Liquefied Natural Gas Fuel for Freight: Synthesis

Prepared for
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Transportation Synthesis Reports (TSRs) are brief summaries of currently available information on topics of interest to WSDOT staff. Online and print sources may include newspaper and periodical articles, NCHRP and other TRB programs, AASHTO, the research and practices of other state DOTs and related academic and industry research. Internet hyperlinks in the TSRs are active at the time of publication, but host server changes can make them obsolete.

Request for Synthesis

This synthesis and literature search, requested by Tim Sexton provides summaries of information available on the use of liquefied natural gas as a fuel for moving freight. It includes reports and articles about liquefied natural gas used in commercial trucks, rail, and maritime applications. Other issues examined include emissions, infrastructure, adoption, incentives, and regulations.

Databases Searched

- TRID - A Transportation Research Database at the Transportation Research Board (TRB)
- Research in Progress (RiP) – A Database of Current Transportation Research at TRB
- Previous Synthesis Reports on WSDOT Research Website
- Google Scholar

Published Sources

Trucks

Case Study – Liquefied Natural Gas
Argonne National Laboratory, June 2013
http://www.afdc.energy.gov/uploads/publication/lng_case_study_8_2013.pdf

As a part of the U.S. Department of Energy's broad effort to develop cleaner transportation technologies that reduce U.S. dependence on imported oil, this study examines advanced 2011 natural gas fueled trucks using liquefied natural gas (LNG) replacing older diesel fueled trucks. The trucks are used 6 days per week in regional city-to-landfill long hauls of incinerator waste with two fills per day. This is a workable fit for the limited range LNG trucks. Reduction of fuel costs and harmful emissions relative to the replaced trucks are significant.

Gnvert/Gdf Suez Promotes LNG As A Fuel For Heavy Trucks In France By Partnership With Truck Manufacturers
Gas Technology Institute, April 2013
http://www.gastechnology.org/Training/Documents/LNG17-proceedings/7-3-Charlotte_Hubert.pdf

GNVERT concludes a partnership with Transports P. Mendy, a French transportation company, and IVECO France, performed in November 2011 the first French tests under operating conditions of heavy vehicles running on Liquefied Natural Gas; Tests on a Volvo dual fuel truck foreseen beginning 2012. Testing program on 3 weeks and running 9000 km with LNG Results: Truck autonomy up to 600 km with one fuel tank of 570L, No incident, LNG consumption lower than expected (35 kg/100 km), Zero particulate, Nox very low, 25% reduction CO2, 50% reduction noise & vibration LNG filling in 5 minutes Over actions : Investment in the first LNG filling station, Initiated partnership contacts with Westport, Renault truck, Chart and Cryostar, Involved in the European program to develop the concept of European LNG blue corridors Market forecast of 9 000t/yer with 18 L-CNG filling stations in 2017.

Feasibility Study for Liquefied Natural Gas Utilization for Commercial Vehicles on the Pennsylvania Turnpike
Prepared by the Penn State Facilities Engineering Institute, October 2012
http://www.mautc.psu.edu/docs/PSU_2011_03.pdf

Recent advances in horizontal drilling and fracturing technology in gas shale formations have increased natural gas supply such that its price has decoupled from petroleum and is likely to remain significantly lower for the foreseeable future. In the meantime, gasoline and diesel fuel prices in the United States have peaked above 4 dollars per gallon several times, creating renewed interest in natural gas as an economical, alternative fuel for long-haul commercial vehicles. Liquified natural gas (LNG) has become particularly attractive for commercial long-haul trucks due to its price and ability to provide a safe traveling distance of approximately 600 miles between stops for refueling if the truck is equipped with dual fuel tanks. Owners of commercial trucking fleets are beginning to recognize the competitive advantages that LNG fuel may bring to their business but remain cautious with new truck purchases or engine conversions. This cautious approach to LNG fuel is a result of the increased price for equipment (as compared to the conventional, diesel-fueled truck) and lack of infrastructure for LNG fueling stations. The Pennsylvania Turnpike Commission recognized the increased spotlight on alternative fuels for vehicles as well and released a white paper in February 2012 titled Feasibility of Utilizing Natural Gas Vehicles Traveling/Maintaining the Pennsylvania Turnpike, from which recommendations to conduct a feasibility study on the topic were recommended. The recommendations from the white paper were further refined for the purposes of this study to focus on the use of LNG as an alternative fuel for the commercial trucking industry along the Turnpike highway system. This study provides detailed information on these issues, including a mathematical model that shows the optimal locations, specific site considerations, and costs for construction of fueling stations at the site of existing service plazas; technical and economic information on LNG engines; and numerous other issues such as safety and benchmarking with other states.

Liquefied Natural Gas (LNG) as Fuel for Road Heavy Duty Vehicles Technologies and Standardization
SAE Technical Paper, November 2011
[*Not available online – contact the WSDOT Library to borrow a copy*]

Natural Gas Vehicle (NGV) engine technology is mainly based on a well-known and already established engine functioning principle, the Otto engine. The recent developments achieved and the OEMs push for

this kind of technology clearly shows the confidence and reliability of this technology, especially when it comes to the use of compressed natural gas (CNG). For the above-mentioned reasons, the number of applications involving NGVs has increased worldwide.

