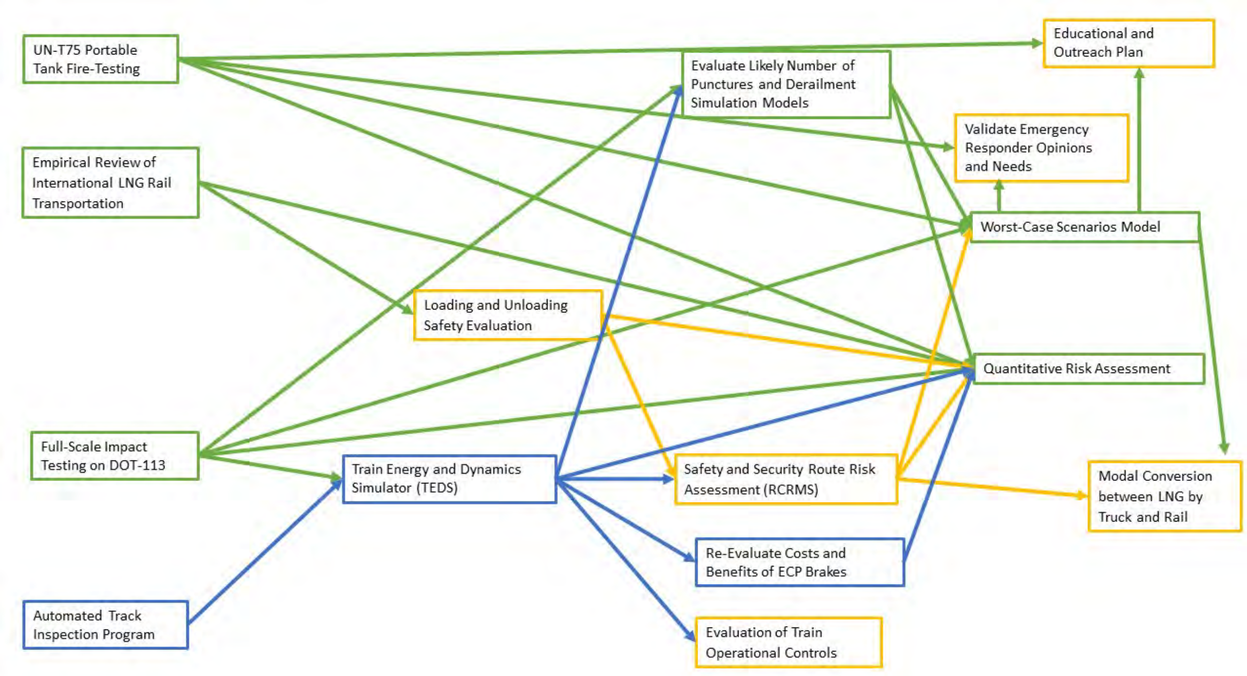

FIGURE S-1 Relationships between the 15 tasks by grouped by relevance to LNG transportation by rail.
NOTES: The six tasks in green are specifically relevant to LNG by rail. The six tasks in yellow are relevant to hazardous materials transport by rail. The three tasks in blue are broadly relevant to railroad safety assurance.

SUMMARY ASSESSMENT

Considering the large and varied number of tasks, their interdependencies, and the major disruptions caused by the COVID-19 pandemic to the execution of several tasks, the committee believes that the Task Force's program is comprehensive as planned. The incomplete status of many of the tasks is justified under the circumstances, particularly because of the interconnections among the tasks. The committee observes that the Task Force's efforts benefited from an ability to make effective use of a number of longstanding programs at PHMSA and FRA, such as the tank car impact testing and automated track inspection programs. Nevertheless, there are areas, in the committee's view, where more complete treatment is warranted, and where the basis for choices about the structure and execution of the tasks, such as those pertaining to experimental design and the selection of parameters for modeling and other analyses, has not been made sufficiently clear to assess the applicability and validity of the results. In a few cases where the grounds for such choices are explained, the committee raises questions about them and offers some suggestions for improvement.

PHMSA and FRA wisely capitalized on a number of longstanding and high-quality research and testing programs to adapt them to the questions surrounding the safe movement of LNG by tank car. For instance, FRA's ATIP builds on approximately four decades of developing track geometry measurement vehicles equipped with state-of-the-art technology for data acquisition about track infrastructure conditions. Likewise, PHMSA has decades of experience collaborating with and supporting the emergency response community. PHMSA conducts regular outreach activities and has long supported identified responder needs through funding to state, local, and industry entities for transportation-related hazardous materials planning, training, and exercises. In addition, the tasks on Full-Scale Impact Testing and Punctures and Derailment Simulation Modeling consist of programs that have been validated experimentally and used to support previous tank car design efforts. Notably, the decision to require a thicker outer tank for the newly specified cryogenic tank car was based on the punctures modeling.

Knowing that the Task Force commenced its work during the outbreak of the pandemic, the committee fully expected to find tasks that required physical testing and site visits to be incomplete or pending, and that these delays would, in turn, lead to the incomplete status of other research and analytic tasks. Notably, impact testing on a tank car filled with liquid nitrogen, which is needed for understanding the puncture resistance of the newly specified DOT-113C120W9, will not take place until late 2021. The results from these pending tests are expected to inform the tasks on the Worst-Case Scenarios Model, Punctures and Derailment Simulation Modeling, and Train Energy and Dynamics Simulator tasks. Other tasks were similarly postponed and thus lacked sufficient information for the committee's review. For example, site visits associated with Train Operational Controls have been postponed, and the analysis for the Modal Conversion Between Truck and Rail is pending submission of a specific shipping route. Although the Safety and Security Route Risk Assessment task is also delayed, the committee was unable to review the relevant security factors that will be considered because the Task Force could not share sensitive information related to the route assessment.

The following are examples of where the committee believes the Task Force should offer a clearer rationale for the choices made in designing and executing tasks, particularly with respect to several of its testing and modeling tasks:

- Full-Scale Impact Testing—Impact testing is conducted to understand the baseline puncture resistance of a tank car design given certain conditions. Because the outer-tank closure seams appear more vulnerable to impact than the center of an outer tank plate (or the post-weld heat treated seam of a tank car), it would be helpful to know why the Task Force did not test for impacts on this part of the tank and whether it intends to do so in follow-on tests.
- Portable Tank Fire Testing—The design of the fire tests involved choices about pool fire size and shape and orientation of the tank with respect to the fire. The test also used a portable tank on a flatcar rather than a tank car. The fuel used for the pool fire was liquefied petroleum gas instead of LNG. These may have been necessary and valid choices under the circumstances (e.g., in the absence of a manufactured newly-specified tank car and because of testing safety concerns about LNG). However, the choices are likely to affect the relevance of the testing to predictions of the survivability of a DOT-113C120W9 tank car engulfed in an LNG pool fire. The Task Force should provide a detailed accounting of these choices that could have bearing on that relevance.
- Worst-Case Scenarios Model—The task uses 40 mph as the speed of a train before derailment based on the results from the puncture and derailment simulation task. Because the task is intended to represent worst-case scenarios, the committee questions why this particular speed was selected rather than the 50 mph speed also

run in the simulations. Several other choices warrant further explanation as well, including the exclusion from the scenarios of the heat flux from a jet fire, cascading cryogenic damage from partial submersion in a pool of LNG, and heat flux from a pool fire to the adjacent tank cars. While there may be valid reasons for excluding these conditions, they should be documented to provide a more convincing case of the task's credible representation of worst-case scenarios.

- Quantitative Risk Assessment (QRA)—The task references a previously conducted QRA for unit train movements of LNG tank cars on routes for a single origin–destination pair. The QRA did not consider LNG movements in a manifest train (i.e., mixed cargo) or under other conditions not represented by those found on the routes of this single origin–destination pair. The committee understands the challenge of conducting QRAs in a generalized manner without specific routes and train configurations that can be subject to analysis. However, the conduct of QRAs for more varied scenarios for LNG routings and train configurations, even if hypothesized, would provide insights into the conduct of QRAs for LNG by rail movements on a national basis.
- Modal Conversion Between Truck and Rail—The Task Force completed an initial examination of the risk implications of diverting LNG traffic from truck to rail and vice versa for possible routes under a 2019 special permit for LNG by rail tank car between Pennsylvania and New Jersey. PHMSA plans to repeat this analysis when the shipper and rail carrier identify an actual route in fall 2020. Missing from this task are the risks entailed in loading and unloading operations. While the conditions during line-haul movement differ between rail and truck, thus presenting different risks, there are also differences in loading and unloading operations. In addition, train assembly and classification activities were also missing from this task. These differences warrant consideration because both are sources of injuries and fatalities in hazardous goods movement.
- Train Energy and Dynamics Simulator (TEDS)—TEDS was used to simulate unit train operations over two rail routes designated for LNG transport by DOT-113 tank cars under various conditions. The simulation results produced train speed, coupler forces, lateral and vertical force ratios, and other results used in other tasks. The committee questions, however, why the model was not run using a train with distributed motive power, which is one of the operational requirements in the rule authorizing LNG by rail. Documenting the placement of the buffer car in the train is also important for assessing the predictive power of the software.

RECOMMENDATIONS ON PENDING WORK

Because the Task Force has already completed a significant amount of work and had a limited lifespan, the opportunities for the committee to advise are limited to suggesting improvements that can be made to the explanation, analysis, and documentation of completed work—as offered above—and recommending changes to planned tasks or to work related to LNG safety that is likely to be pursued by PHMSA and FRA in the future after the Task Force completes its work. The following recommendations are intended for this purpose.

Portable Tank Fire Testing

Recognizing that Phase 2 of the first testing task has not begun, FRA and PHMSA should make several changes to the planned testing to improve data quality and analysis. Changes that should be made include:

- Modify the pool fire by increasing its size and making it circular;
- Remove the flatcar from the experimental setup;
- Place the tank car in a rollover orientation where the pressure relief valve will vent liquid;
- Use LNG as the pool fire fuel;
- Evaluate an LNG fireball and tank fragmentation in the event of a boiling liquid expanding vapor explosion to prepare emergency response personnel; and
- Assess the potential for cryogenic damage cascading to adjacent tanks by evaluating topography surrounding the rail tracks that could support pool formation.

Worst-Case Scenarios Model

Enhancing the modeling for worst-case scenarios will require inputs from the pending tasks on full-scale impact test, punctures and derailment simulation, and fire testing. Once these pending tasks are completed and data are collected and analyzed for incorporation, PHMSA and FRA should further update the model for worst-case scenarios in the following manner:

- Provide upper bound values of predicted number of punctures to identify the worst-case release rather than using nominal values;
- Use a train speed of 50 mph for the predicted number of punctures rather than the 40 mph used;
- Evaluate the heat flux from a jet fire from a punctured tank and impinging on an adjacent tank;
- Evaluate the total amount of LNG that could potentially be released from cascading damage to adjacent tank cars from partial submersion in an unignited pool of LNG and/or partial exposure to the heat flux from a pool fire;
- Evaluate the potential hazard to emergency responders of a rapid phase transition from an LNG spill onto a body of water, considering that track infrastructure commonly runs along rivers; and
- Evaluate explosion hazards from an unignited spill of LNG resulting in vapor dispersion in an environment with confined or congested spaces.

Modal Conversion Between Truck and Rail

PHMSA should add loading and unloading operations and train assembly and classification activities to the assessment of the risk of LNG by rail as compared with highway when repeating this task in fall 2022.

CONCLUDING COMMENT

The committee found it challenging to review and integrate the documentation of the 15 tasks. That documentation and its integration have been complicated by the expedited schedule of tasks and the subsequent interruptions caused by the pandemic. It will be important, however, for the Task Force's work to be carefully documented and the purpose and results of the tasks appropriately connected. This report tries to provide some of that integration, but gaps in the documents and pending tasks will need to be addressed first. In the committee's view, the overarching safety assurance enterprise would be improved by establishing a framework for systematically integrating and reporting the results from the tasks. Ensuring the safety of LNG by rail, like all hazardous materials shipments, is an ongoing process that will require continued monitoring and adjustment of practice and regulations.

1

Introduction

Natural gas production in the United States has increased considerably over the past decade. The application of hydraulic fracturing and directional drilling techniques has enabled the extraction of oil and gas from reserves in regions not previously known for hydrocarbon production such as the Bakken Formation in North Dakota and Marcellus Shale Gas Play centered largely in Pennsylvania. These newly accessible reserves have had far-reaching effects on the country's energy supply and demand, contributing to natural gas' predominance in electric power generation and a growing interest in transporting gas supplies to new domestic and export markets.

Most natural gas produced and consumed domestically is transported under pressure through the country's 300,000-mile system of long-distance transmission pipelines.[2] Likewise, supplies exported to Canada and Mexico are moved almost exclusively by pipeline.[3] However, transmission pipeline capacity is limited in some regions of the country, such as the Northeast, and pipelines are not a practical option for transporting natural gas to regions outside of North America. The efficient transportation of natural gas through means other than pipelines requires compression or liquefaction. When liquefied, the gas is cooled to –260°F (–182°C), decreasing its volume to 1/600th of its gaseous form. This denser, liquefied natural gas (LNG) can be transported in specialized cryogenic tanks via ocean-going marine vessels (i.e., LNG tankers), which can hold tens of millions of gallons,[4] or by truck in smaller intermodal International Organization for Standardization (ISO) containers having a capacity of about 5,000 to 11,000 gallons[5] and in cargo tank trucks capable of holding about 12,700 gallons (in an MC 338 cargo tank).[6] Shippers have moved LNG by marine tankers and trucks for more than 50 years.

Notably, LNG has not been transported to any significant degree by freight railroads in the United States. Indeed, federal hazardous materials transportation safety regulations had not authorized the movement of LNG by rail tank car, although they authorized case-by-case approvals for transport on flatcars in ISO containers. In 2015, the U.S. Department of Transportation's Federal Railroad Administration (FRA), in coordination with the Pipeline and Hazardous Materials Safety Administration (PHMSA), gave approval to the Alaska Railroad

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[2] Pipeline and Hazardous Materials Safety Administration, "Annual Report Mileage for Natural Gas Transmission and Gathering Systems," May 3, 2021, https://www.phmsa.dot.gov/data-and-statistics/pipeline/annual-report-mileage-natural-gas-transmission-gathering-systems.

[3] U.S. Energy Information Administration, "Natural Gas Imports and Exports," July 21, 2020, https://www.eia.gov/energyexplained/natural-gas/imports-and-exports.php.

[4] T. Blanchat, M. Hightower, and A. Luketa, "LNG Use and Safety Concerns," November 1, 2014, p. 7, https://www.osti.gov/servlets/purl/1367739.

[5] Pipeline and Hazardous Materials Safety Administration, "Preliminary Regulatory Impact Analysis," October 22, 2019, p. 15, https://www.regulations.gov/document/PHMSA-2018-0025-0001.

[6] Pipeline and Hazardous Materials Safety Administration, "Risk Assessment of Surface Transport of Liquid Natural Gas," U.S. Department of Transportation, Washington, DC, March 20, 2019, p. 52, https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/research-and-development/hazmat/reports/71651/fr2-phmsa-hmtrns16-oncall-20mar2019-v3.pdf.

Corporation to transport LNG by rail in ISO containers and granted Florida East Coast Railroad similar approval in 2017.[7] These approvals for rail movements in ISO containers were followed in 2017 by an Association of American Railroads (AAR) petition requesting that LNG be included among the commodities permitted for transport in DOT-113C120W and DOT-113C140W cryogenic tank cars.[8] In its petition, AAR maintained that no explicit determination had ever been made that these tank cars are unsuitable or unsafe for transporting LNG. AAR contended that the only reason why the federal regulations did not permit LNG's transport by tank car was because approval had not been sought, as there was no market demand for bulk rail movements of LNG when DOT-113 tank cars were originally authorized to transport other cryogenic liquids such as argon, ethylene, nitrogen, and oxygen.[9,10]

As depicted in Figure 1-1, the DOT-113 class of tank cars consists of an inner tank supported in an outer jacket, hereafter referred to as an outer tank.[11] The inner tank, made of stainless steel, contains the cargo. The outer tank, which is made of carbon steel, supports the inner tank and contains insulation and a vacuum in the annular space between the two tanks to contain cryogenic liquids having boiling points lower than –130°F at atmospheric pressure.[12] The DOT-113 specification is not a pressure tank car.

