STEPS White Paper:

Exploring the Role of Natural Gas in U.S. Trucking (Revised Version)

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Abstract

The recent emergence of natural gas as an abundant, inexpensive fuel in the United States could prompt a momentous shift in the level of natural gas utilized in the transportation sector. The cost advantage of natural gas vis-à-vis diesel fuel is particularly appealing for vehicles with a high intensity of travel and thus fuel use. Natural gas is already a popular fuel for municipal and fleet vehicles such as transit buses and taxis. In this paper, we investigate the possibility that natural gas could be utilized to provide fuel cost savings, geographic supply diversity and environmental benefits for the heavy-duty trucking sector and whether it can enable a transition to lower carbon transport fuels. We find that a small, cost-effective intervention in markets could support a transition to a commercially sustainable natural gas heavy-duty fueling system in the state of California and that this could also advance some of the state's air quality goals. Our research shows that an initial advanced natural gas fueling system in California could facilitate the expansion to other U.S. states. Such a network would enable a faster transition to renewable natural gas or biogas and waste-to-energy pathways. Stricter efficiency standards for natural gas Class 8 trucks and regulation of methane leakage along the natural gas supply chain would be necessary for natural gas to contribute substantially to California's climate goals as a trucking fuel. To date, industry has favored less expensive technologies that do not offer the highest level of environmental performance.

Table of Contents

List of Figures

List of Tables

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Summary of Findings

- *If recent, wide oil and gas price differentials hold, greater use of natural gas in the heavy-duty sector could potentially lower the cost of U.S. freight supply chains, thereby enhancing global U.S. competitiveness by lowering domestic fuel costs for long-distance trucking routes in certain regions.*
- *The use of natural gas in the U.S. freight system improves energy security through geographic supply diversification.*
- *A concentrated regional focus in key markets for early investment is the least-cost strategy to initiate the development of natural gas transportation networks in the United States.*
- *In the case of LNG heavy-duty trucking networks, California is uniquely positioned to launch a profitable natural gas network. The costs to provide dedicated coverage for LNG across California are estimated to be less than $100 million. The Great Lakes and mid-Atlantic areas are also well-positioned to incubate a natural gas transportation network.*
- *Despite the fuel cost advantages that might result from some limited regional natural gas transportation network buildouts, the development of a U.S. national natural gas transportation network will be encumbered by high initial investment costs for new cross country infrastructure relative to the fully discounted, incumbent oil-based network.*
- *Lower levels of methane leakage will be required throughout the natural gas supply system in order to enable natural gas to provide the best possible greenhouse gas benefit relative to diesel. Technologies exist to facilitate this, but supportive policies may be required to encourage their adoption.*
- *Leakage from operating the vehicles, and vehicle fuel efficiency are key parameters in the environmental performance of NGV long haul trucks.*
- *The level of profitability of natural gas fueling infrastructure is more highly correlated with access to a high volume of traffic flows of freight movements than with the locus of surplus supplies of natural gas. Thus, initiatives to introduce natural gas freight fueling businesses in regions with stranded or inexpensive gas resources (natural gas supplies that lack sufficient demand to be commercialized) run a greater risk of failure than efforts to introduce natural gas fueling infrastructure along major freight routes in California, the Great Lakes region and the US Mid-Atlantic.*
- *The cost-benefit for natural gas as a direct fuel is most compelling for heavy truck fleets whose vehicles travel 120,000 miles a year or more.*
- *Current commercial economic drivers mean that conventional stations supported by mini-LNG facilities are likely to be the favored technology in the early stages of the*

market development. Additional options to supply CNG can be an enabling network feature.

- *The lessons for natural gas apply more broadly to the question of the barriers to the development of national networks for alternative fuels. Generally speaking, the lower cost of alternative fuel is an important element of commerciality but is not the only driver to a successful transition to low carbon fuels. The level of costs of new infrastructure is also a significant variable to developing new networks, potentially creating region specific economics.*

Background

Increasingly abundant natural gas supplies are significantly transforming the U.S. energy landscape. Innovations in horizontal drilling and hydraulic fracturing are unlocking vast unconventional reserves of U.S. domestic natural gas and oil. The so-called "shale revolution" has unleashed a giant surge in U.S. natural gas production that is making natural gas a competitively priced fuel in many different applications, including power generation, manufacturing and petrochemical production. Although differences exist in estimates of recoverable unconventional U.S. natural gas resources, the preponderance of geological and commercial assessments project that U.S. natural gas supplies will remain ample, lending credence to the possibility that natural gas could penetrate new markets.