Environmental and economic reasons, on the whole, have been the main drive for this diffusion. Natural Gas chemical properties are an irrefutable proof of the advanced behavior, environmentally speaking, of a fuel that emits less CO_2 (due to its carbon-hydrogen balance when compared to other fuels) and less NOx and PM. In many countries, favorable taxation schemes have helped the development and entrance into the market of the NGV technology, especially for the light-duty vehicles. Until now, practically no heavy-duty vehicles or lorries have taken advantage of this fuel, because of payload restrictions, and due to the cylinders weight required for a suitable range, an issue requested by specific commercial mission profiles.

Issues Affecting Adoption of Natural Gas Fuel in Light- and Heavy-Duty Vehicles
Pacific Northwest National Laboratory, September 2010
http://s3.amazonaws.com/zanran_storage/www.pnl.gov/ContentPages/184758856.pdf

This report provides a preliminary examination of the incentives and barriers for adopting natural gas as the fuel for light-duty passenger cars, heavy duty combination trucks, and fleet vehicles of all types. In all cases the primary incentive to switch from gasoline or diesel fuel to natural gas is the potential savings in fuel costs. Additional benefits at a national level include a reduction in foreign oil imports and reduced vehicle emissions. Barriers to application of CNG to passenger vehicles include the cost premium for the vehicle, significant competition from hybrid vehicles, limited original equipment manufacturer vehicle selection, high cost and poor selection for U.S. Environmental Protection Agency-approved vehicle conversions, and a limited public refueling infrastructure. The purchase and maintenance costs for operating a compressor at home to refuel from a residential gas source is less cost effective than using a public refueling station and provides fuel at a lower cost than gasoline only in regions of the country with the lowest natural gas prices. Heavy-duty vehicles using liquefied natural gas (LNG) with a high-pressure direct injection system (HPDI) engine have improved driving range, efficiency, and power compared to a similar vehicle using CNG with a spark-ignited engine. However, use of LNG makes the lack of a refueling infrastructure even more critical because CNG stations far outnumber LNG stations. Despite the fact that an LNG-equipped truck is much more expensive than a diesel truck, the payback in terms of fuel cost is more rapid than a passenger vehicle because of the higher number of miles travelled per year and the much lower fuel mileage, which increases the potential fuel cost savings.

Norcal Prototype LNG Truck Fleet
US Department of Energy, July 2004 & February 2005
Final Results: http://www.afdc.energy.gov/pdfs/35427.pdf
Final Data Report: http://www.afdc.energy.gov/uploads/publication/36707.pdf

Norcal Waste Systems, Inc. provides services in refuse collection, recycling, waste transfer, and landfill operations to more than 50 com-munities in the San Francisco area. In 2001, Norcal's subsidiary SF Recycling & Disposal began operating 14 heavy-duty liquefied nat-ural gas (LNG) waste transfer trucks equipped with prototype Cummins Westport, Inc. (CWI) ISXG engines. The LNG trucks were evaluated over 2 years of operation as part of the U.S. Department of Energy's (DOE's) Advanced Vehicle Testing Activity (AVTA). Diesel trucks were also evaluated over part of this period for comparison purposes. This report summarizes the results of the prototype LNG truck evaluation at Norcal.

Waste Management LNG Truck Fleet Alternative Fuel Truck Evaluation Project: Final Results
National Renewable Energy Lab, January 2001
http://www.afdc.energy.gov/pdfs/waste_lng_final.pdf

Waste Management, Inc. a private company based in Houston, Texas, began operating a fleet of heavy-duty refuse trucks powered by liquefied natural gas (LNG) at it Washington, Pennsylvania facility in 1997. Waste Management currently operates seven LNG refuse trucks at that site. The U.S. Department of Energy (DOE) Office of Heavy Vehicle Technologies sponsored a research project to collect and analyze data on the performance and operation costs of five Waste Management's LNG trucks in commercial service, for comparison with data on the performance of three diesel trucks operating on similar routes. This report presents an evaluation of five of the first seven LNG trucks produced by Mack. Mack partnered with Waste Management in Washington, Pennsylvania, to field test its natural gas engine design and gain experience.

Raley's Lng Truck Fleet: Final Results
Battelle, March 2000
http://www.afdc.energy.gov/pdfs/raleys.pdf

Raley's Supermarkets (Raley's), a large retail grocery company based in Northern California, began operating heavy-duty trucks powered by liquefied natural gas (LNG) in 1997, in cooperation with the Sacramento Metropolitan Air Quality Management District (SMAQMD). The U.S. Department of Energy (DOE) Office of Heavy Vehicle Technologies (OHVT) sponsored a research project to collect and analyze data on the performance, operation costs, and emissions, of eight of Raley's LNG trucks in the field. Their performance was compared with that of three diesel trucks operating in comparable commercial service.

Using LNG as a Fuel in Heavy-Duty Tractors
Trucking Research Institute, July 1999
http://www.nrel.gov/docs/fy99osti/24146.pdf

By the early 1990s the passenger car, light-duty truck, and transit bus segments of the automotive industry had all accumulated some experience with natural gas, but there was very little experience with natural gas in heavy-duty (line-haul) automotive applications. In 1994, NREL contracted with the Trucking Research Institute (TRI) to obtain a cooperative agreement with Liquid Carbonic. The purpose of this agreement was to (1) purchase and operate liquid natural gas- (LNG-) powered heavy-duty tractor-trailers with prototype Detroit Diesel Corporation (DDC) Series 60 natural gas (S60G) engines in over-the-road commercial service applications; and (2) collect and provide operational data to DDC to facilitate the on-road prototype development of the engine and to NREL for the Alternative Fuels Data Center. The vehicles operated from August 1994 through April of 1997 and led to a commercially available, emissions-certified S60G in 1998. This report briefly documents the engine development, the operational characteristics of LNG, and the lessons learned during the project.