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[7] Pipeline and Hazardous Materials Safety Administration, "Preliminary Regulatory Impact Analysis," p. 9.

[8] Association of American Railroads, "Petition for Rulemaking to Allow Methane, Refrigerated Liquid to Be Transported in Rail Tank Cars," January 13, 2017, https://www.regulations.gov/document/PHMSA-2017-0020-0002.

[9] Pipeline and Hazardous Materials Safety Administration, "Hazardous Materials: Liquefied Natural Gas by Rail—Final Rule," 85 FR § 44994, 2020, https://www.federalregister.gov/documents/2020/07/24/2020-13604/hazardous-materials-liquefied-natural-gas-by-rail. Although nearly obsolete, a non-specification DOT-113 tank car-style tank in a box car had been used for more than 60 years to transport cryogenic atmospheric gases such as argon, nitrogen, and oxygen.

[10] Varying specifications of the DOT-113 tank car exist. For instance, the main difference between the DOT-113C120W and DOT-113C140W specifications is that the former is pressure rated for 120 pounds per square inch gauge (psig) while the latter is rated for 140 psig. Similarly, the primary differences between the DOT-113C120W and the newly developed DOT-113C120W9 is that the outer jacket shell thickness of the former is 7/16 inches, and the enhanced outer jacket shell of the latter must be 9/16 inches and made of AAR TC128 Grade B normalized steel plate.

[11] There is more than one way to refer to the outermost longitudinal section of the DOT-113 tank car. Usage in the 2020 final rulemaking tends heavily toward outer tank and less so toward outer shell, with a handful of instances in formal regulatory text to outer jacket shell or outer jacket. For consistency hereafter, this report uses outer tank throughout.

[12] Association of American Railroads, "2017 Field Guide to Tank Cars," February 6, 2017, p. 2, https://www.aar.org/wp-content/uploads/2017/12/AAR-2017-Field-Guide-for-Tank-Cars-BOE.pdf.

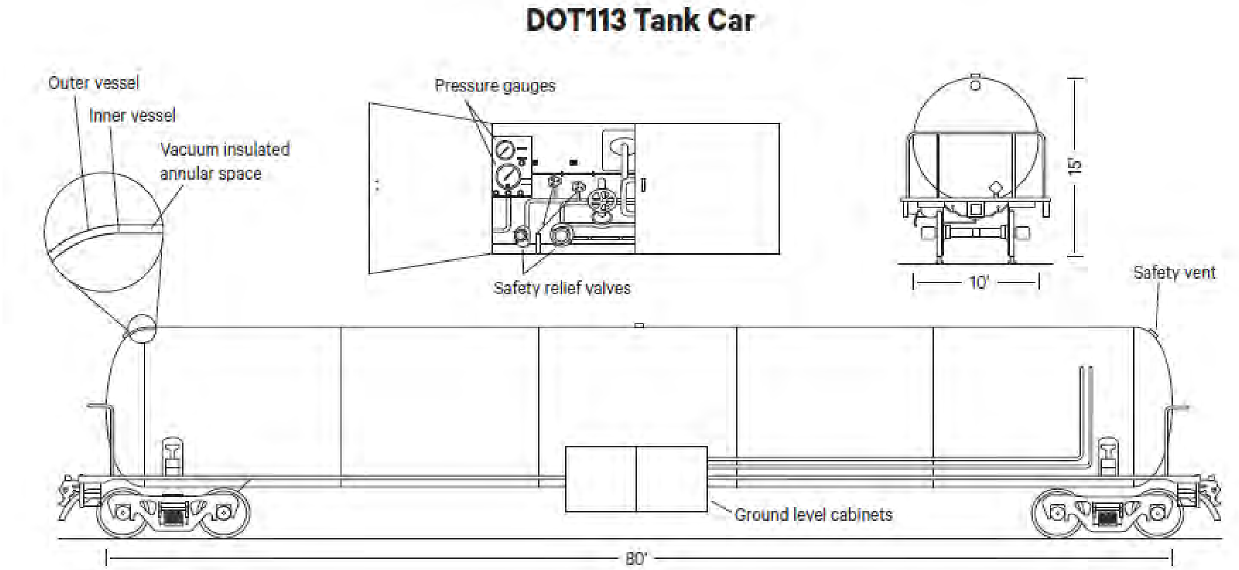

FIGURE 1-1 Schematic of DOT-113 tank car and its key features.
SOURCE: PHMSA.

In December 2019, PHMSA issued a special permit for rail shipments of LNG by the most common DOT-113 tank car, the DOT-113C120W design, on a route from Wyalusing, Pennsylvania, to a planned LNG export terminal in Gibbstown, New Jersey.[13] This special permit marked the first time that LNG was authorized for rail transport in a container other than an ISO container. Because of the small number of eligible DOT-113C120W tank cars in the North American fleet, totaling fewer than 100, PHMSA and FRA anticipated that these movements would initially occur in manifest (i.e., mixed cargo) trains containing a single tank car or small blocks of tank cars rather than in unit trains having only tank cars.

Following this special permit, PHMSA initiated a rulemaking in October 2019 to consider a broader authorization for the transportation of LNG by railroad tank car, as required by an April 2019 Executive Order (EO 13868). The executive order required the agency to propose regulations that "treat LNG the same as other cryogenic liquids and permit LNG to be transported in approved rail tank cars."[14] In July 2020 this broader authorization was granted in a final rule issued by PHMSA in coordination with FRA. The new rule included a stipulation that the DOT-113C120W be modified with an enhanced outer tank, indicated by the new specification suffix "9" (DOT-113C120W9). The design enhancements consist of an outer tank shell that is thicker (increasing to 9/16 inches from 7/16 inches) and made of steel with greater puncture resistance. In addition, the rule stipulated that the rail movements would also be subject to operational controls for braking, monitoring, and routing. The operational controls require:

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[13] Pipeline and Hazardous Materials Safety Administration, "Special Permit DOT-SP 20534, Granted to Energy Transport Solutions, LLC," December 5, 2019, https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/safe-transportation-energy-products/72906/dot-20534.pdf.

[14] Executive Office of the President, "Executive Order 13868, Promoting Energy Infrastructure and Economic Growth," 84 FR Federal Register § 15495, 2019, https://www.federalregister.gov/documents/2019/04/15/2019-07656/promoting-energy-infrastructure-and-economic-growth.

- Use of a two-way, end-of-train device or distributed power for enhanced braking when a train has 20 or more continuous LNG tank cars, or 35 in total;
- Train location and inner tank pressure monitoring for each tank car containing LNG; and
- Compliance with the safety and security route planning requirements already required for certain other hazardous materials rail shipments, including explosives and materials that can be poisonous when inhaled.[15]

REQUEST FOR THIS STUDY

Controversy and questions accompanied PHMSA's 2019 special permit for the transportation of LNG by the DOT-113 tank car and the executive order directing the agency to propose rules to allow broader authorized use of the tank car for LNG shipments. Questions were raised about the potential for one or more tank cars to become damaged in train derailments or other accidents that could cause a loss of containment leading to large quantities of LNG vaporizing and igniting.[16]

To address these concerns, PHMSA and FRA established a special joint LNG-by-rail task force (Task Force) to increase the two agencies' understanding of the types and magnitude of risk posed by LNG when moved in bulk quantities by rail; identify and assess measures that can reduce these risks; and provide a more complete understanding of preparations needed to respond to any incidents that might arise. The Task Force was formed in January 2020, 3 months after the notice of proposed rulemaking to authorize LNG's rail transportation by the standard DOT-113 tank car and 6 months prior to the final rule granting this authorization with conditions for the modification of the tank car's design and operational controls.

The Task Force's initiative was created with 15 tasks intended to contribute to an enhanced understanding of the risks involved in transporting LNG by rail and potential means for managing these risks. As shown in Table 1-1, the tasks were intended to help PHMSA and FRA know, predict, reduce, and prepare for the risks. The tasks associated with first three purposes—to know, predict, and reduce the risks—would consist of research, data gathering, testing, and analyses to identify, prevent, and mitigate the likelihood of a derailment that might lead to a loss of LNG containment from tank cars. The fourth set of tasks would focus on preparations to enhance the capacity of emergency responders to manage a potential incident involving the release of LNG.

[15] Pipeline and Hazardous Materials Safety Administration, "Additional Planning Requirements for Transportation by Rail," 49 CFR § 172.820, May 11, 2021, https://www.ecfr.gov/cgi-bin/text-idx?SID=8635f36b16798bc467af327f88986759&mc=true&node=se49.2.172_1820&rgn=div8.
[16] Pipeline and Hazardous Materials Safety Administration, "Hazardous Materials: Liquefied Natural Gas by Rail, Final Rule," 45022.

TABLE 1-1 Tasks in the Liquefied Natural Gas (LNG) Task Force Project Plan as Categorized by the Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration

KNOW the Risk	PREDICT the Risk	REDUCE the Risk	PREPARE for the Risk
Empirical Review of International LNG Rail Transportation	Evaluate Punctures and Derailment Simulation Model	Electronically Controlled Pneumatic Brakes	Emergency Responder Opinions and Needs
Loading/Unloading Safety Assessment	Worst Case Scenario Model	Train Operational Controls	LNG Educational and Outreach Plan
Quantitative Risk Assessment	Safety/Security Route Risk Assessment	Automated Track Inspection Program	
Full-Scale Impact Testing	Train Energy Dynamics Simulator		
UN-T75 Portable Tank Fire Testing	Modal Conversion Between LNG by Truck and Rail		

On December 19, 2020, the Further Consolidated Appropriations Act of 2020 was enacted.[17] The act directed PHMSA to enter into an agreement with the National Academies of Sciences, Engineering, and Medicine (the National Academies) to convene a committee of independent experts to study the safe transportation of LNG by rail tank car. As noted, however, by that time PHMSA had already issued (on October 24, 2019) the rulemaking notice proposing the authorization of LNG shipments by DOT-113 tank cars[18] and was obligated by EO 13868 to finalize the rulemaking by mid-2020.

While the timing of the rulemaking schedule would preclude the National Academies' study from informing the rulemaking, PHMSA nevertheless viewed the study as an opportunity for an external review of the Task Force's work and plans. The Task Force remained active after the rulemaking to inform future government and industry efforts to ensure the safe transportation of LNG by rail. PHMSA and FRA therefore negotiated a Statement of Task with the National Academies that consists of two study phases, each producing a report by the same study committee. The first phase would entail a review of the Task Force's completed, ongoing, and planned tasks, and is therefore limited to reviewing these tasks. The second phase would consist of a more in-depth study of subject matter relevant to the safe movement of LNG by rail. The second phase is scheduled to be completed in mid-2022. The full Statement of Task is provided in Box 1-1.

In reviewing the Task Force's program, PHMSA requested that the study committee exercise its expert judgment to provide timely and strategic feedback on the quality, completeness, and relevance of the program for decisions that PHMSA and FRA will need to make in overseeing and monitoring the effectiveness of the requirements and conditions of the

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[17] Further Consolidated Appropriations Act of 2020: Committee Print of the Committee on Appropriations, U.S. House of Representatives.

[18] Pipeline and Hazardous Materials Safety Administration, "Hazardous Materials: Liquefied Natural Gas by Rail—Notice of Proposed Rulemaking," 84 FR § 56964, 2019, https://www.regulations.gov/document/PHMSA-2018-0025-0002.

rule authorizing LNG's movement by rail tank car. The committee is asked to make recommendations, as appropriate, that PHMSA and FRA can act on to strengthen the Task Force's plan and its execution.

This report is the outcome of the committee's first phase review. The second phase, which will be informed by this report and future data-gathering sessions, will consider experience transporting LNG in other modes, including marine tankers and cargo tank trucks. It will provide an opportunity for a more in-depth review of what is known about the effectiveness of regulatory and industry measures to ensure the safety of other types of hazardous shipments that may be pertinent to the safety of transporting LNG by rail. It will also examine the applicability of existing emergency response plans, protocols, and guides for responding to hazardous materials transportation incidents more generally to LNG rail transportation.

BOX 1-1
Statement of Task

An ad hoc committee appointed by the National Academies of Sciences, Engineering, and Medicine will review, per request of Congress, current U.S. Department of Transportation (USDOT) plans and activities to inform government and industry decisions about the transportation of liquefied natural gas (LNG) by rail and consider ways to ensure the continued safety of these shipments over the longer term. The committee's review will be carried out in two phases, each producing a report with findings and recommendations as appropriate.

Phase 1

The committee will review ongoing and planned USDOT efforts, as documented and reported by the Pipeline and Hazardous Materials Administration (PHMSA) and the Federal Railroad Administration (FRA), that are intended to inform pending decisions about whether and how bulk shipments of LNG can be safely transported by railroad tank car. The review will focus specifically on the plans and progress of the PHMSA–FRA LNG Task Force, which has developed and begun executing a multi-task program of research, data gathering, analysis, testing, modeling, and risk assessment. Based on the expert judgment of its members, and drawing largely on the Task Force's reports of results, ongoing and planned tasks, and other relevant information, the committee will produce a report with findings on specific tasks and the program overall with regard to quality, completeness, and relevance to the agencies' near-term decision-making needs. The committee may make recommendations in this first report that can be acted on quickly to strengthen the program.

Phase 2

The committee will engage in information gathering and analysis to conduct an in-depth study of topics relevant to ensuring the safe movement of LNG by rail if allowed by special permit or regulatory authorization. At a minimum, the committee will examine:

- The experience of transporting LNG in bulk shipments by other modes, including by water and truck, to identify basic principles applied for safety assurance that can inform measures taken by government and industry to ensure the safe movement of LNG by rail;

- What is known about the effectiveness of special regulatory and industry measures intended to assure the safe transportation of other relevant bulk rail shipments of hazardous materials, especially any routing, speed, and other operational controls applied to high-hazard flammable trains and accompanying enhanced track inspection regimes; and
- The applicability to bulk rail transportation of LNG of current emergency response plans, protocols, and guides for responding to LNG transportation incidents, such as in PHMSA's Emergency Response Guidebook.

In carrying out its review of these topics, the committee may determine that there are other topics directly relevant to the safe transportation of LNG by rail that warrant examination, and it may elect to do so. Based on findings from the study, the committee will issue a second report containing recommendations as appropriate to Congress, PHMSA, FRA, industry, emergency responders, and other relevant parties on actions, both nearer and longer term, that are warranted to improve understanding of the risks associated with transporting LNG by rail, mitigate risks, and prevent and prepare for potential incidents.

STUDY APPROACH AND ISSUES

The committee began its work with a review of Task Force documents. They included the Task Force's initial work plan,[19] an interim progress report issued in July 2020,[20] and various other materials that describe the status and outcomes of the planned and performed tasks. The Task Force members then briefed the committee on the methodologies used in conducting the analyses, modeling, and testing associated with individual tasks and how the results are being, or will be, integrated into the safety assurance mission of PHMSA and FRA.

In reviewing the Task Force's work, the committee focused on the Statement of Task's emphasis on assessing the work's relevance, completeness, and quality to support PHMSA, FRA, and industry decision making going forward to ensure the safety of LNG rail movements and monitor the efficacy of the requirements in the new rule authorizing them. In considering relevance first, the committee considered how closely each of the 15 tasks aligns with the transportation of LNG by rail tank car. The tasks that addressed LNG directly were considered to be most specifically relevant, and thus were examined first for completeness and quality—an example being the Task Force's Worst-Case Scenarios Model, which examines how the hazard characteristics of LNG would affect the consequences of an incident. Next, in terms of relevance, the committee reviewed for completeness and quality the tasks that address rail transportation of hazardous materials more generally, an example being the Task Force's Safety and Security

[19] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "Strategic Initiative for LNG by Rail Project Plan," February 6, 2020, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/TaskFrce_DftProjPlan_Feb6_2020.pdf.

[20] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "FRA–PHMSA LNG by Rail Task Force Interim Report," July 23, 2020, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/July2020_Dft_LNG_IntReport_TmRev.pdf. The interim report also serves as the Task Force's final report.