So far, the shale revolution is providing U.S. domestic natural gas at extraordinarily low prices. Liquefied natural gas (LNG) for trucks has seen a fuel price discount of $12-$16/mmBTU (energy basis equivalent) in 2014. Early in 2015, as both U.S. diesel and spot natural gas prices have declined, the price discount has decreased. At present, even with recent oil price declines, the oil–natural gas differential available on futures markets is averaging around $9-$10/mmBTU (energy basis equivalent) over the next one to three years forward. The price of natural gas is about $9.18/mmBTU (energy basis equivalent) less than oil in the derivatives markets for longer range future purchases (over the next five- to ten-years).

The emergence of natural gas as an abundant, inexpensive fuel in the United States has raised the possibility of a larger shift in the level of natural gas utilized in the transportation sector. The cost advantages of natural gas and the diversity of its geographical sources in North America raises the possibility that natural gas can increase the global competitiveness of the U.S. transportation supply chains. Commercial forecasts for how much natural gas could replace oil in transportation vary widely, with high end estimates in the millions of barrels per day (mbd).[1] That's 5% to 10% of the total available market of about 13 mbd or more than 25% to 50% of the existing 3.9 mbd market for diesel. But

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[1] In its June 2013 report, "Energy 2020:Trucks, Trains and Automobiles," Citi Group projects that a shift to liquefied natural gas (LNG) for heavy trucking could eliminate 1.2 to 1.8 mbd of U.S. diesel demand by 2030 and 3.4 mbd globally.

questions remain about the commercial viability of natural gas in transportation given the broad investment required to create a national fueling infrastructure network and about the environmental performance of natural gas as a fuel for trucks. We investigate whether a shift to natural gas vehicles (NGVs) in the U.S. freight system can be commercially profitable and study the environmental consequences of such a transformation.

The U.S. and Global Natural Gas Vehicle Fleet

Natural gas is already used as a transportation fuel in many applications in the United States and globally. There are currently 17.7 million natural gas vehicles operating worldwide, and 92% are light-duty vehicles.[2] Iran and Pakistan represent the largest markets for NGVs at 3 million and 2.9 million, respectively. Other large markets for light-duty NGVs are India, China, Argentina and Brazil.

Driven mostly by air quality concerns and an abundance of natural gas in some provinces, China has seen a rapid increase in the number of NGVs on the road, from 60,000 in 2000 to more than 1.5 million today. Compressed natural gas (CNG) vehicles are predominant in China’s NGV market, including buses, taxis, private cars and commercial vehicles.[3] China’s national oil company CNPC (China National Petroleum Corporation) is projecting that natural gas use in transportation in China could rise to 54 billion cubic meters (bcm) by 2020, an annual growth rate of 16% a year. China’s 12th Five Year Plan encourages the development of liquefied natural gas (LNG) vehicles. The country currently has 70,000 LNG trucks on the road.[4]

By contrast, there are 250,000 NGVs on the road in the United States including 14,000 municipal buses and 4,000 medium and heavy duty trucks.[5] Roughly 3,600 LNG trucks are operating in the United States.[6] Nearly half of garbage trucks sold in the United States last year ran on natural gas. Only one automobile manufacturer, Honda Motor Co., offers a natural gas passenger vehicle for sale in the United States, but the car has so far failed to capture a large market base.

Across the United States, there is a mature, robust distribution network for diesel fuel and gasoline. There are 59,739 diesel fueling stations and 121,446 gasoline stations, and 2,542 truck stops where fuel is readily and conveniently available. This translates on average to about 20 truck stops for every 400 miles of interstate freeway. By contrast, there are just 800 CNG fueling sites, and just under half are public.[7]

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[2] http://www.ngvaeurope.eu/worldwide-ngv-statistics
[3] UC Davis Institute of Transportation Studies China Workshop Beijing, China, October 2013
[4] UC Davis Institute of Transportation Studies China Workshop Beijing, China, October 2013
[5] http://www.ngvaeurope.eu/worldwide-ngv-statistics
[6] www.afdc.energy.gov/vehicles/natural_gas.html
[7] http://www.afdc.energy.gov/fuels/stations_counts.html

To be successful, a new alternative fuel must offer the same convenience at a lower cost. Otherwise, governments must provide public incentives to investors to provide new stations for an alternative fuel. The slow vehicle turnover and the prolific network of incumbent diesel fueling venues across the U.S. highway system limits the transition rate for alternative fuels.