From Research To Reality: Alternative Fuels In Commercial Trucking
American Trucking Associations, July 1997
[*Not available online – contact the WSDOT Library to borrow a copy*]

In 1990, the American Trucking Associations (ATA) Foundation commissioned the Battelle Memorial Institute to conduct the first study of alternative fuels use in commercial trucking operations. Building on that analysis, the Trucking Research Institute (TRI), in 1991, launched an innovative public-private partnership with the Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) to bring together motor carriers, chassis, component and fuel suppliers, and state and local governments in demonstration projects to study the use of alternative fuels in revenue service operations. TRI's work has resulted in the test and evaluation of several alternatives to diesel fuel -- renewable ethanol, biodiesel, compressed natural gas (CNG) and liquefied natural gas (LNG). The demonstration projects conducted to date have generated crucial information for DOE's Alternative Fuels Data Center. This demonstration experience helped identify LNG as the most promising, economically competitive alternative fuel for trucking. The participating companies and others came together as a subcommittee of the ATA Foundation's Alternatives Fuels Task Force and, working with Failure Analysis Associates, created for the Society of Automotive Engineers (SAE) an industry-accepted Recommended Practice - SAE J2343 - for the design, manufacture, operation and maintenance of LNG-powered heavy duty trucks. Finally, TRI's research partnership also extends to West Virginia University, which operates the DOE-sponsored Transportable Emissions Test Laboratories.

Rail

LNG: fuel of the future?
International Railway Journal, December 2013
http://www.railjournal.com/index.php/locomotives/lng-fuel-of-the-future.html

Efforts to explore alternatives which could help to lower these costs have consequently been stepped up. While trials have taken place with varous bio-diesels, Liquefied Natural Gas (LNG) is the current alternative that is catching the North American railway industry's imagination, particularly given its current $US 0.11 per litre cost at industrial prices. The price is so low due to the current glut of natural gas in the American market as a result of the shale oil and gas boom. And with government policy emphasising domestic energy production, the railways are optimistic that prices will remain low in the long-term.

A closer look at LNG
Railway Age, September 2013
http://www.railwayage.com/index.php/mechanical/locomotives/a-closer-look-at-lng.html

Over its roughly 200 years of history, the North American railroad industry has been shaped by numerous technological milestones, among which are steel rail, automatic knuckle couplers, air brakes, signals, electrification, dieselization, CTC, radio communications, AC traction, gensets, and—still under development—ECP brakes and PTC. Add LNG (liquefied natural gas) to the list of potential evolutionary, if not revolutionary, technologies.

Will LNG be a Railroad Game-Changer?
Railway Age, September 2013
http://www.railwayage.com/index.php/mechanical/locomotives/will-lng-be-a-railroad-game-changer.html

During the 1940s and 1950s, railroads embraced a new locomotive technology: diesel engines. Those that adopted early benefitted from the tremendous cost levers diesel locomotion provided, including the ability to operate longer trains over longer distances, and the need for fewer locomotive servicing and maintenance personnel. The mechanical and operational simplicity of diesel vs. steam was a key factor in the 53% decline in railroad employment numbers from 1944 to 1965. Jump to 2011, and the U.S. Class I rail carriers are spending $11 billion annually for diesel fuel—this despite 15 years of aggressive improvements in fuel consumption, and a resulting increase of 20% in gross ton-miles per gallon of fuel consumed.

A stronger network, with more capacity
Railway Age, September 2013
http://www.railwayage.com/index.php/freight/class-i/a-stronger-network-with-more-capacity.html

BNSF—always a leader in technology—is racing ahead with a program to test locomotives fueled by LNG (liquefied natural gas), which Rose says "may be the next big opportunity for taking cost out of our operations." GE Transportation and Electro-Motive Diesel are each providing three test units, which are expected to begin a one-year evaluation in the fourth quarter. Though few details were available at press time for this issue, Rose did provide some insight into the economic and regulatory issues surrounding LNG.

Marine

The Potential Conversion of the U.S. Great Lakes Steam Bulk Carriers to Liquefied Natural Gas Propulsion: Final Report
Journal of Ship Production and Design
Volume: 29
Issue Number: 4
November 2013
[C*ontact the WSDOT Library to obtain a copy*]

The feasibility and potential benefits of converting 10 remaining U.S. flag Great Lakes steamship bulk carriers to liquefied natural gas (LNG) propulsion using gas engines is investigated. This is the final report of a study that was initially reported at the February 24, 2012, SNAME Section Meeting in Cleveland, OH. The evolving marine air emissions standards and the movement to LNG fuel in U.S. and international non-LNG carriers and the general case for the possible conversion of the remaining U.S. flag Great Lakes steamship bulk carriers to LNG fuel were outlined in the initial report. In this sequel, the final results of a conceptual design study on the conversion of the three AAA class vessels (SS Arthur M. Anderson, SS Cason J. Callaway, SS Philip R. Clarke), focusing primarily on operational and arrangement feasibility and remaining life-cycle economics, are presented. Three cases, a pure diesel conversion, a single-fuel LNG conversion, and a dual-fuel LNG/diesel conversion, are compared.

Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion
Energy
Volume 57
1 August 2013
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Today, most merchant vessels use Heavy Fuel Oils (HFOs) for ship propulsion. These fuels are cost effective but they produce significant amounts of noxious emissions. In order to comply with International Maritime Organization (IMO) rules, Liquefied Natural Gas (LNG) is becoming an interesting option for merchant ships. The aim of the research presented in this paper is to analyse the economic upturn that can result from the use of LNG as fuel for merchant ships and to assess the effects of its utilization in terms of environmental impact. In the first part of the study, a statistical analysis of maritime traffic is carried out in order to identify which merchant ship types could most benefit from using LNG as fuel for ship propulsion. Traffic data of world ships related to the months of May 2008, 2009 and 2010 are analysed. Roll-on/Roll-off vessels (RoRo) and tanker ships spend most of their sailing time in Emission Control Areas (ECA) consequently appear to be the best candidates for LNG use. In particular, the use of LNG is most profitable for tanker ships in the range of 10,000–60,000 DWT (deadweight).

In the second part of the study, operational costs and pollutant emission reduction, following LNG implementation, are calculated for a 33,000 DWT tanker ship. Results show that LNG leads to a reduction of 35% of operational costs and 25% of CO2 emissions. The possibility of improving energy efficiency on board is analysed considering that combustion gases, produced by LNG, are cleaner, thus simplifying the introduction of exhaust gas heat recovery. Two options are considered: simple heat recovery and heat recovery to drive a turbine (ORC). The results show that it is possible to achieve a reduction in fuel consumption of up to 15%.

LNG As Marine Fuel: Challenges To Be Overcome
Gas Technology Institute, April 2013
http://www.gastechnology.org/Training/Documents/LNG17-proceedings/7-2-Pablo_Semolinos.pdf

International Marine Organization (IMO) has introduced restrictions on emissions that will come into force in 2015 in the Emission Control Areas and 2020 for the rest of the world. In order to be compliant with these restrictions, business as usual is no longer an option for the ship-owners. Several solutions are being evaluated, however, LNG has the possibility of remaining the leading candidate in order to retain a substantial share of the world bunker market: proven technology (around 40 ships running on LNG), more than meeting the new emissions requirements and less CO2 emissions. In addition, economics are in many cases in favor of LNG. However, several uncertainties need to be further evaluated and solutions found in order to have LNG become the preferred choice also in this segment. Investments have to be committed all along the value chain and the market faces the classical chicken-and-egg dilemma: Longer term volume commitment from both suppliers and ship-owners that can justify the investments required. The solution will probably be a longer term ramp-up of supply and demand in line with progressive infrastructure investments. Development of regulations, codes and standards has to be made to balance carefully the excellent safety records of the LNG industry without too constraining barriers for the development of new LNG infrastructure required to supply the marine fleet. The world's potential bunker market is equal to the world's LNG production. Consequently, the questions of LNG availability and value/pricing have to be further evaluated. Bunker LNG has a realistic potential to represent around 45 Mtpa by 2030, which is equal to 9 LNG classic trains dedicated. In the future, with an expected even tighter energy market, LNG for bunker will naturally be in competition with other LNG markets.

Liquefied Natural Gas as a Marine Fuel
National Energy Policy Institute, May 2013

http://nepinstitute.org/get/NEPI_Working_Papers/Liquefied_Natural_Gas_as_a_Marine_Fuel_20130613_FINAL.pdf

New rules by the International Maritime Organization and the U.S. EPA have created limitations on the sulfur emissions for the marine industry and changed the economics of LNG as a marine fuel. Compared to other emissions compliance options, LNG is an economically viable option for some vessels. Over time the lower operating costs (fuel and emissions compliance) can pay for the large capital investment in an LNG conversion project or new build LNG powered vessel. Tote Inc., an early adopter of LNG fuel in their marine operations has shared their insight into their decision to convert two large (Ro/Ro) containerships to LNG power for the Alaska trade and to invest in two new LNG powered containerships for the Puerto Rico trade. Key to TOTE's success are 1) the ability to have a long term outlook on their investment 2) building a partnership to provide LNG fuel at the right price, and 3) in the case of the retrofit - an EPA/Coast Guard exemption from 2012 sulfur limits during the time that they convert their vessels to LNG. Vessels that spend the majority of their voyage within Emission Compliance Areas (ECA's) and those with high utilization and high fuel use will maximize the fuel savings of LNG compared to other more expensive, low sulfur fuel blends that would otherwise be required to comply with emissions standards. These vessel operators will look seriously at LNG as a marine fuel as the most stringent ECA sulfur emissions limits approach in 2015. These early adopters will likely need to build partnerships in order to develop LNG supply and bunkering infrastructure for their vessels. With its high fuel use per vessel, the marine industry has a unique opportunity to act as a critical core customer for the development of new LNG infrastructure projects and, in the process, establish LNG supplies for other transportation industries in the region.

Liquefied Natural Gas as a Marine Fuel in the USA: The Commercial Realities
FC Business Intelligence, January 2013
http://www.wecc.biz/committees/BOD/TEPPC/SPSG/Lists/Events/Attachments/426/LNG%20for%20Marine%20Transport.pdf

The US shipping industry is facing a period of upheaval. As tighter environmental restrictions come in to force over the next decade, ship owners, fuel refiners, bunkering providers and other stakeholders must adjust accordingly. Substantial investment will be unavoidable during this period; however deciding when and in which capabilities to invest presents a challenge. On the one hand, ship owners/operators must be sure of the infrastructure to support their new fuelling choices prior to investing in conversions or placing new orders. On the other hand, refiners and bunkering providers are stymied by uncertainty as to the nature and scale of future demand. Operational, logistical and safety concerns will likely have some influence, but mostly, the popularity of future marine fuels will rest upon commercial considerations i.e. the comparative costs of different solutions. However, even this apparently straightforward methodology brings immense difficulties, not least the impossibility of accurately forecasting energy prices. The challenge of going green comes as the US shipping industry continues to navigate commercial difficulties. Many shipping firms have been forced to find innovative ways to preserve or recover margins eroded by lower shipping rates and higher overall costs. Given the high capital costs involved with switching to greener fuels, substantial additional financing will be required in the years ahead, an additional hurdle that must be overcome.