Route Risk Assessment. Finally, the committee considered the completeness and quality of tasks that relate to railroad safety generally, such as the task on the Automated Track Inspection Program.

This regrouping of the tasks based on their specific relevance to LNG and its safe transportation by rail is not intended to be a prioritization of the 15 tasks with respect to their overall significance for understanding and reducing risk. The groupings, as shown in Table 1-2, provide an organizing framework for the report.

TABLE 1-2 Grouping of 15 Tasks by Relevance to Liquefied Natural Gas (LNG) Transportation by Rail

Specifically Relevant to LNG by Rail
International Experience Transporting LNG by Rail
Full-Scale Impact Testing for Tank Cars
Punctures and Derailment Simulation Modeling
Portable Tank Fire Testing
Worst-Case Scenarios Model
Quantitative Risk Assessment
Relevant to Hazardous Materials Transport by Rail
Loading and Unloading Safety Assessment
Safety and Security Route Risk Assessment
Train Operational Controls
Modal Conversion Between Truck and Rail
Emergency Responder Opinions and Needs
Educational and Outreach Plan
Broadly Relevant to Railroad Safety
Train Energy Dynamics Simulator
Electronically Controlled Pneumatic Brakes
Automated Track Inspection Program

REPORT ORGANIZATION

The remainder of the report consists of four chapters. The next chapter (Chapter 2) provides background on LNG and its properties that can cause hazards when transported by rail and other modes. Chapters 3 through 5 assess the completeness and quality of the 15 tasks grouped according to the relevance criteria explained above. The task groupings in Chapters 3, 4, and 5 are as follows:

Chapter 3 reviews the tasks having most specific relevance to rail transport of LNG: International Experience Transporting LNG by Rail, Full-Scale Impact Testing for Tank Cars, Punctures and Derailment Simulation Modeling, Portable Tank Fire Testing, Worst-Case Scenarios Model, and Quantitative Risk Assessment. These six tasks were considered to be most specifically relevant to LNG's transportation by rail.

Chapter 4 reviews the tasks that concern the safe rail transportation of hazardous materials more generally: Loading and Unloading Safety Assessment, Safety and Security Route Risk Assessment, Train Operational Controls, Modal Conversion Between Truck and Rail, Educational and Outreach Plan, and Emergency Responder Opinions and Needs. These six tasks were considered to be relevant to the safe transportation of any hazardous materials by rail, not exclusively to LNG.

Chapter 5 reviews the remaining tasks that pertain to railroad safety more generally: Train Energy Dynamics Simulator, Electronically Controlled Pneumatic Brakes, and Automated Track Inspection Program. These three tasks relate to railroad transportation safety more broadly.

It merits noting that the Task Force was formed and began its work during the COVID-19 pandemic. A mandatory work-from-home order issued by the federal government took effect in March 2020, and by necessity significantly delayed the execution of several items in the Task Force's program plan, including tank car testing and site visits. At the outset of the study, therefore, the committee expected to find that some of the program's tasks, including a few originally expected to be completed in 45 days or less, had not been completed or even initiated. Indeed, some were incomplete at the time of the committee's review, which commenced in fall 2020. The varied status of the tasks, in terms of completeness, is noted in the report.

2

Background on Liquefied Natural Gas and Its Transport

This chapter provides background on liquefied natural gas (LNG), its chemical and physical properties, and hazard characteristics. The chapter then discusses these hazards in the context of rail transportation.

WHAT IS LNG?

Natural gas is a mixture of hydrocarbons extracted from underground reservoirs that consists primarily of methane (CH_4) and small amounts of ethane, propane, and other heavier hydrocarbons. Natural gas extractions can also include trace amounts of nitrogen, helium, carbon dioxide, sulfur compounds, water, and in some cases, mercury. As noted in the previous chapter, natural gas can be liquefied to reduce its volume by a factor of about 600. Liquefaction allows for the transportation of supplies overseas and to domestic markets lacking gas transmission pipelines or requiring additional supplies to supplement pipeline gas. However, liquefaction alone does not transform natural gas into LNG. Before natural gas is liquefied, it is processed to remove impurities and meet end-user specifications. Table 2-1 lists the typical components of natural gas and supplies of LNG readied for transport. Natural gas processed to create LNG contains a higher percentage of methane and smaller amounts of other elements and compounds than unprocessed natural gas.

TABLE 2-1 Typical Molecular Composition of Natural Gas and Gas Processed for Liquefaction to LNG

Component (formula, name)	Mol % in Natural Gas[21]	Mol % in LNG[22]
CO_2, carbon dioxide	0.1–1.0	0.0
N_2, nitrogen	1.3–5.6	0.0–1.0
CH_4, methane	87.0–96.0	84.55–96.38
C_2H_6, ethane	1.8–5.1	2.0–11.41
C_3H_8, propane	0.1–1.5	0.35–3.21
i-C_4H_{10}, i-butane	0.01–0.3	0.0–0.7
n-C_4H_{10}, n-butane	0.01–0.3	0.0–1.3
i-C_5H_{12}, i-pentane	trace–0.14	0.0–0.02
n-C_5H_{12}, n-pentane	trace–0.04	0.0–0.04
n-C_6H_{14}, n-hexane	trace–0.06	0.0
Others	trace–0.12	0.0
Total	100.0	100.0

[21] North American Energy Standards Board, "Natural Gas Specs Sheet," n.d., p. 5, https://www.naesb.org/pdf2/wgq_bps100605w2.pdf.
[22] W.C. Ikealumba and H. Wu, "Some Recent Advances in Liquefied Natural Gas (LNG) Production, Spill, Dispersion, and Safety," *Energy & Fuels* 28, no. 6 (June 19, 2014):3556–3586, https://doi.org/10.1021/ef500626u.

LNG PROPERTIES AND HAZARD CHARACTERISTICS

As the primary constituent of LNG, methane and its chemical and physical properties determine the behavior of LNG cargoes. LNG, like natural gas, is transparent and colorless. However, unlike the processed natural gas moved in pipeline distribution systems, transported supplies of LNG are odorless. While processed natural gas is generally odorized for pipeline transportation to enable detection of leaks,[23] cryogenic temperatures prevent adding an odorant to LNG. Instead of odorization, carriers use detectors to monitor for methane leaks.

The cryogenic temperature leads to important differences in the properties of vapors from LNG and natural gas at ambient temperature. Because colder gases are denser than warmer gases, cold LNG vapor is heavier than natural gas at ambient temperature such as might be released from a pipeline (see Table 2-2). While methane is lighter than air of the same temperature and will disperse quickly in the event of a release from containment, LNG vapor is heavier than air because it is significantly colder and will sink when released to the atmosphere. If a sufficient amount of LNG is spilled, the cryogenic liquid can form a pool that will be accompanied by a dense cloud of vapors that will flow along the ground before dispersing as its temperature increases. Skin contact with an LNG pool or vapor cloud will cause cryogenic burns. Cryogenic damage to materials is also a concern because some exposed materials can become brittle and crack. In addition, like the vapors from other cryogenic liquids, a sufficiently high concentration of LNG vapor, especially in an enclosed area, can cause asphyxiation because it displaces oxygen in the area.

LNG is flammable as it returns to a gaseous state and mixes with air at ambient temperatures, which poses a combustion hazard once its concentration in the air reaches 5 percent and continues to do so up to 15 percent (see Table 2-2). LNG rapidly vaporizes into natural gas when it is spilled onto land or water to form a dense vapor cloud that has a very low height relative to its horizontal dimensions because the cold LNG vapor density is initially >1.5 times that of air. Owing to its low temperature, the cloud will not become immediately buoyant but will spread much farther and persist longer than hydrocarbon gases at ambient temperature that are lighter than air when immediately released. A low lying, dense cloud has a much greater chance of reaching an ignition source than one that readily disperses into the atmosphere. Moreover, once ignited, the heat radiated to objects in proximity to an LNG pool fire[24] is more extreme than the heat radiated from pool fires involving other hydrocarbon gases, such as liquefied petroleum gas (LPG). For example, the average surface emissive heat flux of an LPG pool fire is 48 kW/m^2 compared to 153–286 kW/m^2 for an LNG pool fire.[25] Likewise, the radiant

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[23] Title 49, CFR § 192.625, Odorization of gas.

[24] A pool fire can occur when a flammable liquid spills, spreads, mixes with air as it vaporizes, and finds a source of ignition. The fire is fueled by the continuing vaporization of the volatile liquid such that the mixture with air remains within its flammability limit.

[25] G.A. Mizner and J.A. Eyre, "Large-Scale LNG and LPG Pool Fires," 1982, 147–163; T.K. Blanchat et al., "The Phoenix Series Large Scale LNG Pool Fire Experiments," December 1, 2010, https://doi.org/10.2172/1044989. For LNG, the lower value is found in the work of Mizner and Eyre, the upper value in that of Blanchat et al. In addition, the range for a 35 m LNG pool in D. Nedelka et al. ("The Montoir 35 m Diameter LNG Pool Fire Experiments," in *Proc LNG IX, 9th Int Conf & Exp on LNG*, Nice, France, 1989) is 257–273 kW/m^2.

heat flux of an LNG fireball[26] (475–540 kW/m^2)[27] is also much higher than the heat flux from an LPG fireball (195–287 kW/m^2).[28,29] For an object engulfed by an LNG fire, the heat flux is about double that for one engulfed by an LPG fire.[30]

TABLE 2-2 Select Properties of Methane[31]

	Methane
Chemical formula	CH_4
Initial boiling point	–258.7°F
Vapor pressure, in mm Hg	
At 100°F	258,574
At –258.7°F	760
Relative vapor density (air = 1)	0.55
Flash point	–306°F
Auto-ignition temperature	1,004°F
Flammability limits, lower	5%
Flammability limits, upper	15%

HAZARDS IN THE CONTEXT OF RAIL TRANSPORTATION

Despite its hazards, LNG has been safely transported by marine vessel and cargo tank truck for several decades. The rail environment, however, is different, and therefore a central concern of the Task Force is examining these hazards in context, such as by presenting risks from a loss of containment during a derailment or by an error during transfer of the product to and from a rail tank car.

In a 2016 safety assessment, the Federal Railroad Administration (FRA) identified LNG's flammability, cryogenic, and handling properties as potentially creating hazards that

[26] A fireball can occur when a dense vapor cloud is ignited, which, for example, could be precipitated by the rupture of a container caused by a boiling liquid expanding vapor explosion. The dynamics of a fireball result in rapid consumption of the fuel and extreme heat.

[27] S. Betteridge and L. Phillips, "Large Scale Pressurised LNG BLEVE Experiments," January 2015, p. 9, https://www.scopus.com/inward/record.uri?eid=2-s2.0-84958212719&partnerID=40&md5=a4a0547c56b80bd20b4ecd4305318337.

[28] T. Roberts, A. Gosse, and S. Hawksworth, "Thermal Radiation from Fireballs on Failure of Liquefied Petroleum Gas Storage Vessels," *Process Safety and Environmental Protection* 78, no. 3 (May 1, 2000):184–192, https://doi.org/10.1205/095758200530628.

[29] Roberts, Gosse, and Hawksworth; D.M. Johnson, M.J. Pritchard, and British Gas plc. Research and Technology Division, *Large Scale Experimental Study of Boiling Liquid Expanding Vapour Explosions (BLEVEs)*, British Gas plc., Research and Technology Division, 1991, http://www.opengrey.eu/item/display/10068/632267. In referencing fireball tests of similar masses, the upper value of 540 kW/m^2 for LNG is comparable to 195 kW/m^2 for propane. The lower value of 475 kW/m^2 for an LNG fireball is comparable to an average of values (287 kW/m^2 and 344 kW/m^2) found in studies on LPG.

[30] Blanchat et al., "The Phoenix Series Large Scale LNG Pool Fire Experiments"; Pipeline and Hazardous Materials Safety Administration, "UN-T75 Portable Tank Fire-Testing Task Resource," August 2020, fig. 42. The committee compared Figure 42 in the section on "Fire Performance of Cryogenic ISO UN-75" in this resource document with the work by Blanchat et al.

[31] National Oceanic and Atmospheric Administration, "Chemical Datasheet: Methane," CAMEO Chemicals, n.d., https://cameochemicals.noaa.gov/chemical/8823.

warrant assessment for safe rail transportation.[32] With respect to each, FRA pointed to the following issues warranting attention:

1. Flammability—A spill of LNG, on land or on water, will rapidly evaporate, and the resulting vapor cloud will move via wind patterns before dispersing. If flammable concentrations come in contact with an ignition source, then it will ignite, and a flash fire will form down- and possibly upwind;
2. Cryogenic properties—In addition to the risk of cryogenic burns to people, materials such as metals that become embrittled at cryogenic temperatures are susceptible to cracking. In rail transportation, the TC-128 grade B steel outer tank shell of a DOT-113 tank has the potential for cracking from embrittlement when exposed to a release of LNG,[33] which could cause a loss of vacuum; and
3. Handling—Without a properly functioning pressure release valve system, the expansion ratio of LNG (600 to 1) could cause overpressurization, which could result in the rupture of the container. An overpressure can also result from a rapid phase transition, which is a mechanical explosion with a blast of enough magnitude to be a hazard to emergency response personnel working in close proximity to the release. Additionally, friction from flowing LNG may accumulate a static electric charge during the loading and unloading process without bonding and grounding. Training in the handling of LNG cargo is necessary to avoid a static discharge in the presence of flammable LNG vapor, which may be sufficient to cause ignition.

These and other hazards, as they pertain to the rail environment, are the subject of the Task Force's activities as reviewed in the chapters that follow.

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[32] Federal Railroad Administration Office of Research, Development and Technology, "LNG Safety Assessment Evaluation Methods," July 2016, Table 4, https://railroads.dot.gov/sites/fra.dot.gov/files/fra_net/16555/LNGSafetyAssessmentEvalMethods_final.pdf.
[33] B.W. Williams et al., "Capturing Variability in the Fracture Response of TC128B Steel Using Damage Mechanics," *Procedia Structural Integrity*, 1st Virtual European Conference on Fracture—VECF1, 28, January 1, 2020:1024–1038, https://doi.org/10.1016/j.prostr.2020.11.118.

3

Tasks Specifically Relevant to Transporting LNG by Rail

This chapter examines the completeness and quality of 6 of the 15 tasks in the Pipeline and Hazardous Materials Safety Administration–Federal Railroad Administration (PHMSA–FRA) Task Force initiative that have specific relevance to the transportation of liquefied natural gas (LNG) by rail tank car because of their focus on LNG and its properties and/or the DOT-113 specification tank car authorized for LNG transportation. The six tasks are International Experience Transporting LNG by Rail; Full-Scale Impact Testing; Punctures and Derailment Simulation Modeling; Portable Tank Fire Testing; Worst-Case Scenarios Model; and Quantitative Risk Assessment.

INTERNATIONAL EXPERIENCE TRANSPORTING LNG BY RAIL

The Task Force reviewed the available literature on the transportation of LNG by rail in other countries and the regulations and guidance that these countries provide for safe transportation. The Task Force identified seven countries besides the United States that authorize the transportation of LNG by rail, although only four of them—Germany, Japan, Portugal, and Spain[34]—are actively transporting the product by rail and all use portable tanks, such as International Organization for Standardization (ISO) containers, rather than tank cars. An important difference between these countries and the United States is that the railroad systems in the former are used primarily for passenger transportation, whereas the U.S. railroad system is used mainly for the movement of freight in much larger and heavier cars and on longer trains.

The Task Force reviewed the experience in Japan in the most depth, finding that 8 to 10 railcars carry LNG per day. All shipments are in intermodal portable tanks having a proprietary design rather than in ISO containers.[35] Operational regulations in Japan limit LNG shipments, like all other freight, to nighttime movements in relatively short train lengths commensurate with shorter emergency braking distances. All rail and shipper personnel who load and unload LNG and who are responsible for responding to incidents must undergo mandatory safety training on an annual basis.

Japan reports no unintended releases of LNG in transport for the past 20 years.[36] The Task Force members could not find reports of major incidents in the other three countries with active LNG shipping (Germany, Portugal, and Spain); however, rail safety databases in these countries do not always record incidents by commodity type.