U.S. consumers are unlikely to adopt NGVs in large numbers because other, more convenient alternative fuel options are becoming available and those alternative fuel vehicles are perceived as more environmentally friendly and modern. By contrast, natural gas has high potential to make inroads as a fuel for commercial use, particularly for long-distance freight movement.

In the light-duty sector, U.S. consumers have not gravitated widely to NGVs. In a 2006 U.S. National New Car Buyers survey, non-NGV drivers did not rate natural gas well, compared to alternatives, and ranked NGVs fifth after other options including “electric”, “all biofuels”, “hydrogen”, and “I have no idea.” Polling indicates that CNG is perceived as an older technology, in contrast to plug-in electric vehicles (PEVs) which are viewed to represent innovative, forward-looking technologies. The primary reason consumers buy NGVs is cheaper fuel and access to high occupancy vehicle lanes in urban centers. In contrast, fleet owners gravitate to NGVs to comply with clean air standards. Vehicle range and initial cost remain barriers. The Honda Civic NG, with improved fuel economy and acceleration, can go 248 miles without fueling, about 10% farther than the previous NG version, the Honda Civic GX, and has roughly a seven-year payback period.

The economic advantage of utilizing natural gas to save on fueling costs is highly correlated to both the relative efficiency of the vehicle and intensity of travel. In the United States, most individual drivers do not travel sufficient miles in daily driving to reap cost advantages from a switch to natural gas, given other attractive highly fuel-efficient light-duty vehicle alternatives such as hybrids and PEVs.[8] But for commercial fleet vehicles, which regularly undertake intensive travel, natural gas can potentially offer cost savings and some environmental benefits. Figure 1 shows the annual fuel savings as a function of annual vehicle miles traveled under three different scenarios of LNG fuel discount to diesel.

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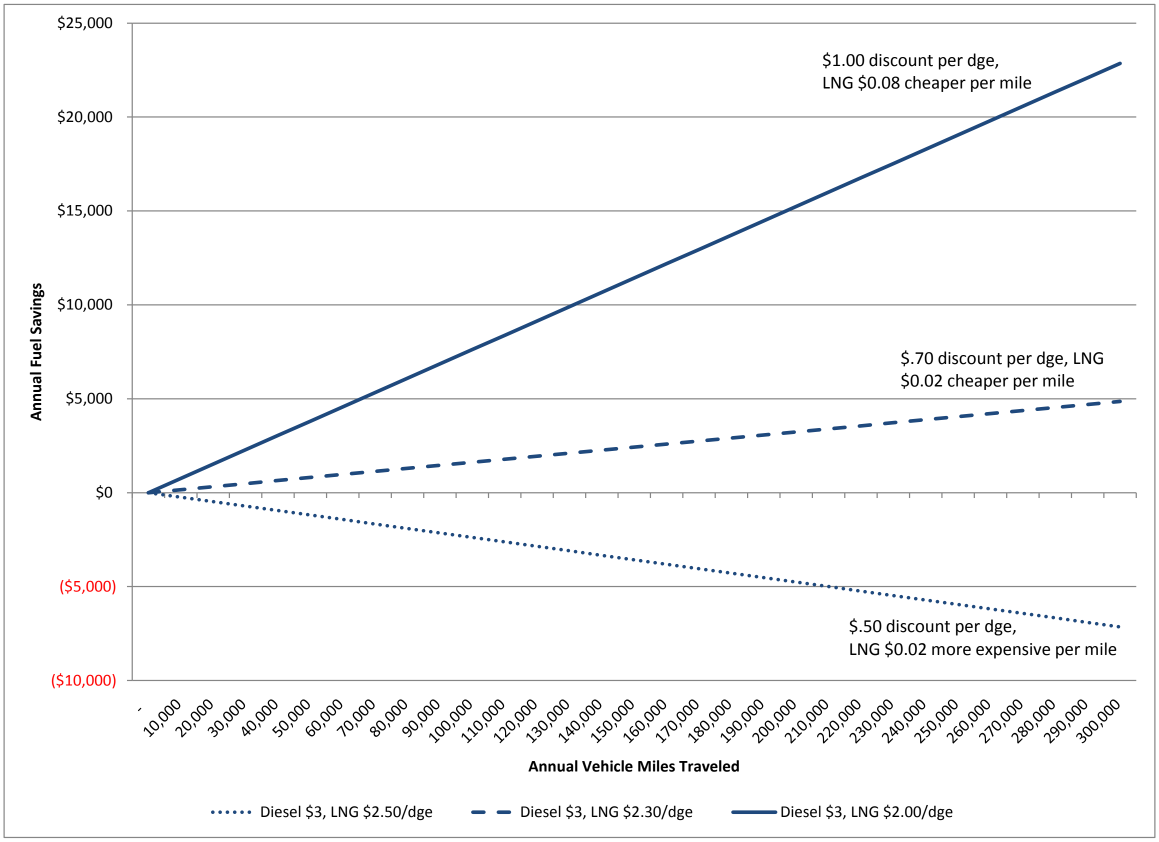
[8] For a more detailed analysis of the economics of CNG-fueled light duty vehicles, see Alan J. Krupnick, Will Natural Gas Vehicles Be in Our Future? Resources for the Future Issue Brief 11-06, May 2011