The future of natural gas as a fuel in marine gas turbine for LNG carriers
Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment
Volume: 226

Issue Number: 4
November 2012
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This paper discusses the suitability of using natural gas as a fuel for marine gas turbine electric propulsion (DFGE), utilizing natural boil-off gas and forced boil-off gas, as well as investigating its economical and environmental benefits over other propulsion options. The benchmark ship chosen for this study has a capacity of 150,000 m3 and is powered by conventional steam propulsion. For this purpose a spreadsheet model was developed to determine the liquefied natural gas carrier operating costs for different propulsion options. This is in addition to a sensitivity analysis to study the effect of varying range, heavy fuel oil (HFO) and natural gas prices on ship operating cost. Recently, about 40% of the new orders shifted to slow speed diesel engines with re-liquefaction plant and dual fuel diesel electric propulsion. To date, marine gas turbines are not used in liquefied natural gas carriers. It was found that using natural gas as a fuel with the proposed marine gas turbine cycle at current HFO and natural gas prices provides the highest cost saving for a distance less than 4000 nautical miles (NM). With the expected changes in fuel prices, the proposed cycle achieves cost saving of 3% per round trip, and this saving is directly proportional to increasing fuel prices, compared to other options.

Infrastructure

Resource Guide for Heavy-Duty LNG Vehicles, Infrastructure, and Support Operations
Battelle, March 2002
http://www.afdc.energy.gov/pdfs/lng_resource_guide.pdf

This Guide is designed to assist decision makers and fleet managers, in considering the use of liquefied natural gas (LNG) in heavy-duty vehicles. The objective of the Guide is to answer questions regarding implementation of LNG fuel in the fleet, e.g., getting started, likely costs, benefits, and lessons others have learned. This Guide also provides you with contact information for representatives of companies now using these fuels, manufacturers and suppliers of the fuels, and technical and governmental reference materials. The information in the Guide is intended to be useful for both new and existing end-users of heavy-duty LNG vehicles, so that operations can be initiated or conducted in a cost-effective manner with minimal disruptions related to the new fuel technology.

Market, Adoption, and Incentives

LNG: Breaking the Chicken and the Egg: Widespread Adoption of LNG among Operators Hinges on Fuel Supply, Regulation
Marine Log, May 2013
[C*ontact the WSDOT Library to obtain a copy*]

Liquefied natural gas (LNG) is gaining acceptance as a transportation fuel in the United States, with the first signs of a transition to LNG appearing in both the marine and land transportation industries. In contrast to these first tentative steps, LNG development in Europe and elsewhere is accelerating and LNG may soon become a component of national energy and environmental policies around the world. Several factors account for the movement toward the use of LNG in the marine and transportation industries. Because of existing and forthcoming emissions requirements, LNG is a logical and practical solution; especially when the price advantage of LNG is compared with diesel fuels. The tremendous

increase in gas production, particularly in the U.S., virtually assures potential users that this price advantage will continue. These factors are leading to recognition that LNG has the potential to transform the marine and transportation industries in much the same way that oil replaced coal.

Natural gas in transport: an assessment of different routes
CE Delft, May 2013
https://www.tno.nl/downloads/natural_gas_in_transport_tno_ce_delft_ecn_4818.pdf

Faced with a changing energy supply in the coming years, in which natural gas will play an important role, it was necessary to assess what the different routes of natural gas to transport are. Determine what conditions both environmental and safety, would have to be addressed in order to allow for natural gas to be used in the transport sector as an intermediate fuel on a road towards more sustainable alternatives. The study was overseen by a supervisory interdepartmental group which consisted of representatives from the Ministries of Finance and Economic Affairs in the Netherlands. From within the Ministry of Infrastructure and Environment, representatives of all different transport modes , environment and external safety and risk management took part of the supervisory group. Furthermore the study made use of valuable input that was gathered from stakeholders and industries in the field of natural gas. For this purpose a number of stakeholder consultations were organised in 2012 and 2013. The following assessment is a first guidance document on how natural gas can best be used in transport and what issues need to be addressed. As natural gas will play an important role in the energy mix in Holland, Europe and the world the coming years, we are confident that more information on the application of natural gas in transport will become more readily available and provide us with better data. Thereby allowing to make more accurate assessments in the field of environmental performance and safety standards.

U.S. and Canadian Natural Gas Vehicle Market Analysis
America's Natural Gas Alliance, February 2013
http://anga.us/media/content/F7D3861D-9ADE-7964-0C27B6F29D0A662B/files/Comparative%20and%20Scenario%20Analysis1.pdf

With the primary objective of identifying the most productive and effective means to increase the use of natural gas vehicles (NGVs) in the U.S. and Canada, the TIAX team has conducted a thorough and independent assessment of the NGV market. To highlight the major opportunities to spur the market's development and expansion, this assessment examines the key technical, economic, regulatory, social, and political drivers and challenges that shape this market. Discussed in this report are: Comparative and Scenario Analysis; Natural Gas Vehicle Industry Overview; Market Segmentation; Heavy-Duty Vehicle Ownership and Production; Light- and Medium-Duty Vehicle Ownership and Production; and Liquefied Natural Gas Infrastructure. This assessment was sponsored by: America's Natural Gas Alliance with the support of participating American Gas Association companies.