[34] PHMSA states that Canada authorizes a rail tank car equivalent to the DOT-113, the TC-113. However, LNG has only been used as fuel for locomotives.
[35] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, “FRA–PHMSA LNG by Rail Task Force Interim Report,” p. 8.
[36] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, “International Empirical Review Task Resource,” August 13, 2020. Response from Japan Petroleum Exploration Company on FRA Questions, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/Intl_Review.pdf. Loss of containment has occurred, for example, because of a faulty valve.

Observations About Completeness and Quality

The major differences in the freight rail systems among the United States and other countries that authorize the movement of LNG by rail limit the applicability of their experience to the U.S. context, although the committee believes the Task Force was obligated to conduct this international review given its potential to identify relevant safety-related information.

In general, it appears that LNG has been moving without major incidents in the handful of countries where there is demand for its transportation by rail and approval to do so. The Task Force's review centered mostly on Japan's experience and was largely cursory, in part because of the limitations of incident data records. However, a more thorough and detailed review of the experience transporting LNG in other countries would be difficult to justify given the rail systems and containers used, none of which are characteristic of the U.S. situation. The Task Force did, however, learn that personnel in Japan who work with the LNG shipments must undergo annual safety training. More information on these training practices specific to LNG could be instructive for U.S. railroad and shipper personnel, a possible supplement to the task on Loading and Unloading Safety Assessment.

FULL-SCALE IMPACT TESTING FOR TANK CARS

The Task Force's Full-Scale Impact Testing of a DOT-113 tank car is part of an ongoing FRA testing program intended to develop standardized testing and simulation methodologies for quantifying the puncture resistance of tank cars. The testing program originated in 2007 when The Dow Chemical Company, Union Pacific Railroad, and Union Tank Car Company collaborated with FRA and the Volpe National Transportation Systems Center on the Next Generation Rail Tank Car Project[37] for testing designed to be repeatable and reproducible.[38] Impact testing establishes the baseline puncture resistance of a given tank car design reported in relation to speed and impactor size. The results from multiple tests on a range of tank car designs are used to establish the relative puncture resistance of different tank car designs. Test results also provide empirical data for the development and validation of impact and puncture finite element (FE) model capabilities. After validation, these capabilities are used to simulate the puncture resistance associated with various changes in impact conditions and tank design parameters.

In November 2019, Task Force members conducted a full-scale impact test on a standard DOT-113 tank car built with an outer tank shell thickness of 7/16 inches, as consistent with design specifications effective before the July 2020 rule authorizing the rail transportation of LNG in a modified DOT-113 tank car (i.e., a standard DOT-113C120W). The test entailed propelling a ram car equipped with a 12×12 inch impactor, at a velocity informed by the FE model, into the side of an empty tank car placed against a support wall. The tank car's inner tank and outer shell were punctured by the impactor at a closing speed of 16.7 mph, which validated

[37] Federal Railroad Administration, "Next Generation Tank Car Project (NGRTC)," November 13, 2019, https://railroads.dot.gov/program-areas/hazmat-transportation/next-generation-tank-car-project-ngrtc.
[38] F. Gonzalez III, "FRA Hazmat Tank Car Impact Test Research," *Railway Age*, March 3, 2021, https://www.railwayage.com/regulatory/fra-hazmat-tank-car-impact-test-research.

the FE model's prediction.[39] In June 2020, the researchers tested an empty, custom-built tank car as a surrogate for the newly specified DOT-113C120W9. It had an outer tank shell thickness of 9/16 inches and was made of a stronger grade of steel. This time, when traveling at a slightly higher closing speed of 17.3 mph, the impactor failed to puncture either wall of the surrogate tank car.[40]

Further tank car testing scheduled for 2020 and early 2021 had to be suspended due to travel restrictions during the pandemic. The testing program, however, is expected to resume in late 2021 with two additional tests with tanks holding a cryogenic liquid. The first test will use another surrogate tank car filled with liquid nitrogen. The second test will use a new DOT-113C120W9 (currently being manufactured) also filled with liquid nitrogen.

In discussing this activity with the committee, the Task Force members noted that the impact testing has interdependencies with several other tasks. For instance, performance of the Worst-Case Scenarios Model, Punctures and Derailment Simulation Model, and Train Energy and Dynamics Simulator tasks will benefit from the empirical data and increased understanding obtained from the DOT-113 tank car's structural response to impacts.

Observations About Completeness and Quality

Because of the pandemic, the most relevant impact test involving a newly specified DOT-113 car loaded with a cryogenic liquid will be conducted after this review is completed. The testing to date, however, supports use of FRA's FE model to predict puncture resistance of a standard DOT-113 tank car and the enhanced resistance of a surrogate tank built with a stronger outer tank shell as required in the new DOT-113 specification. Indeed, testing and simulation are critical for understanding low-frequency punctures in contrast to the extensive experience with tank car service-life performance, such as failures caused by tank deterioration over time.

A few clarifying points would have strengthened the Task Force's reporting on this task and its purpose to avoid misinterpretations. The Task Force's description should explain that the testing is designed to measure baseline puncture resistance under controlled conditions. The measurements will allow for comparisons to be made among tank cars for the development of data-driven tank car design changes. It is important to recognize that the impactor's closing speed is not intended to represent a train's operational speed when derailing. The relationship between impactor speed and operational speed is complicated by the chaotic nature of train derailments.

A point requiring explanation is the choice of tank impact location. The committee views the outer tank shell circumferential closure seams as a potentially more vulnerable location to impact than the center of an outer tank shell plate or the post-weld heat treated seam of a tank. An explanation for not testing the impact at the closure seams would be helpful.

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[39] Federal Railroad Administration Office of Research, Development and Technology, "Full-Scale Shell Impact Test of a DOT-113 Tank Car Surrogate," July 2020, p. 2, https://railroads.dot.gov/elibrary/full-scale-shell-impact-test-dot-113-tank-car-surrogate.

[40] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "FRA–PHMSA LNG by Rail Task Force Interim Report," p. 13.

PUNCTURES AND DERAILMENT SIMULATION MODELING

The Punctures and Derailment Simulation Modeling task had two objectives: to estimate the number of tank cars that would derail at a given train speed, and to estimate how many of the derailed tank cars would be punctured given different tank car design specifications. Simulations were run for multiple scenarios where:

- The derailment initiates at 30, 40, and 50 mph with the leading truck of the first car;
- Terrain varies;
- Loads experienced by the tank vary;
- Objects impacting the tank vary (i.e., such as a coupler head or broken rail); and
- Tank car designs vary.

The number of punctures for the standard and newly specified DOT-113 tank cars is simulated relative to the baseline case of how the general purpose, single-tank DOT-111 tank car would perform in a derailment under the same conditions.[41]

The simulation used the modeled forces at the three initiating derailment speeds (30, 40, and 50 mph) to predict the likely puncture resistance of tanks having outer shell thicknesses of 7/16 inches and 9/16 inches, corresponding with the standard DOT-113C120W and the newly specified DOT-113C120W9. The model simulated 18 derailment scenarios for each of the three initiating speeds under varying conditions to estimate the collision impact forces. For instance, it also simulated varying terrains based on three different values for the friction between steel and soil.[42] The results from the scenarios were grouped by speed to represent collision impact forces of a typical derailment at 30, 40, and 50 mph,[43] which are used to calculate the performance of different design specifications.

This task is part of an ongoing PHMSA and FRA research program and will be completed in winter 2021–2022 after the Full-Scale Impact Testing has concluded and its results inform the model. However, the model was used earlier to inform the requirement for DOT-113 tank cars carrying LNG to have a 9/16-inch-thick outer shell and for maximum train operating speeds of 40 mph.[44] That earlier model simulated the derailment of a unit train consisting of 100 LNG tank cars. The model predicted that DOT-113C120W9 tank cars would sustain 4.2 punctures in a derailment at 40 mph, compared with standard DOT-113 tank cars sustaining 5 punctures.[45] At 50 mph, the DOT-113C120W9 tank cars would sustain 6 punctures, compared

[41] Federal Railroad Administration Office of Research, Development and Technology, “Evaluation of Risk Reduction from LNG Tank Car Design Improvements,” July 2020, p. 2, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/Pnctr_Prob_LtrReport_July2020.pdf.

[42] Federal Railroad Administration Office of Research, Development and Technology, “Evaluation of Risk Reduction from LNG Tank Car Design Improvements” (Washington, DC, July 2020), 3.

[43] Federal Railroad Administration Office of Research, Development and Technology, p. 6.

[44] Pipeline and Hazardous Materials Safety Administration, “Hazardous Materials: Liquefied Natural Gas by Rail—Final Rule.”

[45] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, “Punctures and Derailment Modeling Task Resource,” April 6, 2020, pp. 5–7, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/PunctureDerailment_Sim.pdf.

with 7.3 for the standard DOT-113 tank cars.[46] It merits noting the model predicted that some of the tank cars could sustain multiple punctures so that the number of punctured tank cars could be lower than the total number of punctures.[47]

The simulation results relate to other tasks regarding tank car design and derailment dynamics. As discussed below, the Worst-Case Scenarios Model task uses the predicted number of punctures and derailed tank cars as input for assessing the likely consequences of an accident. The Worst-Case Scenarios Model will, in turn, inform the Quantitative Risk Analysis guidance being developed by the Task Force. As noted above, refinement of the puncture and derailment modeling awaits empirical data from the Full-Scale Impact Testing scheduled for later in 2021.

Observations About Completeness and Quality

This task provides qualitative and quantitative information for understanding the factors that affect a tank's ability to resist puncture. The results provide support for the proposition that the DOT-113C120W9's thicker outer tank shell is more robust than the standard DOT-113 design, and thus more likely to resist loss of containment in a derailment.

The committee recognizes that the simulation did not intend to include all possible derailments scenarios as there may be diminishing returns when increasing the granularity of a model. However, more discussion of the various conditions and factors that can be important for predicting the number of derailed cars is warranted. Examples include:

- Track type and class;
- Track grade and curvature;
- Abrupt changes in the track stiffness (e.g., grade crossings; bridges and other track structures or features);
- Effects of buffer car size on the derailment forces;
- Location of initiation of derailment; and
- Planar (2D) versus space (3D) kinematics.

Without knowing these conditions, some of the results presented from the simulation would be difficult to verify or reproduce. Reducing the uncertainty about these parameter choices would build confidence in the model's applicability. More explanation for some of the scenario choices would also be helpful, for instance, by giving the reason that derailment forces are always presumed to be located at the leading truck of the first car, which is not valid for all derailments.

PORTABLE TANK FIRE TESTING

This two-phased task evaluates how an ISO container (a UN-T75 portable tank) would perform when exposed to a fire in a derailment scenario. The UN-T75 portable tank was selected because

[46] Federal Railroad Administration Office of Research, Development and Technology, "Evaluation of Risk Reduction from LNG Tank Car Design Improvements," p. 13.
[47] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "Punctures and Derailment Modeling Task Resource," p. 3.

its shares the same basic design as the DOT-113C120W9 tank car, as both have an inner tank enclosed by an outer tank shell with a vacuum-insulating space in between. The testing's purpose is to predict the performance in a fire of the DOT-113's tank, pressure relief valve (PRV) system, and tank insulation in preventing a boiling liquid expanding vapor explosion (BLEVE) that could cause severe harm to emergency responders, bystanders, and property as a result of the fireball and shrapnel from tank fragmentation.

The testing under the first phase has been completed, but additional analysis of Phase 1 data remains to be done. The second phase has been delayed because of the pandemic. In the first phase, the portable tank was filled with liquid nitrogen, placed on a rail flatcar, and exposed for 2 hours and 35 minutes to liquefied petroleum gas (LPG) burners configured to simulate a rectangular pool fire. LNG was not used as the fuel for the pool fire because of the difficulty of handling it in the test environment. Instead, LPG was selected because it has combustion characteristics similar to LNG. In addition to the fire testing, this phase entailed modeling activities.

The results from the Phase 1 test indicated that the PRV system worked properly to evacuate the vaporizing liquid nitrogen to prevent a tank rupture or BLEVE; but the insulation degraded, the tank vacuum was lost, and the steel in the flatcar underneath the tank exceeded its softening temperature and sagged into the burners and piping. The PRV system continued to release jets of nitrogen for nearly 4 hours after the fire test ended.[48] Phase 1 modeling results predicted that the failure pressure for a heated tank will be lower than for a tank at ambient temperature. The model also indicated that more testing is needed to characterize the performance of the tank's annular vacuum when exposed to heat and to understand how heat flux to the tank is affected by experimental design features such as wind, shielding from the flatcar, and burner size.[49]

The report from this testing identified additional data analysis needed to support the second phase of testing, including measurements of internal tank conditions, degradation of the insulation material, the heat flux applied to the tank, and the flow out of the PRVs as a function of time and internal pressure.

The plan for the second phase of testing is to fill the portable tank with LNG and place it on a flatcar exposed to an LPG pool fire. The aim of Phase 2 is to more thoroughly characterize the effect of wind on heat flux to the tank and performance of the thermal insulation. Another aim is to characterize the formation of a vapor cloud from leaks and a torch fire from the ignition of vapors released from the PRV system. This second phase will include a tank filled with LNG to various levels and subjected to extreme heat to determine the effects on tank materials, internal pressure, and fluid level. Additional work could include use of data collected in Phase 1 to validate modeling methods (e.g., internal temperature and pressure) and the rapid phase change and expansion of LNG as it relates to causation of a BLEVE, but a detailed analysis plan for this possible work was not presented.

Knowledge of the types and extent of fire hazards gained from this testing will inform the level of risk in the task on Quantitative Risk Assessment and determinations about the likelihood

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[48] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "Portable Tank Fire-Testing Task Resource," August 13, 2020, p. 67, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/UNT75_Fire_Test.pdf.
[49] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, pp. 67–68.

of certain hazards in the Worst-Case Scenario Model. The test results will also provide insights about resources needed for emergency response as part of the Educational and Outreach Plan.

Observations About Completeness and Quality

Characterizing the degree to which the survivability of a portable tank engulfed in an LPG pool fire predicts the survivability of a DOT-113C120W9 tank car engulfed in an LNG pool fire is difficult to do for various reasons. One reason is that the two tanks differ with regard to thermal mass, construction, and insulation. Another reason is that the heat flux from an LNG pool fire is 2 to 3 times greater than the heat flux to an engulfed object from an LPG pool fire.[50] Acknowledgment of these two major differences and their implications is needed for making valid characterizations. Likewise, although the Task Force stated that the design characteristics are basically the same, details about similarities and differences in the PRV systems of the portable tank and DOT-113 tank car are needed for this purpose.

Recognizing that Phase 2 has not commenced, the committee believes that there is time to make changes to the planned testing that could improve the quality of the data collected and their analysis. Changes that should be made include

- Increasing the pool size, changing the pool shape to circular, and moving the pan upwind relative to the portable tank. These changes will enhance full fire engulfment and ensure consistent impingement of the tank under wind conditions;[51]
- Removing the flatcar from the experimental setup. This will allow for better assessment of the thermal response of the tank because the flatcar offers thermal protection;[52,53]

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[50] Blanchat et al., "The Phoenix Series Large Scale LNG Pool Fire Experiments"; Pipeline and Hazardous Materials Safety Administration, "UN-T75 Portable Tank Fire-Testing Task Resource," fig. 42. The committee compared Figure 42 in the section on "Fire Performance of Cryogenic ISO UN-75" in this resource document with the work by Blanchat et al.

[51] P.A. Croce, K.S. Mudan, and J. Moorhouse, "Thermal Radiation from LNG (Liquefied Natural Gas) Trench Fires. Volume 1. Main Report. Final Report, September 1982–September 1984," September 1, 1984, https://www.osti.gov/biblio/6192926-thermal-radiation-from-lng-liquefied-natural-gas-trench-fires-volume-main-report-final-report-september-september.

[52] The committee notes that FRA stated that the height of the flatcar deck places the portable tank at the point where the heat is greater than if the portable tank were immersed in a pool fire because the temperature is hottest at 1–2 meters above the pool (personal communication).