Figure 1. Annual Fuel Savings by Vehicle Miles Traveled



In this study we use a proprietary spatial modeling program to investigate the possible advantages and disadvantages of natural gas as a transportation fuel and its potential role in enabling other alternative fuels for the United States. In considering the future role of natural gas in U.S. transportation, we analyze vehicle applications where natural gas could potentially offer sustained fuel cost advantages in the commercial sector and investigate whether such fuel price savings would be sufficiently large to generate commercial drivers for construction of a national network of natural gas fueling infrastructure.

We also analyze the environmental impacts of a shift to natural gas compared to diesel in commercial applications. We consider what such a change in fuel type would mean both for air quality in terms of criteria pollutants (i.e., urban pollutants) and for cumulative greenhouse gas emissions. Finally, we use our results to consider whether a public role might be justified in the development of natural gas fueling infrastructure and, if so, where or how such an intervention might be most productive. Several U.S. states, including Oklahoma and Utah, have policies to promote natural gas vehicle use and investment. We investigate the optimum locations for such public policy measures and the specific benefits that might result from a shift to natural gas as a transport fuel in those locations.

We begin by summarizing our findings and then proceed to discuss cost, technical and environmental issues in more detail. We conclude with a policy analysis discussion based on our findings.

Freight Supply Chain Competitiveness

Natural gas station developer Clean Energy recently estimated that the cost benefit of natural gas as a fuel is most compelling for heavy truck fleets whose vehicles travel over 90,000 miles a year or more[9]. Our results support this analysis in part. Further, we find that greater use of natural gas in the heavy-duty sector could potentially lower the cost of U.S. freight supply chains and thereby enhance competitiveness and energy security. In particular, we find that while NGVs can be more expensive upfront than conventional diesel-powered medium- and heavy-duty vehicles, the fuel savings can produce attractive payback for natural gas fleet owners in less than three years.

Of course, this result is sensitive to changes in the price differential between diesel and natural gas. The cost advantage for LNG compared to diesel has been hovering around $8-$16/mmBTU in recent years but has narrowed recently with the crude oil price collapse in the second half of 2014. A significant differential remains since the spot price of U.S. natural gas has declined 30%, while U.S. diesel prices have also dropped 25% since the summer. Fuel switching will be based on long term price trends, where natural gas supplies at present appear to be more prolific and less risk prone than oil.

Energy Security through Geographic Diversification

A shift to natural gas in the freight sector provides key energy diversification benefits to the nation. It brings the transportation sector in line with America's power sector—where electricity providers can choose between a half a dozen fuels other than oil. The result is more flexibility, increased price competition and greater security of supplies. On the power sector side, supply and price competition from natural gas and other diverse fuels have benefited the U.S. economy and average Americans resulting in lower electricity prices and increased global competitiveness, according to studies by the Congressional Research Service and other think tanks.[10] The shift to natural gas from coal has also contributed to a 10% drop in U.S. greenhouse gas emissions between 2005 and 2012.[11] Similar benefits could come from a greater diversity of fuel choices in the transportation sector.