Natural Gas for Marine Vessels: U.S. Market Opportunities
American Clean Skies Foundation, April 2012
http://www.cleanskies.org/wp-content/uploads/2012/04/Marine_Vessels_Final_forweb.pdf

The authors of this report, economists and engineers led by Thomas Balon and Dana Lowell, are optimistic about the prospects for increased use of natural gas as a marine fuel, both in the U.S. and worldwide. However, natural gas conversion will not be an obvious choice for all vessels due to the high conversion cost. Despite the potential for significant annual fuel cost savings after conversion,

this analysis suggests that the payback period for conversion of many vessels could be 10 years or more. Most marine vessels operate on liquid petroleum fuel – either marine distillate or marine residual oil. Worldwide there are fewer than 50 vessels in-service or on order that operate on natural gas; the majority of these are car and passenger ferries. Virtually all of them operate in Norway or the Baltic or North Sea

Natural Gas Vehicles: Status, Barriers, and Opportunities
Argonne National Laboratory, August 2010
http://www.afdc.energy.gov/pdfs/anl_esd_10-4.pdf

In the United States, recent shale gas discoveries have generated renewed interest in using natural gas as a vehicular fuel, primarily in fleet applications, while outside the United States, natural gas vehicle use has expanded significantly in the past decade. In this report for the U.S. Department of Energy's Clean Cities Program we have examined the state ofnatural gas vehicle technology, current market status, energy and environmentalbenefits, implications regarding advancements in European natural gas vehicletechnologies, research and development efforts, and current market barriers andopportunities for greater market penetration. The authors contend that commercial intracity trucks are a prime area for advancement of this fuel. Therefore, we examined an aggressive future market penetration of natural gas heavy-duty vehicles that could be seen as a long-term goal.

State Alternative Fuel Vehicle Incentives: A Decade and More of Lessons Learned
National Conference of State Legislatures, February 2001
http://www.afdc.energy.gov/pdfs/lessons_learned.pdf

This report assesses the effectiveness of state incentives and suggests incentives that might encourage new vehicle technologies. It does not assess whether a state should promote alternative fuel vehicles or whether such vehicles are the most effective means to reduce air pollution. Rather, the analysis analyzes the effectiveness of state incentives of the past decade and describes the characteristics of effective alternative fuel vehicle incentives and the fiscal implications for a state that is committed to support an effective alternative fuel vehicle program.

Washington Laws and Incentives for Natural Gas
http://www.afdc.energy.gov/laws/laws/WA/tech/3253

Federal Laws and Incentives for Natural Gas
http://www.afdc.energy.gov/laws/laws/US/tech/3253

Emissions

A Few Clean Breakthroughs
Railway Age, September 2013
http://www.railwayage.com/index.php/mechanical/locomotives/a-few-clean-breakthroughs.html

This article discusses efforts of railroads and locomotive builders to meet the U.S. Environmental Protection Agency's Tier 4 locomotive emissions standards, scheduled to take effect in January 2015. The new standards will require manufacturers of locomotive diesel engines to lower particulate matter (PM) by 70% and nitrogen oxide (NOx) by 76%, compared to engines introduced in 2005. Also described

is a new technological and economic breakthrough for the industry, liquefied natural gas (LNG) used as a locomotive fuel. The article highlights locomotive engine testing that has taken place in the U.S. and Canada, and provides a breakdown of locomotive emissions standards.

Does Natural Gas Make Sense for Freight? Environmental and Resource Implications of the "Pickens Plan"
National Center for Freight and Infrastructure Research and Education (CFIRE), April 2013
http://www.wistrans.org/cfire/documents/FR_CFIRE0422.pdf

The "Pickens Plan" is a highly promoted U.S. energy strategy, proposing to use natural gas as a transportation fuel to displace imported oil and, simultaneously, to increase renewable contributions to national electricity production. While the principal goal of the Pickens Plan is to improve domestic energy security and its associated foreign trade imbalance, the authors investigated the proposed strategies for their environmental benefits. They simulated a variation of the Pickens Plan across a seven-state Midwestern U.S. region to evaluate the greenhouse gas (GHG) and air quality implications of the plan. In this scenario, liquefied natural gas (LNG) is used to replace 100 percent of long-haul, diesel-powered freight, while wind-power is roughly doubled over the anticipated 2020 levels under existing renewable portfolio standards. Relative to a business-as-usual (BAU) reference case, the Pickens scenario reduces NOx, SO2, and GHG emissions. Most reductions occur within the electricity sector versus the freight sector: 73 percent of NOx reductions, 99 percent of SO2 reductions, and 94 percent of GHG reductions occurred within the power sector. While the LNG truck is estimated to have 21 percent lower GHG emissions than its diesel counterpart, methane leakage from the natural gas fuel cycle significantly reduces the GHG benefit from LNG trucking. Thus, LNG-powered freight only slightly reduces greenhouse gas emissions relative to the diesel-powered freight. To assess the benefits of natural gas in the transportation sector (Pickens Plan) versus the electricity sector, the authors considered a scenario where natural gas is increased in the electricity sector instead of the freight sector. This scenario yielded greater emissions reductions than the Pickens plan for all species, suggesting that natural gas fuel switching has more impact as an emissions mitigating measure within the electricity sector, rather than within the freight sector. To assess how emissions reductions would affect ambient pollutant concentrations, and the formation of secondary air pollutants, the authors employed a regional air quality model. Under the Pickens scenario, ambient concentrations of SO2, NO2, O3 and PM2.5 were all reduced relative to BAU. In general, the largest reductions were simulated near metro areas, along major highways, and in the Ohio River Valley.