[53] Federal Railroad Administration Office of Research, Development and Technology, "Temperatures, Pressures, and Liquid Levels of Tank Cars Engulfed in Fires: Volume 1, Results of Parametric Analyses," June 1984, https://railroads.dot.gov/elibrary/temperatures-pressures-and-liquid-levels-tank-cars-engulfed-fires-volume-1-results.

- Placing the tank car in an orientation (approximately 120° rollover angle) where the pressure relief valve will vent liquid, based on National Transportation Safety Board reporting,[54,55] which presents a more severe test of the PRV system;[56]
- Using LNG as the fuel, stored in a protected location in case of a BLEVE, for the pool fire because an LNG pool fire has approximately 2–3 times higher heat flux loads to engulfed objects than LPG;[57,58]
- Performing the fire test for 100 minutes and a torch fire for 30 minutes in conformance with regulation to provide consistency in evaluating fire performance according to tank car specifications;[59]
- Evaluating an LNG fireball and tank fragmentation in the event of a BLEVE to prepare emergency response personnel for combustion and non-combustion hazards;
- Assessing the potential for cryogenic damage cascading to adjacent tanks by evaluating topography surrounding the rail tracks that could support pool formation because a cryogenically damaged tank impacted by a pool fire can potentially alter PRV performance;[60,61] and
- Performing a non-destructive thermal test of an LNG-laden DOT-113C120W9 tank car using radiant heat panels to gather data on the internal thermal response of the tank that could be used to assess model performance with regard to predicting heat transfer and multi-phase behavior.

WORST-CASE SCENARIOS MODEL

The Worst-Case Scenarios Model task posited four hazard scenarios involving a release of LNG simultaneously from five tank cars damaged from a unit train derailment accident. The task simulates the severity of the consequences and characteristics of the hazards under high wind conditions to understand how to mitigate harm to emergency response personnel. The hazard scenarios include (a) an unconfined LNG pool spread following a release; (b) dispersion of unignited vapors from the spreading pool, which has the potential to result in a flash fire; (c) thermal radiant heat emitted by pool fire exposing an area to the hazard; and (d) a fireball resulting from a BLEVE exposing an area to the hazard. The simulation results from the

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[54] National Transportation Safety Board, "Derailment of Norfolk Southern Railway Company Train 68QB119 with Release of Hazardous Materials and Fire New Brighton, Pennsylvania, October 20, 2006," Accident Report, May 13, 2008, fig. 1, https://www.ntsb.gov/investigations/AccidentReports/Reports/RAR0802.pdf.
[55] 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, Washington, DC, February 14, 2012, fig. 3, https://www.ntsb.gov/investigations/AccidentReports/Pages/RAR1201.aspx.
[56] Federal Railroad Administration Office of Research, Development and Technology, "Temperatures, Pressures, and Liquid Levels of Tank Cars Engulfed in Fires: Volume 1, Results of Parametric Analyses."
[57] G.A. Mizner and J.A. Eyre, "Large-Scale LNG and LPG Pool Fires."
[58] Blanchat et al., "The Phoenix Series Large Scale LNG Pool Fire Experiments."
[59] Pipeline and Hazardous Materials Safety Administration, "Thermal Protection Systems," 49 CFR § 179.18, n.d., https://www.govinfo.gov/content/pkg/CFR-2013-title49-vol3/pdf/CFR-2013-title49-vol3-sec179-18.pdf.
[60] J. McKinley, "Strength, Creep, and Toughness of Two Tank Car Steels: TC128B and A516-70," Transport Canada, 2019, https://epe.lac-bac.gc.ca/100/201/301/weekly_acquisitions_list-ef/2020/20-39/publications.gc.ca/collections/collection_2020/tc/T86-56-2019-eng.pdf.
[61] B.W. Williams et al., "Capturing Variability in the Fracture Response of TC128B Steel Using Damage Mechanics," vol. 28, 2020, pp. 1024–1038, https://doi.org/10.1016/j.prostr.2020.11.118.

scenarios were presented to the committee during meetings, but a final report was not available for the committee's review.

The modeling methodology for the four hazard scenarios uses Monte Carlo simulation to generate probabilities for harm to health and the environment along segments of an LNG transportation route based on various factors such as population density and the areas affected by the hazards. The model assumes that a unit train consisting of standard DOT-113 tank cars (with an outer shell thickness of 7/16 inches) that derails will experience five punctures in the bottom of the tanks.[62] The tank punctures are created by an object comparable in size to a coupler (i.e., 12×12 inches) and lead to the full contents of the tank being released in less than 1 minute. (Some of these assumptions derive from the results of other tasks discussed above.) Other values in the model (e.g., derailment speed, number of tank cars derailed and punctured, derailment impact area) are based on historical data from derailments of unit trains that were hauling crude oil or ethanol. For modeling the hazard areas, heat flux, and overpressure blast, the Task Force used the explosive TNT as a proxy for LNG.[63]

The worst-case scenario model of the pool spread predicts that the released LNG will cover a circular area having a diameter of 95 meters, which amounts to a pool having a maximum radius of about 10 times the length across a five–tank car pileup. The concentration of LNG vapors sufficient to remain a combustion hazard (i.e., the lower flammability limit) was estimated to extend as far as 2,380 meters (1.5 miles) from the source of the release. The radiant heat flux[64] emitted by a pool fire and a fireball from a BLEVE were estimated to be 165 kW/m^2 and 250 kW/m^2, respectively.[65] This heat exposure would cause a person to experience second degree burns at a distance of 670 meters (0.4 miles) from the longer burning pool fire (60 seconds) and 230 meters (0.14 miles) from a fireball (15 seconds) measured from the fire's center.[66]

Analyses that have not been completed include evaluating the physical and thermal conditions that can result in a BLEVE and unit train derailment modeling assuming that the tank cars are the newly specified DOT-113C120W9 design (i.e., outer-shell thickness of 9/16 inches). The Task Force intends to do more work to understand the BLEVE scenario. However, Task Force members expressed the view that it is highly unlikely that an undamaged DOT-113 tank car involved in a derailment would fail due to a BLEVE. The reason for their confidence is that the DOT-113 tank car is designed to avoid a BLEVE by meeting the standards for loading pressure requirements for cryogenic materials, redundant pressure relief systems (valves and safety vents), and insulation systems (an insulating wrap and annular vacuum space to prevent external heat reaching the inner tank).

The Worst-Case Scenarios Model interrelates with three other tasks that are specifically relevant to LNG transport by rail and one more broadly in support of railroad safety. The modeling of punctures and derailments provides the number of punctures given a derailment

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[62] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "Worst-Case Scenarios Model Task Resource," August 13, 2020, p. 3, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/WorstCase_Model.pdf.
[63] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, pp. 113–114.
[64] Radiant heat flux is the rate of heat transferred as thermal radiation for a unit area.
[65] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "Worst-Case Scenarios Model Task Resource," p. 130.
[66] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "FRA–PHMSA LNG by Rail Task Force Interim Report," pp. 16–17.

scenario. That modeling, in turn, is supported by the portable tank fire testing and DOT-113 impact-testing tasks. In 2022, the Worst-Case Scenarios Model task will inform an analysis of the modal conversion for LNG transportation between truck and rail.

Observations About Completeness and Quality

The quality of the modeling in this task could not be fully assessed in the absence of a detailed final report and the results of pending tasks that are related. However, based on what could be gleaned from Task Force presentations, the committee believes that there are opportunities to improve the design and execution of the task.

With regard to the scenario assumptions about the number of DOT-113 tank punctures in a derailment, the Task Force relied on the predictions from the Punctures and Derailment Simulation Modeling task discussed above. It is important to point out, however, that the puncture analysis did not predict absolute values for the number of punctures of DOT-113 tank cars, but rather the number of punctures relative to baseline modeling of punctures sustained by a DOT-111 tank car. The committee, therefore, recommends the following considerations to improve the quality of the punctures and derailment simulation as it pertains to the worst-case scenarios modeling:

- Providing upper bound values of predicted number of punctures to identify the worst-case release rather than using nominal values; and
- Using a train speed of 50 mph for the predicted number of 7.3 punctures, rather than the 40 mph used, because it was the upper speed evaluated in the puncture and derailment simulation.

While the hazard analyses for pool spread, vapor dispersion, area encompassed by a flash fire, and thermal radiant heat emitted by pool fire have been completed, pending analyses include the conditions that would cause a BLEVE and the modeling of a unit train comprised of the newly specified DOT-113C120W9 tank cars. The worst-case scenarios simulation results could be updated on the basis of the results from the pending fire testing and full-scale impact testing of the DOT-113C120W9 tank car. Furthermore, for completeness of the task, the Task Force should make the following enhancements:

- Evaluating the heat flux from a jet fire from a punctured tank and impinging on an adjacent tank to assess the potential for cascading damage from this combustion event because it was missing from the hazards initially listed in the model;
- Evaluating the potential for valve damage and ruptured lines that could contribute to a release, which was not included in the initial model;
- Evaluating the total amount of LNG that potentially could be released from cascading damage to adjacent tank cars from partial submersion in an unignited pool of LNG and/or partial exposure to the heat flux from a pool fire;
- Evaluating the potential hazard to emergency responders of a rapid phase transition from an LNG spill onto a body of water, considering that track infrastructure commonly runs along rivers;

- Evaluating explosion hazards from an unignited spill of LNG resulting in vapor dispersion in an environment with confined or congested spaces because the model only represents the scenario occurring in an open area without any factors that could affect the spread of the pool or vapor cloud;
- Discussing fire propagation in a high-density environment and the potential resulting semi-confined, confined, or congested hazard areas because the model does not account for the population exposed;
- Using the thermal radiant heat flux range of 475–540 kW/m^2 instead of the 250 kW/m^2 currently used in the model for an LNG fireball when determining the hazard area because the higher value is LNG-specific and greater than what is reported for an LPG fireball;[67] and
- Using an approved code (i.e., LNGFIRE3)[68] that meets the requirements specified in regulations to determine hazard areas from thermal radiant heat flux emitted by pool fires, fireballs, and jet or torch fires (while the dispersion calculations were performed with an approved code, the models used to evaluate thermal radiant heat flux emitted by pool fire and fireball were not). The Task Force acknowledged the use of TNT as a proxy was a limitation of the model because it does not account for the specific properties of LNG, including its temperature, vaporization, likelihood of ignition, or fire type (i.e., pool fire, flash fire from spreading vapor, and fireball).

QUANTITATIVE RISK ASSESSMENT

Quantitative Risk Assessment (QRA) is intended to measure risk quantitatively to inform the selection of operational and other controls to apply on transportation routes. The methodology entails a systematic accounting for hazards, the potential consequences, and the likelihood of their occurrence between the origin and destination of a commodity. The Task Force noted that a QRA can provide useful insights to the main contributors to LNG transport risk, allowing mitigation measures to be focused where they are most effective in controlling or reducing risk. For example, a QRA can inform comparative analyses of alternate modes and routes to support selection of the best option for a planned movement of hazardous materials. The inputs for such an analysis include, for instance, historical accident records for derailments and releases of hazardous materials and the population data along the route.

Although the Task Force initially intended to perform a QRA as part of this task, it was later clarified that the scope would be limited to the development of a framework for the requisite data and a suggested methodology for an effective QRA.[69] The rationale given for the revised scope is that because of a lack of a historical record of past shipments of LNG by tank

[67] Betteridge and Phillips, “Large Scale Pressurised LNG BLEVE Experiments.”
[68] Federal Energy Regulatory Commission, “Recommended Parameters for Solid Flame Models for Land Based Liquefied Natural Gas Spills,” January 2013, https://www.ferc.gov/sites/default/files/2020-04/RecommendedParametersforSolidFlameModelsforLandBasedLNGSpills.pdf. In addition, 49 CFR § 193.2057 (“Thermal radiation protection”) requires the use of the solid flame model LNGFIRE3 for predicting radiant heat from LNG pool fires on land.
[69] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, “Quantitative Risk Assessment Task Resource,” March 15, 2018, pp. 13–24, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/QRA1.pdf.

car and few details on planned shipments, there is insufficient data and context to conduct an analysis. With such limited information, a QRA would require unsupportable assumptions about candidate origin–destination pairs. Instead, the Task Force cited the Volpe National Transportation Systems Center's review of a risk assessment submitted for a 2019 special permit granted by PHMSA for the shipment of LNG by DOT-113 tank cars over a rail transportation route between Wyalusing, Pennsylvania, and Gibbstown, New Jersey.[70] The findings from this review were used by the Task Force to develop recommendations for actions needed to construct an improved framework for a QRA for LNG transport by rail.

The Volpe Center determined that the methodology in the QRA for the special permit was reasonable and achieved several of its stated goals. The review also concluded, however, that the analysis was limited in several areas, including a comparison with the risks involved in other modes long-permitted to transport LNG (i.e., marine tankers and trucks) to use as a benchmark for an equivalent level of safety and the consideration of hazards and failure modes other than a release caused by a derailment. Drawing on these findings, a white paper prepared by the Task Force for its QRA framework guidance recommended the following:[71]

- Further structural analysis of the puncture resistance of the standard DOT-113 tank car to understand the conditions during a derailment that could cause a puncture of the inner tank;
- Enhancement of train dynamics modeling, such as the Train Energy and Dynamics Simulator, to better anticipate the amount of LNG that would be released in the case of a puncture, which would be accomplished by estimating the probabilities of different puncture sizes of the inner tank;
- Estimation of the likely frequency of LNG spills at loading and unloading facilities by review of LNG trucking operations and the loading and unloading of tank cars in chemical and petrochemical facilities;
- Modeling the amount of the time an LNG release will result in various hazards such as pool spread, vapor dispersion with flash fire, pool fire, fireball, or a BLEVE so as to know when a particular hazard is possible and its likelihood; and
- Examination of the factors that could contribute to a BLEVE in a DOT-113 tank car with a vacuum-insulated inner tank enclosed in an outer tank, which, as noted above regarding worst-case scenario modeling, is not currently understood.

Observations About Completeness and Quality

In re-scoping this task, the Task Force identified important areas where additional work is needed to strengthen the applicability of QRA to LNG rail transport, based on an assessment of the QRA submitted with the 2019 special permit for LNG shipments between Pennsylvania and New Jersey. However, the Task Force's recommendations, as cited above, need to be implemented to improve the effectiveness of a QRA for LNG transportation by rail. A fully executed QRA can serve as a mechanism for pulling together the results of other Task Force evaluations, such as the tasks for puncture and derailment analyses, tank car performance in

[70] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, pp. 25–34.
[71] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, p. 24.

accidents, worst-case scenario modeling, loading and unloading operations, route analyses, and security evaluations. Moreover, a QRA can serve as a means of continuous improvement by integrating information as new results from the Task Force's program and other safety assurance activities progress. To be sure, the QRA submitted for the special permit would have been enhanced by integrating the results of the interdependent tasks mentioned above. However, there is no evidence to date that the Task Force intends to update that QRA to integrate the results of the other task evaluations.

4

Tasks Relevant to Hazardous Materials Transport by Rail

This chapter examines the completeness and quality of 6 of the 15 tasks in the Pipeline and Hazardous Materials Safety Administration–Federal Railroad Administration (PHMSA–FRA) Task Force initiative that are relevant for shipments of any hazardous materials cargo by rail, including liquefied natural gas (LNG)-laden tank cars. The six tasks are Loading and Unloading Safety Assessment, Safety and Security Route Risk Assessment, Train Operational Controls, Modal Conversion Between Truck and Rail, LNG Educational and Outreach Plan, and Emergency Responder Opinions and Needs.

LOADING AND UNLOADING SAFETY ASSESSMENT

The Task Force conducted the Loading and Unloading Safety Assessment task to evaluate the safe loading, unloading, and transloading operations of LNG cargo by performing a literature review, analyzing incident data from PHMSA's database, interviewing subject-matter experts, and reviewing the training and equipment involved in loading and unloading operations. Safety measures taken in response to the COVID-19 pandemic interrupted this task, especially in-person site visits to LNG liquefaction and transportation sites in Florida at Hialeah and Jacksonville for interviews with facility personnel about and demonstrations of training and operating practices.