In the case of natural gas as a transportation fuel, we find that the diverse geographic location of U.S. natural gas supplies offers a strategic and economic benefit. Greater

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[9] UC Davis Natural Gas Workshop February 2013

[10] http://fas.org/sgp/crs/misc/R42814.pdf

[11] http://www.scientificamerican.com/article/us-greenhouse-gas-emissions-fall-10-since-2005

geographical diversity of domestic energy supply sources is a key benefit coming from the shale oil and gas boom and thus could similarly be transferred into the transportation sector by adoption of natural gas as a heavy-duty vehicle fuel. Shale gas geologic formations are distributed across the country with natural gas production disseminating from onshore shale gas abundance not only in the U.S. Southwest, but also in the U.S. Northeast, Midwest and North Dakota. This broad geographic distribution across the country helps shore up supply resiliency. In contrast, imported oil and traditional U.S. domestic oil reservoirs and oil refining infrastructure are heavily concentrated in the Gulf of Mexico and interruptible by severe storms. Shale gas is, in fact, ushering in a changed paradigm where consuming countries like the United States will increasingly be able to source their supply at home, lowering geopolitical and weather and climate change-related risks and enhancing economic benefits.[12]

Least Cost Options

The geographic diversity of natural gas supply opens the question to the optimal locations to build natural gas fueling infrastructure. For the past two decades, researchers have investigated the optimum way to transition to cleaner, more secure, alternative fuels in the U.S. transportation sector. Hundreds of scholarly articles have been published on pathways for hydrogen,[13] biofuels,[14] methanol,[15] and electricity,[16] among other alternatives. Less attention was paid to the prospects that natural gas could become a major transport fuel, given its importance as an efficient feedstock for power generation and industry.

To answer the question about the optimum locations for natural gas fueling, we use a modeling framework that utilizes spatial mapping of existing major interstate highways, trucking routes, key fueling routes for fleets and heavy-duty trucks, and fueling

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[12] Medlock, Kenneth, Amy Myers Jaffe, Meghan O'Sullivan, "The Global Gas Market, LNG Exports and the Shifting US Geopolitical Presence," Energy Strategy Reviews, Special Issue, Current and Emerging Strategies for US Energy Independence, December 2014

[13] For example, Bandivadekar, A., Bodek, K., Cheah, I., Evans, C. Groode, T., Heywood, J. Kasseris, E. Kromer, M. and Weiss, M., *On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions*. MIT Laboratory for Energy and the Environment, 2008. Greene, D. L., Leiby, P. N., James, B., Perez, J., Melendez, M., Milbrandt, A., Unnasch, S., and Hooks, M., "Analysis of the Transition to Hydrogen Fuel Cell Vehicles and the Potential Hydrogen Energy Infrastructure Requirements," ORNL/TM-2008/30. Oak Ridge National Laboratory, March 2008. Ogden, J. and Nicholas, M. "Analysis of a "Cluster" Strategy for Introducing Hydrogen Vehicles in Southern California", *Energy Policy*, 39, 2011, pp.1923–1938.

[14] For an example of our work on this topic Morrison, Geoffrey, Nathan C. Parker, Julie Witcover, Lewis Fulton, Yu Pei, (2014) Comparison of Supply and Demand Constraints on U.S. Biofuels Expansion. *Energy Strategy Reviews* 5, 42-47Dominguez-Faus, Rosa, Christian Folberth, Jungo Liu, Amy Myers Jaffe, Pedro J. Alvarez (2013) Climate Change Would Increase the Water Intensity of Irrigated Corn Ethanol Environmental Science & Technology, 47 (11) 6030-6037 ; Christopher R. Knittell, Reducing Petroleum Consumption from Transportation, Journal of Economic Perspectives, 26 (10 Winter 2013

[15] Joan M Ogden, Margaret M Steinbugler, Thomas G Kreutz, A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development, Journal of Power Sources, 79 (2) 143-168; George Apanel, Eric Johnson, Direct Methanol Fuel Cells –ready to go commercial Fuel Cells Bulletin, November 2004

[16] *The influence of financial incentives and other socio-economic factors on electric vehicle adoption.* Sierzchula, W., et al**.** 2014, Energy Policy, Vol. 68, pp. 183-194. *Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electricvehicles (PHEVs) and vehicle-to-grid (V2G) transition.* Sovacool, B.K. and Hirsh, R.F. 2009, Energy Policy, pp. 1095-1103.