A comparative life cycle assessment of marine fuels liquefied natural gas and three other fossil fuels
Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment
Volume: 225
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August 2011
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Air emissions from shipping have received attention in recent years and the shipping industry is striving for solutions to reduce their emissions and to comply with stricter regulations. Strategies to reduce emissions can consist of a fuel switch, engine changes, or end-of-pipe technologies, but they do not necessarily imply reduced life cycle emissions. The present paper assesses the environmental performance of marine fuels from well-to-propeller using life cycle assessment (LCA). Four fossil fuels are compared: heavy fuel oil (HFO), marine gas oil, gas-to-liquid (GTL) fuel, and liquefied natural gas

(LNG), combined with two exhaust abatement techniques: open-loop scrubber and selective catalytic reduction. LNG and other alternatives that comply with the SECA 2015 and Tier III NOx requirements give decreased acidification and eutrophication potentials with 78–90 per cent in a life cycle perspective compared with HFO. In contrast, the use of LNG does not decrease the global warming potential by more than 8–20 per cent, the amount depending mainly on the magnitude of the methane slip from the gas engine. None of the fossil fuels scrutinized here would decrease the greenhouse gas emissions significantly from a life cycle perspective. The study supports the need for LCA when evaluating the environmental impact of a fuel change, e.g. it is found that the highest global warming potential during the whole life cycle is connected to the alternatives with GTL fuel.

Zero Emissions Vessels
In: *Sustainabilty in the Maritime Industry: A collection of relevant papers*, January 2011
[*Contact the WSDOT Library to obtain a copy*]

This paper proposes a LNG-fueled coastal RO/RO for the East Coast of the US trade to meet upcoming Emission Control Area (ECA) requirements. The exhaust system for this vessel is proposed to be a wet system so there is no airborne emission. The CO2 remaining in the exhaust system is removed in the exhaust stream, and remaining exhaust components are combined with cooling water to provide a cooling effluent that meets Environmental Protection Agency (EPA) requirements. The concept design is carried to the point of determining operating economics, and the environmental effect of operating such ships is assessed as compared to conventional truck traffic. It was found that each ship will reduce East Coast highway truck traffic by over 1900 trucks per week. Since there are no emissions from the ship, each ship will also bring environmental advantages. It appears the ship would be economically competitive with conventional truck transport: the cost for transporting a single 53' trailer via ship is roughly $996, compared to $1245 via truck. Furthermore, the proposed three vessel shipping service could potentially remove nearly 300,000 vehicles from the road annually.

Pathways to Low Carbon Shipping - Abatement Potential Towards 2030
Det Norske Veritas, 15 December 2009
http://www.dnv.com.cn/Binaries/Pathways%20to%20low%20carbon%20shipping%202030_tcm142-400655.pdf

In June 2009 DNV issued the first Pathway to Low Carbon Shipping which demonstrated the potential to reduce the CO2emission of the existing fleet by 15% in a cost efficient manner. In this second Pathway to Low Carbon Shipping DNV has analysed the projected fleet in 2030. The study demonstrates that CO2 emissions by 2030 can be reduced by 30% below baseline in a cost-effective way, and by almost 60% if all the identified measures are included. While there is no single measure which could make it all happen, the aggregated effect of all the measures is significant. This will ensure an industry that operates in a more energy efficient manner and also accepts its share of the common responsibility to reduce CO2 emissions.

Assessment of the Greenhouse Gas Emission Benefits of Heavy Duty Natural Gas Vehicles in the United States
Center for Climate Change and Environmental Forecasting, September 2005
http://climate.dot.gov/documents/natgasvehic092205.pdf

This paper presents a review of existing literature on emission factors, emission data collection techniques and analytic approaches; presents the results of SAIC's analysis of available CO2 and CH4

GHG emission data from chassis dynamometer tests of heavy-duty vehicle exhaust; identifies sources of emission factor uncertainty; and provides suggestions for further reducing this uncertainty. The summary includes the background, methodology, results, and conclusions. The research focused on emissions data from diesel-, LNG- and CNG-fueled heavy-duty vehicles, but the some of the paper's findings about statistical issues may be extrapolated to emission factors for different vehicle types and technologies.

Regulations

Natural Gas Systems: Suggested Changes to Truck and Motorcoach Regulations and Inspection Procedures
Federal Motor Carrier Safety Regulations, March 2013
http://www.fmcsa.dot.gov/facts-research/research-technology/report/Natural-Gas-Systems-Report-508.pdf

This report provides recommendations for suggested changes to Federal Motor Carrier Safety Regulations (FMCSRs), North American Standard (NAS) inspection procedures, and out-of-service (OOS) criteria to accommodate and facilitate the use of natural gas (compressed or liquefied) as an alternative to traditional fuels such as diesel and gasoline in commercial vehicles. In addition to providing specific recommendations for changes, this report summarizes the process used to arrive at these recommendations, which included a literature review and gap analysis, industry site visits/consultations, and a formal peer review process. Current FMCSRs, NAS inspection procedures, and OOS criteria are targeted primarily toward liquid-fueled vehicles. They address the unique characteristics of gaseous-fueled vehicles in a very limited way and fail to address cryogenic fuels. The purpose of this project was to identify changes to the current FMCSRs and inspection procedures, if any, that would specifically and fully address the unique characteristics of natural gas used as a fuel and serve to improve the overall safety of commercial vehicle operations by ensuring that commercial vehicles powered by natural gas meet appropriate safety criteria at all times while operating on public roads.