The literature consulted for loading and unloading operations and procedures includes documentation from regulatory agencies and incident data. The Task Force reviewed LNG-related materials on authorized tank car designs for cryogenic cargo, the state of the practice for loading and unloading at marine ports and on cargo tank motor vehicles, and safety and security in transportation and at fixed facilities.[72] The incident data included six incidents reported between 1984 and March 2020 that occurred while loading or unloading LNG cargo transported by truck and involved two hospitalizations and no fatalities. In one instance, there was a significant fire, though the tank did not fail.[73]

The Task Force interviewed subject-matter experts at the PHMSA Office of Pipeline Safety (OPS), U.S. Environmental Protection Agency Office of Emergency Management (OEM), and an equipment manufacturer. The interviews with OPS covered oversight of LNG facilities and training. In particular, OPS staff stressed the importance of training, which they noted as being similar for any cryogenic liquid, and the use of certified facilities for repairs to reduce the potential for human error causing an incident. OEM staff outlined how they collaborate with FRA, especially in cases when there is overlap in or transition between the

[72] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "Loading and Unloading Safety Assessment Task Resource," August 13, 2020, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/LoadingUnloading_Assess.pdf.

[73] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "FRA–PHMSA LNG by Rail Task Force Interim Report," p. 9.

agencies' jurisdictions. The most salient example regarding jurisdictional issues is when rail tank cars are used for storage at a yard (OEM) and transportation (FRA). OEM staff emphasized the importance of establishing a response plan in advance to manage the risk of a potential incident. Interviewing a product manager at an equipment manufacturer confirmed observations made by OPS training staff who likewise noted that the equipment used for LNG loading and unloading has a proven safety record, and that training for personnel should be a top concern to ensure the integrity of valves, fittings, and hoses to avoid leaks of the odorless, cryogenic material.

Through its analysis of the collected literature, incident data, and interviews with subject-matter experts, the Task Force concluded that marine and highway transportation of LNG has occurred safely for several decades and identified training and maintenance of equipment as being crucial to safe loading and unloading operations. They further concluded that the LNG industry has learned from previous incidents and maintains a strong safety culture. The Task Force intends to build on these takeaways when it resumes this task with a site visit to a facility that handles flammable cryogenic cargo in late 2021. The results from this task can inform the risk profile of LNG transportation, but the task itself is not a dependency of other tasks in the overarching LNG safety initiative.

Observations About Completeness and Quality

As a potential source of releases, loading, unloading, and transloading activities warrant evaluation. Indeed, the assessment of non-accident releases is central to meeting the objective of reducing the risk of transporting LNG by rail.

The committee concurs with the Task Force's stress on clear policies and procedures to mitigate the risk of non-accident releases, with training and equipment maintenance being key to that effort. For LNG transportation by marine and highway modes, the equipment, training, and procedures have demonstrated a good safety record. It is important that railroads apply similar rigor in training and emergency preparedness for LNG transportation to reduce the risk beyond the minimum requirements in the Hazardous Materials Regulations for transport by rail.

The task could be improved by issuing a single, well-organized document that provides a summary of the literature reviewed, conclusions drawn from the literature, completed expert-interview questionnaires, and key recommendations from the experts. Notably, an explanation for the Task Force's positive assessment of the LNG industry's safety culture would also be instructive. A synthesis of this information and details regarding required hardware, operational procedures, training, and emergency response plans for loading and unloading operations—including transloading[74]—would enable the Task Force to more thoroughly cover all potential safety issues arising from LNG transportation by rail.

SAFETY AND SECURITY ROUTE RISK ASSESSMENT

The Task Force intends to conduct its own safety and security route risk assessment of the three route options under consideration for the special permit for movement of a unit train of LNG between Wyalusing, Pennsylvania, and Gibbstown, New Jersey, once the applicant submits a shipping plan. The results of the Task Force's assessment will be compared to the assessment

[74] Title 49, CFR § 174.67.

submitted by the railroad for compliance with the Hazardous Materials Regulations. These federal regulations require a safety and security assessment of the route used for transporting hazardous materials using 27 factors, such as the amount of hazardous material to be hauled, proximity to iconic targets, high-consequence targets, known threats, population density along the route, train speed, and training and skill level of crews.[75]

The assessment considers the 27 factors by means of a risk analysis that may be conducted quantitatively, qualitatively, or some combination thereof. There is no single required methodology for the risk analysis in recognition of variation among railroads and their operating environments so long as the methodology is documented for the route to be analyzed. However, PHMSA and the railroad industry have collaborated in a privately developed and widely used geospatial information system-based software package called the Rail Corridor Risk Management System (RCRMS) that satisfies the requirements of the regulations. The basic inputs for RCRMS, or any route risk assessment, are origin–destination pair, commodity type, container type, annual volume, operating speeds, and track characteristics. RCRMS output is an overall risk score used to rank route options.

Once the shipping plan is available, PHMSA and FRA will compare their RCRMS results for the three route options with those scores generated on behalf of the shipper to determine whether additional measures are needed for safety assurance. Beyond a description of the planned RCRMS analysis, the Task Force presented the committee with an FRA memorandum that briefly summarizes the results of a favorable audit of Norfolk Southern Corporation (NS), a potential carrier for LNG under a 2019 special permit, covering topics such as its security plan, emergency response and oil spill plans, hazardous materials training, and routing assessment using RCRMS.[76] Other materials were unavailable because of security concerns about sensitive information.

Although not specifically a dependency or successor of another task in the Task Force's work, a route risk assessment would generally account for conditions at the origin, an intermediate point, and destination for loading, unloading, and transloading operations. Likewise, the information in the route risk assessment could inform modeling for worst-case scenarios.

Observations About Completeness and Quality

The pending status of the task and scant resources for review limited the committee's ability to fully consider this part of the Task Force's program. That is, details such as risk assessment parameters, assumptions, and route-specific details are unavailable for review. Therefore, the committee cannot form a view on the quality of the assessment task or clearly know, for instance, what constitutes the definition of a more or less attractive route for LNG transportation.

However, without knowing more about the assessment, the committee considers the task to be incomplete without consideration of manifest trains, rather than a focus solely on unit train movements, because the LNG shipment configuration may represent different consequences during an accident. For example, it is plausible that an LNG release during a worst-case scenario

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[75] Title 49, CFR § 172.820; Title 49, Appendix D to Part 172.

[76] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "Safety and Security Route Risk Assessment Task Resource," August 13, 2020, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/SafeSec_Route_Asssess.pdf.

event involving a manifest train could be worse than a unit train scenario because of the potential interactions and effects between multiple hazardous materials.

Similarly, the committee lacks information about how security factors were addressed. That is, the task would be incomplete without considering how to prevent or mitigate deliberate efforts to cause an incident, such as by sabotage or terrorism, which is something that would be explored in the second phase of the study.

TRAIN OPERATIONAL CONTROLS

The Task Force conducted site visits with rail carriers to document their compliance with the industry-developed, voluntary standard for transporting hazardous materials, AAR Circular OT-55-Q: Recommended Railroad Operating Practices for Transportation of Hazardous Materials (Circular OT-55).[77] Circular OT-55 applies to trains carrying hazardous materials that meet the definition of a "key train," which, for the purposes of LNG-laden tank cars, entails a train with 20 or more car loads of hazardous material. Thus, a unit train or a manifest train with 20 or more tank cars of LNG would be a key train. The principal restriction for a key train is a limit on the maximum speed to 50 mph.

The evaluation for compliance with Circular OT-55, especially maximum operating speed, contributes to reducing the risk of transporting LNG by rail, as well as other hazardous materials. While a significant portion of the national rail network allows freight trains to operate at 60 mph or higher, the maximum operating speed of a key train reduces the magnitude of energy available compared to a non-key train in the same accident scenario.

PHMSA and FRA staff conducted site visits with NS and Conrail Shared Assets Operations (Conrail) for compliance with Circular OT-55. Additional Circular OT-55 reviews are planned, with a site visit to CSX Transportation scheduled for summer 2021. To assist in the review of these railroads' hazardous materials-handling practices, PHMSA and FRA used a checklist to guide discussions during site visits with questions about the implementation of Circular OT-55, preparedness for worst-case scenarios, and training for both.[78] The agencies' staff determined that NS and Conrail comply with Circular OT-55 and have integrated it as the basis of their training, self-audits, and daily operations.

Supplementing the site visits, the agencies reviewed the results from a simulation-based analysis, using the Train Energy and Dynamics Simulator,[79] of the proposed route for LNG between the origin in Pennsylvania and the destination in New Jersey under a 2019 special permit to compare the 50 mph limit for a key train to the likely speed traveled in accordance with the maximum authorized speed. The Task Force found that, when terrain and track curvature were considered, the route conditions would allow a 100-car LNG unit train to travel at 50 mph

[77] Association of American Railroads, "AAR Circular OT-55-Q, Recommended Railroad Operating Practices for Transportation of Hazardous Materials," April 26, 2019, https://public.railinc.com/sites/default/files/documents/OT-55.pdf.
[78] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "Train Operational Controls Task Resource," August 13, 2020, chap. OT-55 Safety Verification of Rail Carriers, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/Train_Op_Cntrl.pdf.
[79] See Chapter 5, Train Energy and Dynamics Simulator.

for 13 percent of the route, about 18 percent at 40 mph, and at 35 mph or slower for the remainder.[80]

Observations About Completeness and Quality

The assessment of rail carriers' compliance with the key train restriction on maximum operating speed under Circular OT-55 provides useful insight into a means of limiting the potential energy involved in a derailment scenario. Although the results of this task show that two railroads adhere to the voluntary standards for hazardous materials transportation—indeed, have incorporated them into their training and daily operations—completing additional reviews of freight railroad operations, as well as including any other rules that might affect operating practices, will strengthen understanding of the operating practices across the nation's freight rail network.

While it is understandable that the pandemic has delayed the Task Force from conducting additional in-person site visits, the committee believes that completion of a remote, preliminary evaluation would have been feasible with information available to agencies under existing regulatory authority. That is, the task would have been significantly improved if its results included an evaluation of railroads' compliance with Circular OT-55 based on documentation submitted under federal recordkeeping regulations about filing copies of new amendments to railroad operating rules, timetables, and timetable special instructions.[81]

MODAL CONVERSION BETWEEN TRUCK AND RAIL

The Task Force has developed modeling to compare the risk profile of the linehaul movement required to transport equivalent volumes of LNG by truck and rail between a single origin–destination pair based on the route that was authorized under the 2019 special permit for LNG by tank car between Pennsylvania and New Jersey. The objective of the task is to understand the relative potential exposure of people using an assessment of the rail route (i.e., RCRMS) and the likely highway routing using geospatial, population, and modal incident data. Because of the focus on this particular origin–destination pair, the Task Force's analysis was not an attempt to assess whether this route was generalizable to other potential movements.

The model examines two types of risk: the risk involved in a particular mode (e.g., fatalities and injuries resulting from train derailments and highway traffic collisions) and in the potential release of any hazardous material, not only LNG. Each mode entails differing risk characteristics. Typically, highway transportation of hazardous materials passes through highly populated areas, though trucks avoid dense population centers. By contrast, railroads tend to travel across rural areas and through cities.[82] Also, because of the capacity of the packaging corresponding to each mode, three cargo tank motor vehicles are needed to carry the same volume of cargo in one rail tank car. The differential in capacities results in the need for many

[80] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "FRA–PHMSA LNG by Rail Task Force Interim Report," p. 24.
[81] Title 49, CFR § 217.7, Operating rules; filing and recordkeeping.
[82] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "FRA–PHMSA LNG by Rail Task Force Interim Report," p. 20.

more vehicles on highways, and more opportunities for traffic accidents, relative to the number of trains.

For mode-specific risk, the calculation comparing truck and rail freight transportation yields values in units of fatalities and injuries per ton-mile traveled using data from FRA (2019), the Federal Motor Carrier Safety Administration (2018), and the Commodity Flow Survey (preliminary data for 2017).[83] The calculation of risk involving a hazardous materials release also yields values in the same units. However, this component of the model considers the extent of the population exposed to a potential release using a geospatial overlay of the hazard diameters along the route for trucks and as determined for the 2019 special permit in the task on the Worst-Case Scenarios Model. The simulation estimates that rail transportation of LNG presents 30 percent of the risk that highway transportation entails.[84]

This model has limitations, as do all models. This task examines risk from all hazardous materials, but estimating exposure to LNG-related hazards requires information on the volume of cargo flowing through a corridor. The commodity flow information from the special permit for linehaul between Pennsylvania and New Jersey is used in this task, but the Task Force stated that not enough information is available to set parameters for new routing and volumes for other hypothetical origin–destination pairs. To remedy the lack of information about the volume of LNG cargo, the Bureau of Transportation Statistics will modify its existing survey of tank car production facilities[85] to include data collection on the number of DOT-113 tank cars built and production capacity, which will assist PHMSA in assessing exposure and potential exposure from LNG-laden tank cars beginning in fall 2022.[86]

PHMSA will repeat this analysis when the shipper and rail carrier operating under the Pennsylvania–New Jersey special permit identify a specific route. The model of modal conversion between truck and rail uses inputs from the tasks on Worst-Case Scenarios Model and Safety and Security Risk Route Assessment (i.e., scoring from the RCRMS software).

Observations About Completeness and Quality

The analysis as reported only considered the risk of fatalities and injuries during the linehaul movement and did not consider the loading and unloading activities along with their associated risks. The committee believes that incorporating factors for risks entailed in loading and unloading operations by mode would facilitate a more accurate comparison between truck and rail. The latter carry smaller containers and thus involve more handling operations than railroads. Also, the analysis left out risks involved with train assembly and classification activities in the case of rail movements. However, because shippers are not yet filling DOT-113 tank cars regularly, nor are end users emptying them, the committee lacks the evidence base to offer advice in this area. The loading facilities in particular are likely to be outside of large petrochemical complexes where loading hazardous material into railcars is typically

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[83] Pipeline and Hazardous Materials Safety Administration, "Methodology of Modal Conversion Between Truck Transportation of LNG and Rail Transportation of LNG," February 11, 2021, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/Modal_Convrsn_Calc.pdf.
[84] Pipeline and Hazardous Materials Safety Administration.
[85] Bureau of Transportation Statistics, "Tank Car Facility Survey," n.d., https://www.tankcar.bts.gov/survey.
[86] Pipeline and Hazardous Materials Safety Administration, "Methodology of Modal Conversion Between Truck Transportation of LNG and Rail Transportation of LNG."

accomplished today. Furthermore, these facilities are unlikely to be established or controlled by the rail carriers themselves. This phase of transportation may warrant particular attention and coordination among shippers and rail carriers once regular shipments begin.

Therefore, PHMSA should add loading and unloading operations and train assembly and classification activities to the assessment of the risk of LNG by rail as compared with highway when repeating this task in fall 2022.

EMERGENCY RESPONSE COORDINATION

The Task Force developed an overarching plan to prepare for the risk of shipping LNG by coordinating with the emergency response community to ensure that the appropriate level of awareness, training, and resources were available to keep themselves and the public safe. The Task Force divided their work into two emergency response-oriented tasks. The Validation of Emergency Responder Opinion and Needs task focuses on fully characterizing the extent of the perceived risk as well as developing a baseline for current response capabilities and community readiness. In the task on development of an LNG Educational and Outreach Plan, the Task Force identified the outreach and educational materials that are currently available from industry, government agencies, and stakeholder organizations; performed a gap analysis to see where PHMSA could facilitate coordination between organizations to enhance education outcomes; and developed an action plan to bridge any identified gaps with new educational materials. These tasks continue and complement an array of longstanding PHMSA activities in coordination with and grants to the emergency response community, which includes first responders, emergency managers, emergency response teams representing carriers and shippers, and specialized emergency response contractors. It is this well-established set of activities and programs, which applies an all-hazards approach to emergency response, that led the committee to classify the following two tasks as relevant to any hazardous materials transport by rail.

Emergency Responder Opinions and Needs

The Task Force provided materials about ongoing PHMSA and FRA initiatives to ensure that the emergency response community has the information and tools to safely respond to an LNG-by-rail incident, as well as overarching emergency preparedness. PHMSA and FRA hosted an LNG town hall meeting in Lancaster, Pennsylvania, where input was gathered from a broad swath of the emergency preparedness, response, and recovery communities on October 14, 2019. This initial engagement in a series of town hall-type meetings and a follow-up report is similar to past work that PHMSA has done with emergency responders and provides a foundation for the LNG communications effort.[87]

In addition to the LNG town hall meeting series, PHMSA, FRA, the National Fire Academy of the U.S. Fire Administration (USFA), and the International Association of Fire Chiefs jointly sponsored a Hazardous Materials (HM) Roundtable. The initial roundtable in 2019 brought together personnel from federal agencies, standards development organizations, and response industry stakeholders, and included dozens of attendees from across the emergency

[87] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, “Emergency Responder Opinions and Needs Task Resource,” August 13, 2020, p. 24, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/ER_Opinion_Needs.pdf.

response community, government, industry, and trade associations.[88] This meeting resulted in a report, the HM Roundtable Report, with recommendations focused on planning, prevention, response, training, standard of care, funding, and information sharing. The HM Roundtable Report included a notable recommendation for the formation of a federal interagency hazardous materials training group consisting of participants from PHMSA, FRA, the U.S. Environmental Protection Agency, the Federal Emergency Management Agency, USFA, and the Occupational Safety and Health Administration.[89] The group has come to be known as the Federal HazMat Partners (FHMP).

The joint sponsors of the roundtable decided that the HM Roundtable Report would become a "living document" to track, update, and modify the path forward at future roundtable meetings on an annual basis. As with many programs, delays in execution occurred because of the pandemic. However, the FHMP have met twice in 2020 to initiate their coordination and activities. In March 2021, a meeting of the FHMP stakeholders and the 2019 roundtable participants was held to initiate planning for the next HM Roundtable in late 2021.

In addition to the town hall and roundtable activities under this task, PHMSA has a track record of working closely with the emergency response community to ensure that they have the information and tools necessary to safely respond to transportation-related hazardous materials incidents, with a recent emphasis on rail incidents. While the Task Force member agencies are not the trainers, they provide grants, training materials, and technical assistance to the emergency response community.

The Hazardous Materials Emergency Preparedness grant program is an example of a federal program that has supported the emergency response community with resources to develop and implement training and preparedness capabilities in local, territorial, tribal, and state governments.[90] PHMSA's grants program has been in operation for dozens of years to respond to emerging issues such as pipeline emergencies and, as updated by the Fixing America's Surface Transportation Act, high-hazard flammable trains[91] (HHFTs) carrying crude oil and ethanol.[92]

While the pandemic has slowed the speed at which the Task Force has been able to validate emergency response needs and opinions, they have continued to do so by using virtual forums such as the HM Roundtable.

Observations About Completeness and Quality

While there is a body of knowledge and experience pertaining to the transportation of LNG by marine tanker and cargo tank truck, there is little North American precedent in training materials and incident experience on the transport of LNG by rail. Filling in that gap, the town hall and

[88] Pipeline and Hazardous Materials Safety Administration et al., "Hazardous Materials Roundtable Meeting," April 3, 2019, https://www.usfa.fema.gov/downloads/pdf/hazmat_roundtable_meeting_report_2019.pdf.
[89] Pipeline and Hazardous Materials Safety Administration et al., p. 19.
[90] Pipeline and Hazardous Materials Safety Administration, "Hazardous Materials Emergency Preparedness (HMEP) Grant," April 22, 2021, https://www.phmsa.dot.gov/grants/hazmat/hazardous-materials-emergency-preparedness-hmep-grant.
[91] Title 49, CFR § 171.8 defines an HHFT as a single train transporting 20 or more loaded tank cars of a Class 3 flammable liquid in a continuous block or a single train carrying 35 or more loaded tank cars of a Class 3 flammable liquid throughout the train consist.
[92] P.L. 114-94 § 7203.

roundtable series are indicative of robust efforts to understand and support the needs of the emergency response community. In addition, PHMSA has a mature grants program that has been used to effectively support identified needs through funding to state, local, and industry entities for transportation-related hazardous materials training and exercises, similar to the grants responsive to the increased traffic of HHFTs in the mid-2010s.

EDUCATIONAL AND OUTREACH PLAN

The Task Force recounted outreach activities and educational resources developed by the railroads, industry associations, government agencies, and other stakeholder organizations for the emergency response community. A selection of these activities and resources include:

- The Transportation Community Awareness Emergency Response (TRANSCAER®), with grant support from FRA, is developing an LNG training curriculum with technical assistance from industry associations;
- The Class 1 railroads engage directly with local emergency response organizations, as well as in collaboration with the Security and Emergency Response Training Center, along hazardous materials routes to deliver training and raise awareness about the AskRail® mobile application for the identification of specific railcar cargo; and
- The Short Line Safety Institute is focused on LNG training for emergency responders along short line railroads' track within the larger freight rail network.[93]

Following the review of the activities and resources above, the Task Force determined that a single place for consolidated access to regulatory documents, data, maps, and educational materials would greatly benefit the emergency responder community. PHMSA intends to ensure ease of access through a dedicated LNG webpage at the PHMSA site for this purpose.

Also, the Task Force identified educational and outreach gaps that needed to be addressed. PHMSA is thus developing a Commodity Preparedness and Incident Management Reference Sheet, based on the reference sheet created for HHFTs, to standardize incident management with recognized approaches to planning and preparedness. The reference sheet will focus on transportation safety and precautions, hazard assessment and risk evaluation, risk safety procedures, logistics, and the tools, equipment, and resources necessary to prepare for and respond to LNG rail transportation incidents. The agency is also producing digital illustrations and models of the DOT-113 tank car. A need for models of the UN-T75 portable tanks and the MC-338 cargo tank motor vehicle was also identified during the review process.

Although this task was mostly completed, the LNG training curriculum being developed by TRANSCAER® and the Commodity Preparedness and Incident Management Reference Sheet are expected in late 2021.

[93] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "FRA–PHMSA LNG by Rail Task Force Interim Report," pp. 28–29.

Observations About Completeness and Quality

The Task Force provided a comprehensive overview of the resources currently available, under development, and proposed to meet the needs of emergency responders and planners. In addition to the efforts discussed above, further support to ensure a comprehensive approach would:

- Continue to support national level activities to support the emergency planning and response communities, such as the HM Roundtable and HMFP;
- Create a map of first responders, railway emergency response teams, and specialized emergency response contractor resources along the LNG routes; and
- Develop suggested training programs with consideration of their relationship to existing professional qualifications (e.g., NFPA 470—Hazardous Materials Standards for Responders[94]).

[94] See https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=470.

5

Tasks Broadly Relevant to Railroad Safety

This chapter examines the completeness and quality of 3 of the 15 tasks in the Pipeline and Hazardous Materials Safety Administration–Federal Railroad Administration (PHMSA–FRA) Task Force initiative that are foundational to railroad safety assurance, whether freight or passenger movements. The three tasks are Train Energy Dynamics Simulator, Electronically Controlled Pneumatic Brakes, and Automated Track Inspection Program.

TRAIN ENERGY DYNAMICS SIMULATOR

The objective of this task is to simulate liquefied natural gas (LNG) train operations under various conditions for a single origin–destination pair from Wyalusing, Pennsylvania, to Gibbstown, New Jersey, through Philadelphia, Pennsylvania, using the Train Energy and Dynamics Simulator (TEDS) software. TEDS simulates train behavior based on models that rely on train operations, head-end or distributed power, braking, the type of railcar that makes up the train, and track and environmental conditions. TEDS was developed and validated using real-world train operations for FRA from 2013 to 2016. As used in this task, 100-car unit train operations were simulated over two rail routes designated for LNG transport in DOT-113 tank cars under various conditions.

The TEDS simulation of the LNG unit train for this origin–destination pair includes three head-end locomotives followed by one buffer car with an approximate train length of 8,500 feet (1.6 miles). The simulation results produced train speed, coupler forces, and lateral and vertical force ratio (L/V ratio)[95] predictions within recognized industry safety limits.[96] There is significant overlap between the two routes considered in the simulation.

Simulation studies are essential tasks in the analysis and prediction of new or different train operations. They can assess dynamic performance and engineering risks; produce physics-based results; and quantify the dynamic parameters for a wide range of geometric, environmental, and operating conditions. Such data can be used within either a deterministic or statistical framework for identifying, quantifying, and assessing the risk and effectiveness of mitigation measures. The TEDS model informs and is informed by other tasks. The model uses data from the Automated Track Inspection Program, and the simulation results can inform the tasks on Punctures and Derailment Simulation Modeling, Safety and Security Route Risk Assessment, and Train Operational Controls.

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[95] The lateral and vertical force ratio, or L/V ratio, is a relationship in railway engineering between the lateral and vertical forces imparted to the rail and wheel that is used to understand the risk of a derailment caused by excessive lateral force pushing up the wheel over the rail.
[96] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "FRA–PHMSA LNG by Rail Task Force Interim Report," p. 18.

Observations About Completeness and Quality

The Task Force showed that an appropriate simulation tool was used to analyze a proposed unit train with a consist of 100 DOT-113 tank cars, and that the results exhibit coupler forces and L/V ratio predictions within recognized industry safety limits for the particular origin–destination pair. Also, the simulated train handling achieves acceptable speed and braking.

However, there were a number of gaps in the model regarding train make-up, motive power, and the buffer car. The committee views the decision to simulate only LNG movements by unit train as a shortcoming because manifest (i.e., mixed freight) operations are commonplace in freight railroad operations. The model also omitted distributed power (DP), a common form of motive power wherein locomotives may pull from the front, push from the rear, or assist midway within a train. The predictions of in-train forces, such as coupler forces, can vary significantly depending on the location and quantities of the locomotives. Indeed, DP is one of the two options for compliance with an operational requirement under the final rulemaking in 2020. In addition, the specifics of the buffer car were not clearly documented. In some cases, the length and weight of a buffer car can contribute to derailments from excessive wheel climb risk. For example, because a typical DOT-113 for LNG is about 80 feet, a buffer car of less than 45 feet in length or weighing less than 90,000 pounds may be unsuitable.

In summary, this task would be improved by providing justification for the selected train make-up parameters (e.g., placement and number of locomotives, number and variety of freight cars) and considering alternative route parameters while explaining their omission from the model. Additional details such as these would strengthen the report because it is not clear how the simulation of a single train on two specific routes "will inform future activities to prepare for the future transportation of LNG by rail" in a general sense.[97]

ELECTRONICALLY CONTROLLED PNEUMATIC BRAKES

The Task Force evaluated the costs and benefits of requiring electronically controlled pneumatic (ECP) brakes for LNG by rail transportation. LNG movements by rail will require a new DOT-113 tank car fleet (i.e., the newly specified DOT-113C120W9), providing a potential opportunity to include alternate braking systems in the design if cost-effective and beneficial to safety. Task Force members completed all planned analyses, but will coordinate with the Bureau of Transportation Statistics to track the demand for the new DOT-113 tank cars, as an increase in demand could change the assumptions, and thus the findings, of the analysis.

The Task Force reviewed the existing ECP braking analysis for HHFTs to assess whether ECP braking systems are cost-justified and feasible for LNG transportation by rail. Assumptions in the analysis included:

- DOT-113C120W9 car production would consume the maximum build capacity currently available;
- Equipment costs would be zero on new builds although there would be training costs on the use of such braking systems;

[97] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, p. 20.

- Braking effectiveness was based on a Transportation Research Board study;[98] and
- All existing and produced cars would be used full-time for LNG transportation.[99]

Only these assumptions were presented; no actual analysis was available. Based on the assumptions, the Task Force determined that nearly 50 years of maximum production of ECP-equipped tank cars would be needed to reach the point where the business and safety benefits exceeded the costs of adding and using ECP brakes. Detailed information, whether qualitative or quantitative, regarding the assumptions and calculations was not provided.

Observations About Completeness and Quality

The implementation of ECP brakes could be a risk-mitigating factor included in a comprehensive QRA of LNG by rail. Any resulting change in risk would then inform the final cost–benefit analysis of ECP brakes. However, because of the paucity of information available to the committee for its review, there are insufficient grounds to support or assess the conclusions of the ECP braking analysis or to inform the consideration of ECP brakes as a mitigation measure in a comprehensive QRA. Without details on how the costs were derived and the basis of assuming the effectiveness of the ECP brakes, the quality of the Task Force's recent evaluation cannot be determined.

Specific gaps in the available information include justification of the actual effectiveness of ECP systems; consideration of the need for locomotives and buffer car(s) to also be ECP brake-equipped in a unit train for ECP braking systems to function; and recognition that LNG tank cars in a manifest train would effectively have no brakes if only the DOT-113 tank car designs are modified, as ECP brakes do not function with the conventional air brakes found on the other cars in a manifest train.

AUTOMATED TRACK INSPECTION PROGRAM

This task focuses on assessing the track quality, maintenance, and safety of the two routes designated in the 2019 special permit for transportation of LNG by DOT-113 tank car between Wyalusing, Pennsylvania, and Gibbstown, New Jersey. The track data along those routes informing this task were obtained in March 2020 through the Automated Track Inspection Program (ATIP),[100] a decades-long FRA track inspection effort implemented network-wide to ensure track safety. The earliest iteration of the technologies used in this inspection program dates back to the late 1960s and is related to the initial efforts to use track geometry data for maintenance-of-way planning in 1971.[101]

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[98] National Academies of Sciences, Engineering, and Medicine, *A Review of the Department of Transportation's Plan for Analyzing and Testing Electronically Controlled Pneumatic Brakes Letter Report (Phase 2)*, 2017, https://doi.org/10.17226/24903.
[99] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "FRA–PHMSA LNG by Rail Task Force Interim Report," July 2020, pp. 22–23.
[100] Federal Railroad Administration, "History of Automated Track Inspection Program (ATIP)," November 17, 2019, https://railroads.dot.gov/track/automated-track-inspection-program-atip/history-atip.
[101] Federal Railroad Administration Office of Research, Development and Technology, "Acquisition and Use of Track Geometry Data in Maintenance-of-Way Planning," pp. 11, 17, n.d.,

An FRA-developed fleet of eight vehicles are central to ATIP activities and are deployed to survey (i.e., inspect) track infrastructure for compliance with federal standards, not merely those related to hazardous material transportation. The inspection vehicles range in capabilities, from crewed and uncrewed operations to LiDAR (light detection and ranging) and track component imaging systems, and generally are instrumented at least for:

- Differential Global Positioning System for enhanced accuracy in measuring location;
- Track Geometry Measurement System for track gauge, cross-level, alignment (i.e., straightness of the rail), and rail surface (i.e., the relative elevation of points on parallel rails);
- Ride Quality Measurement System; and
- Rail Impact Detection System to detect damage at rail joints.

Collected data are directly related to operational safety and drive inspection and maintenance activities. In case of exceptions (i.e., track issues), FRA performs an initial verification and issues a report to the maintaining railroad for further action that will ensure compliance with federal track safety standards,[102] possible upgrades to the infrastructure, or both. In 2019, FRA inspected 125,000 miles of track under ATIP.[103]

FRA compared the data from March 2020 with test data collected over the previous 10 years on the same routes to identify trends in track safety. The Task Force reported that the route through Enola, Pennsylvania, in the Harrisburg area (i.e., Route 1)[104] has fewer track exceptions based on current and past measurements. Indeed, the 2020 inspection found no significant decreases in track condition on this route, an improvement over the six found in the past.[105] FRA plans to continue the ATIP-based surveys nationwide and will also reinspect the designated routes before the first LNG shipment to ensure compliance.

The amount of data generated by ATIP surveys is massive. To support ATIP data management, FRA staff explained that the agency created a technology group in 2020 to examine its data infrastructure and analytics capabilities. There will also be consideration of cybersecurity issues.

The rail carriers conduct automated track inspections using comparable technologies as a part of their normal inspection process on a voluntary basis. FRA staff noted that industry data and its own could be integrated, and that they regularly share information with the railroads. The data from track surveys could be used to validate the analysis in simulation tasks, although no documentation was available about ATIP survey data used elsewhere in the Task Force's work.