Regulatory Compliance for Marine LNG Import Terminals in California
Journal of Legal Affairs and Dispute Resolution in Engineering and Construction
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California's projected natural gas demand, coupled with the reality of moribund supply basins, has prompted plans for the import of liquefied natural gas (LNG). Several project applications for the siting, design, construction, and operation of onshore and offshore LNG import terminals have recently undergone a rigorous federal and state regulatory appraisal. The environmental, public safety, and security mandates encoded in current legal statutes were the dominant compliance issues. Addressing compliance required comprehensive risk assessment with extensive modeling of the potentially perilous scenarios, including natural and malevolent intentional hazards for LNG tanker movements and marine terminal operations. The objective was to evaluate the effect of adverse consequences on public and property not associated with LNG terminal. On the basis of this evaluation experience, the principal federal and state laws, regulations, standards and concerns, and jurisdictional and technical conflicts

relevant to environmental, public safety, and security compliance for a marine LNG import terminal are outlined. This will benefit others planning similar ventures in California or elsewhere.

Liquefied Natural Gas (LNG) Import Terminals: Siting, Safety and Regulation
Congressional Research Service, May 2005
http://www.cnie.org/NLE/CRSreports/10Jan/RL32205.pdf

Liquefied natural gas (LNG) is a hazardous fuel frequently shipped in large tankers to U.S. ports from overseas. While LNG has historically made up a small part of U.S. natural gas supplies, rising gas prices, current price volatility, and the possibility of domestic shortages are sharply increasing LNG demand. To meet this demand, energy companies have proposed building dozens of new LNG import terminals throughout the coastal United States. But many of these terminals would be built onshore near populated areas, so local communities fear the terminals would expose them to unacceptable safety and security hazards. Potentially catastrophic pool fires or vapor cloud fires could arise from a serious accident or attack on LNG infrastructure. Faced with the widely perceived need for greater LNG imports, and persistent public concerns about LNG safety, Congress is examining the adequacy of safety provisions in federal LNG siting regulation. The Federal Energy Regulatory Commission (FERC) grants federal approval for the siting of new onshore LNG facilities under the Natural Gas Act of 1938. This approval process incorporates minimum safety standards for LNG established by the Department of Transportation, which, in turn, incorporate siting standards set by the National Fire Protection Association (NFPA). Although LNG has had a record of relative safety for the last 40 years, and no LNG tanker or land-based facility has been attacked by terrorists, experts have questioned the adequacy of key LNG siting regulations related to safety zones, marine hazards, hazard modeling, and remote siting. Experts have also questioned the validity of LNG hazard studies used by federal regulatory agencies which suggest that LNG terminal risks, while significant, are not as serious as is popularly believed. Congress may not see a compelling need to change current federal LNG siting requirements if it views the current regulations and processes as sufficient. Holders of this view would continue to rely on the judgment of LNG experts in federal agencies and standards committees to appropriately balance local public safety with national energy needs. On the other hand, Congress may conclude that some aspects of new LNG terminals do pose excessive public risks, or that there is still too much uncertainty about key risks to make final conclusions about public safety. In this case, Congress has several options to further address LNG terminal safety concerns. These options include 1) banning onshore LNG terminals, 2) redefining federal and local siting authority, 3) imposing more stringent federal LNG safety standards, 4) encouraging more LNG research, 5) curbing U.S. natural gas demand, and 6) developing alternatives to natural gas imports. Each of these policy alternatives has significant limitations, however, and may have undesirable consequences for national energy markets and other hazardous material infrastructure. Legislation addressing federal and state roles in terminal siting, H.R. 6 and H.R. 359, has been introduced in the 109th Congress, and LNG policies continue to be debated.

TRB Research in Progress projects

Great Lakes LNG Feasibility Study
http://rip.trb.org/view/2012/P/1233408

This study would complement the Current Great Lakes Fleet Study and look at the various benefits and challenges of using liquefied natural gas (LNG) as a key fuel to address air emissions in the Great Lakes.

Among the items evaluated would be the cost of engine repower or retrofit, fuel availability and landside infrastructure. Supports the MAR-410 Strategic Plan by continuing to promote environmental sustainability and reduce emissions and the dependence on traditional energy sources. This project would build on the limited work that has been done looking into the viability of LNG for marine fuels in such markets as the Great Lakes. The information from the study could be used to support a public/private partnership to bring LNG to the Great Lakes.

Feasibility Study on the Use of Liquefied Natural Gas as an Alternative Fuel on the Pennsylvania Turnpike Highway System
http://rip.trb.org/view/2012/P/1233928

In this project, researchers will examine locating LNG (liquefied natural gas) fueling stations along the Pennsylvania turnpike for commercial use. A literature review will be performed to identify related problems to potential locations. Relevant factors to be considered in the ranking process such as traffic flow of trucks, proximity to restaurants/hotels, availability of qualified mechanics, etc. will be identified. Candidate LNG locations will then be organized and analyzed using a structured technique such as the Analytic Hierarchy Process (AHP) and then ranked. Other factors such as operating and maintenance costs, contracting methods, funding mechanisms, environmental impacts, training and safety requirements of the public and employees will be explored to determine feasibility. A review of other states' incentive programs will be conducted. Researchers will identify the number of trucks using the turnpike as well as the Average Daily Traffic (count) for pre-selected LNG dispensing locations. Key supply chain routes of both major and mid-size trucking companies will be identified.