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https://railroads.dot.gov/sites/fra.dot.gov/files/fra_net/16595/1717%20Acquisition%20and%20Use%20of%20Track%20Geometry%20Data%20in%20Maintenance-of-Way%20Planning.pdf.

[102] Federal Railroad Administration, "Track Safety Standards," 49 CFR § 213, 2019, https://www.govinfo.gov/content/pkg/CFR-2019-title49-vol4/xml/CFR-2019-title49-vol4-part213.xml.

[103] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "FRA–PHMSA LNG by Rail Task Force Interim Report," p. 25.

[104] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "Train Energy Dynamics Simulator Task Resource," August 13, 2020, p. 23, http://onlinepubs.trb.org/onlinepubs/dvb/LNGrail/Train_Engy_Dyn_Sim.pdf.

[105] Pipeline and Hazardous Materials Safety Administration and Federal Railroad Administration, "FRA–PHMSA LNG by Rail Task Force Interim Report," pp. 25–26.

Observations About Completeness and Quality

ATIP is a well-established and mature program that uses track geometry measurement vehicles equipped with state-of-the-art technology for data acquisition. This task successfully demonstrates the effectiveness of the ATIP in identifying track issues in the designated routes for LNG transportation to ensure track quality, maintenance, and safety. Also, the committee was encouraged by a formal FRA effort to bolster its digital infrastructure and analytics for large datasets such as ATIP-generated data.

Although this task appears to lack interaction with others, the survey data can be of great value for simulation studies in other tasks, such as TEDS, to develop more realistic models of track conditions and simulation scenarios. The usefulness of this type of data cannot be overstated. Rail carriers already voluntarily implement track geometry car systems as a quality assurance measure in fulfilment of required track inspection and maintenance. This task could be improved by incorporating industry-collected track geometry data for this route to enhance FRA's own. Based on the value of the track condition survey in this task, the consistent implementation of ATIP surveys and data analysis on future routes designated for LNG transportation by rail is important to support mitigating risk related to track component defects.

Appendix A

Study Committee Biographical Information

Craig E. Philip (NAE) is the Research Professor and the Director of the Vanderbilt Center for Transportation and Operational Resiliency. He spent 30 years with Ingram Barge Company, serving as the President and the Chief Executive Officer for 14 years until his retirement in 2014. He began his career at the Consolidated Rail Corporation and later served with Southern Pacific Railroad, where he was the Vice President of its Intermodal Division. His research focuses on the application of systems engineering to complex infrastructure network problems, operational safety and resilience, and organizational responses to these problems, especially in the maritime sector. He has been actively engaged in transportation and logistics industry leadership, serving as the Chair of The American Waterways Operators, the National Waterways Conference, and the U.S. Chamber of Commerce's Transportation Infrastructure and Logistics Committee. He is currently a member of the Transportation Research Board's (TRB's) Executive Committee and is the Vice Chairman of its Marine Board. He served on the TRB Committee for a Study of Domestic Transportation of Petroleum, Natural Gas, and Ethanol, as well as a reviewer for several TRB special reports, including *Modernizing Freight Rail Regulation*. He serves on numerous boards, including the ArcBest Corporation, the Cumberland River Compact, the Cumberland Heights Foundation, and Seamen's Church Institute, which presented him with its Lifetime Achievement Award in 2015. In 2010, he was designated as a Distinguished Diplomate in the Academy of Coastal, Ocean, Port & 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.

H. Norman Abramson (NAE) is the former Executive Vice President of Southwest Research Institute. He is known internationally in the field of theoretical and applied mechanics. His specific area of expertise is in the dynamics of contained liquids in astronautical, nuclear, and marine systems. He began his career as an Associate Professor of aeronautical engineering at Texas A&M University and has served as the Vice President and Governor of the American Society of Mechanical Engineers and as the Director of the American Institute of Aeronautics and Astronautics. As a member of the National Academy of Engineering (NAE), he served on its council from 1984 to 1990. He has been appointed to many other NAE and National Research Council committees, including the Transportation Research Board's (TRB's) Research and Technology Coordinating Committee and the Committee on the Federal Transportation R&D Strategic Planning Process, all of which he served as the Chair. He served as a member of the U.S. Air Force Scientific Advisory Board from 1986 to 1990. He earned a B.S. in mechanical engineering and an M.S. in engineering mechanics from Stanford University, and a Ph.D. in engineering mechanics from The University of Texas at Austin.

Nii Attoh-Okine is a Professor of civil and environmental engineering at the University of Delaware and the Interim Academic Director of the university's Cybersecurity Initiative. He is an expert in data analytics as applied to railroad safety and engineering. His research areas include railway engineering and safety, machine intelligence in railway condition data, image and signal processing, and cyber resilience. He has published extensively in cross-disciplinary areas, including two books: *Big Data and Differential Privacy in Railway Track Engineering* (Wiley, 2017), which introduces researchers and railway track engineers to the emerging areas of the book's title, and *Resilience Engineering: Model and Analysis* (Cambridge Press, 2016). He holds professional society memberships in the American Society of Civil Engineers (ASCE) and the Institute of Electrical and Electronics Engineers (IEEE). He serves on the ASCE Committees on Risk and Resilience Measurements and Vulnerability and Risk. He was a Founding Associate Editor for the ASCE/American Society of Mechanical Engineers' *Journal of Risk and Uncertainty in Engineering Systems*, which he still serves. He has served as an Associate Editor of various ASCE and IEEE journals. He is a past member of the Transportation Research Board committees on Artificial Intelligence (A5008) and Application of Emerging Technology (A2F09). He earned an M.Sc. in civil engineering from the Rostov State Institute of Civil Engineering, Russia, and a Ph.D. in civil and environmental engineering from The University of Kansas. He is a registered professional engineer in Delaware and Kansas.

Amos A. Avidan (NAE) is a retired energy and construction industry executive with 40 years of experience. He served as the Senior Vice President and the Manager of Engineering and Technology at Bechtel Corporation. He has led people, technology research and development and engineering, large-scale operations, marketing, and large capital projects teams in Mobil Oil and Bechtel. He has more than 20 years of experience in natural gas and liquefied natural gas systems. He is interested in a broad range of fields ranging from leading people and businesses to all established and emerging energy systems and technologies, broad sustainability considerations, impacts of economic growth on society, and addressing global climate change issues related to energy, sustainability, and economic growth. He has authored many technical publications and patents. He holds a B.S. from the Technion–Israel Institute of Technology, an M.S., and a Ph.D. from The City University of New York, both in chemical engineering. He was elected to the National Academy of Engineering in 2009.

Christina M. Baxter is the Chief Executive Officer of Emergency Response TIPS, LLC, that provides practical, evidence-based solutions for emergency response through the development of next-generation tools for enhanced situational awareness and responder safety and instructional design materials for instructor-led and web-based programs in the areas of chemical, biological, radiological, nuclear, and high yield explosives (CBRNE); hazardous materials; and clandestine laboratory response. Prior to forming Emergency Response TIPS, LLC, Dr. Baxter was the Program Manager of the CBRNE program at the U.S. Department of Defense's Combating Terrorism Technical Support Office, where she was responsible for managing domestic and international CBRNE research and development programs to combat terrorism on behalf of the U.S. government as well as overseeing the international CBRNE agreements with Australia, Canada, Israel, Singapore, and the United Kingdom. She is the Chair for the National Fire Protection Association standards for CBRNE personal protective equipment and a committee member for hazardous materials operations arenas with more than 20 years of experience. She holds B.S. degrees in chemistry and environmental science from the University of Massachusetts Amherst and a Ph.D. in analytical chemistry from the Georgia Institute of Technology.

Lisa M. Bendixen is an expert in hazardous materials risk and safety and has addressed risk management, risk assessment, security, and resilience challenges across numerous industries for fixed facilities and transportation systems. She is a Vice President at ICF, consulting on critical infrastructure security and resilience, mission assurance, and other risk management issues with the U.S. Departments of Defense (DOD), Energy (DOE), and Homeland Security (DHS). She served on the Transportation Security Panel for the National Research Council's (NRC's) report *Making the Nation Safer: The Role of Science and Technology in Countering Terrorism* and was on the NRC committee that produced the report *Terrorism and the Chemical Infrastructure: Protecting People and Reducing Vulnerabilities*. She also served on several other national committees focusing on transportation risks, including spent fuel. She was the project manager and the primary author of the *Guidelines for Chemical Transportation Risk Analysis*, published by the American Institute of Chemical Engineers' Center for Chemical Process Safety, and served on the center's technical steering committee. Her work with DHS has included long-term support on critical infrastructure security and resilience, including several versions of the National Infrastructure Protection Plan, development and implementation of the Chemical Facility Anti-Terrorism Standards, and strategic and policy support to the Office of Infrastructure Protection. She has supported DOE on work related to grid security from natural hazards and adversarial threats. She is also actively supporting DOD on critical energy and communications infrastructure. She has played leading roles in several safety and risk associations. Ms. Bendixen holds a B.S. in applied mathematics and an M.S. in operations research from the Massachusetts Institute of Technology.

Jorge A. Carrasco is the Technical Director of Ambipar USA and has more than 40 years of experience in emergency management. He has been providing hazardous materials response services and specialized training worldwide in the areas of industrial emergencies, weapons of mass destruction (WMDs), and emergency management to clients at the chemical producers, railways, mining companies, ports, governments, and emergency responders in Argentina, Brazil, Chile, Colombia, Mexico, Northern Africa, Peru, Spain, Venezuela, and the United States. He began his career as a Vessel Engineer in the Chilean Merchant Marine before moving into the railroad industry as Safety Operations Manager at the Antofagasta (Chile) and Bolivia Railway Company, where he specialized in hazardous materials and tank car safety. Afterward, he became the Manager of International Hazmat Operations at the Security and Emergency Response Training Center, based at the Transportation Technology Center, Inc., in Pueblo, Colorado. Since 2012, he has been a Principal on the Technical Committee for the Standard for Competence of Responders to Hazardous Materials/Weapons of Mass Destruction Incidents (National Fire Protection Association [NFPA] 472) and serves on three other NFPA technical committees concerned with standards for hazardous materials and WMD response. He earned a diploma in solid-state chemistry at the Massachusetts Institute of Technology.

Anay Luketa is a Principal Member of the Technical Staff of the Fire Science and Technology Department at Sandia National Laboratories. She is currently evaluating computational fluid dynamics models to predict dispersion and fire hazards for liquefied natural gas (LNG) facilities and is developing model evaluation protocols for LNG and non-LNG fires. This evaluation also includes assistance with reviews by the Pipeline and Hazardous Materials Safety Administration of hazard modeling software to comply with 49 CFR 193. She has provided independent review and analysis of explosion hazards from a natural gas pipeline for the Nuclear Regulatory Commission (NRC) in response to safety concerns identified in a report by the NRC Inspector General and evaluated LNG models for fire and dispersion. Her LNG studies include a safety analysis of large LNG carriers and fire and dispersion analyses of LNG over water. She has also published models for LNG dispersion about large-scale LNG spills. She earned a B.S. in mathematics and a B.A. in psychology from Seattle University, as well as an M.S. and a Ph.D. in mechanical engineering from the University of Washington.

Gregory G. Noll is the Senior Planning Specialist for the South Central Task Force, a nine-county, all-hazards emergency preparedness organization in south-central Pennsylvania. He is also the Principal at GGN Technical Resources, LLC, a consulting firm specializing in emergency planning, response, and incident management issues. He is the past Chair and a current member of both the National Fire Protection Association Technical Committee on Hazardous Materials Response and the InterAgency Board Training and Exercises SubGroup. He is the recipient of a number of national-level awards, including the 2011 John M. Eversole Lifetime Achievement Award by the International Association of Fire Chiefs and the 2010 California Continuing Challenge HazMat Lifetime Achievement Award. In 2019, he was inducted into the National Fire Heritage Center's Hall of Legends, Legacies and Leaders for his lifetime contributions to the fire service. As a Certified Safety Professional and a Certified Emergency Manager, he has been involved in many national emergency response initiatives involving hazardous materials and energy products. A retired member of the U.S. Air Force Reserve with 29 years of service, he is the author of nine textbooks on hazardous materials emergency response topics. 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.

Dimitris Rizos is an Associate Professor in the Civil and Environmental Engineering Department at the University of South Carolina (UofSC) and the Associate Chair of the department. He is also the coordinator of the Advanced Railroad Technology Group at UofSC. In this capacity, he has developed the railway engineering curriculum, established sponsored research, and is the Director of the Graduate Certificate in Railway Engineering. He has more than 30 years of experience in computational and experimental structural mechanics, structural dynamics, and soil–structure interaction and directs sponsored research relevant to the railway and highway infrastructure with emphasis on remote sensing and smart monitoring of track and structures; railway dynamics; train–track interaction; and analysis and design of freight, passenger, and high-speed railway structures (bridges, tunnels, and track). He is the current Chair of the American Society of Civil Engineers (ASCE) Transportation & Development Institute Rail Transportation Committee. His involvement with the professional community includes membership in organizing committees of conferences, seminars, and workshops; membership in ASCE, the Transportation Research Board, and American Railway Engineering and Maintenance-of-Way Association committees; and has served as the general chair of the Joint Rail Conference 2016. He received a B.Sc. in civil engineering from the University of Patras, Greece, and an M.Sc. and a Ph.D. in civil engineering from UofSC.

William (Bill) C. Shust is a mechanical engineer and the consulting owner of Objective Engineers Inc., since 2000. He performs mechanical analyses and testing for clients, including railroads, other industries, and four national laboratories. He has more than 35 years of mechanical and structural engineering experience and dynamics and has taught courses on vehicle crash testing and mechanical testing and analysis. He has published and presented more than 40 technical papers in refereed journals or conferences and authored reports for the Association of American Railroads and others. He is active in professional societies such as the American Society of Mechanical Engineers, SAE International, the Society for Experimental Mechanics, and the American Railway Engineering and Maintenance-of-Way Association. He is a registered professional engineer in Colorado and Illinois and earned bachelor's and master's degrees in mechanical engineering from Michigan Technological University.

Patrick J. Student has more than 40 years of experience with industry regulations governing hazardous materials transportation by rail. Mr. Student currently consults for the Association of American Railroads (AAR) as an editor for the AAR *Manual of Standards and Recommended Practices for Interoperable Fuel Tenders for Locomotives*, *M-1004 Specifications for Fuel Tenders*. In 2016, he retired as the Director of Hazardous Material, Union Pacific Railroad, where he was responsible for interpreting hazardous materials regulations, railroad operating rules for train makeup and powering, and developing systems for compliance with the rules and regulations. While at Union Pacific, he served on the AAR Hazardous Materials Committee, Tank Car Committee, and Electronic Data Interchange Hazardous Materials Technical Advisory Group. He also served on the Next Generation Rail Tank Car Project and Advanced Tank Car Collaborative Research Project. Mr. Student holds a bachelor's degree in chemistry from the University of Missouri-Rolla.

Appendix B

Disclosure of Unavoidable Conflicts of Interest

The conflict-of-interest policy of the National Academies of Sciences, Engineering, and Medicine (www.nationalacademies.org/coi) prohibits the appointment of an individual to a committee like the one that authored this Consensus Study Report if the individual has a conflict of interest that is relevant to the task to be performed. An exception to this prohibition is permitted only if the National Academies determine that the conflict is unavoidable and the conflict is promptly and publicly disclosed.

When the committee that authored this report was established a determination of whether there was a conflict of interest was made for each committee member given the individual's circumstances and the task being undertaken by the committee. A determination that an individual has a conflict of interest is not an assessment of that individual's actual behavior or character or ability to act objectively despite the conflicting interest.

Mr. William (Bill) C. Shust was determined to have a conflict of interest because he owns Objective Engineers Inc., which performs mechanical testing and analysis for clients in the railroad industry.

Mr. Patrick J. Student was determined to have a conflict of interest because he consults for a railroad industry trade association that represents freight rail carriers.

In each case, the National Academies determined that the experience and expertise of the individual was needed for the committee to accomplish the task for which it was established. The National Academies could not find another available individual with the equivalent experience and expertise who did not have a conflict of interest. Therefore, the National Academies concluded that the conflict was unavoidable and publicly disclosed it through the National Academies Current Projects System (https://nationalacademies.org/pa).