infrastructure for CNG for fleet operation and LNG for long-haul trucks to make infrastructure planning decisions. Spatial network theory and network analysis are used to calculate the most profitable trucking corridors to establish LNG infrastructure.[17]

By and large, alternative fuel research has focused on hydrogen-based systems, as evidenced by a recent review[18], and revolves around refueling network research for planning and designing future hydrogen supply chains. As discussed by Dagdougui, the approaches for planning and designing the hydrogen supply chain can be classified as follows: 1) optimization methods (most prominent); 2) geographic information systems (GIS) based methods; and 3) scenario dependent transition models[19]. There are a small number of studies that combine the strengths of a national energy system optimization approach with a spatially explicit infrastructure optimization approach. Stachan et al. described an integrated approach linking spatial GIS modeling of hydrogen infrastructures with an economy-wide energy systems (MARKAL) model's supply and demand[20]. Parker et al. used an annualized profit maximization formulation to study the optimal distribution network for bio-waste to hydrogen[21]. Kuby et al. for example applied a flow-capturing location model to optimizing the locations hydrogen stations in Florida using real world traffic and demographic data[22].

We expand on this literature to improve knowledge related to transportation applications for natural gas. Our special optimization model is designed to determine the most profitable transportation networks and locations for natural gas flows into transportation markets in California and nationwide. Our model uses the spatial infrastructure data and compares costs for transportation of natural gas by source, distribution method, and other market development variables through mathematical optimization. In other words, we study where the most cost-effective and profitable locations to build natural gas fueling infrastructure would need to be located in order to minimize the costs of an overall national system of natural gas fueling along major inter-state highways. A previous study by Rood Werpy concludes that high costs, limited refueling infrastructure, and uncertain environmental performance constitute barriers to widespread adoption of natural gas as a transportation fuel in the US[23] but, in another substantial contribution to the literature, Krupnick finds

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[17] Allen Lee, Nathan Parker, Rosa Dominquez-Faus, Daniel Scheitrum, Yueyue Fan, Amy Myers Jaffe, "Sequential Buildup of an LNG Refueling Infrastructure System For Heavy Duty Trucks" Proceedings and Presentation to Transportation Research Board Annual Meeting, January 2015

[18] H. Dagdougui, "Models, methods and approaches for the planning and design of the future hydrogen supply chain," Int. J. Hydrogen Energy , vol. 37, no. 6, pp. 5318 – 5327, Mar. 2012.

[19] H. Dagdougui, "Models, methods and approaches for the planning and design of the future hydrogen supply chain," Int. J. Hydrogen Energy , vol. 37, no. 6, pp. 5318 – 5327, Mar. 2012.

[20] N. Strachan, N. Balta- ozkan, D. Joffe, K. Mcgeevor, and N. Hughes, "Soft -linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low-carbon UK energy system," Int. J. Hydrogen Energy , vol. 34, no. 2, pp. 642–657, 2009.

[21] N. Parker, Y. Fan, and J. Ogden, "From waste to hydrogen: An optimal design of energy production and distribution network," Transp. Res. Part E Logist. Transp. Rev. , vol. 46, no. 4, pp. 534 – 545, Jul. 2010.

[22] M. Kuby, L. Lines, R. Schultz, Z. Xie, J.-G. Kim, and S. Lim, "Optimization of hydrogen stations in Florida using the Flow-Refueling Location Model," Int. J. Hydrogen Energy, vol. 34, no. 15, pp. 6045-6064, Aug. 2009.

[23] Rood Werpy M., Santini D, Burnham A., and Mintz M. 2010. Natural Gas Vehicles: Status, Barriers, and Opportunities ANL/ESD/10-4 Energy Systems Division.

that the move from a long-haul route structure to a "hub and spoke" structure could facilitate the development of natural gas refueling infrastructure in the highway system[24]. Our study is the first to utilize supply chain optimization techniques with network spatial analysis and link to a simplified natural gas demand model to explore and analyze natural gas infrastructure for the on-road heavy-duty and freight transportation sector.

Our inquiry assumes that all commercial players would benefit most from a system that would allow the widest number of stations at the lowest possible cost per total capital deployed and cheapest available fuel. Our main study finding is that concentrated regional focus in key markets for early investment is the least-cost strategy for developing a broader national network over time.

High Traffic Density Routes: California's Unique Characteristics

The cost benefit for natural gas as a direct fuel is most compelling for heavy truck fleets whose vehicles travel 120,000 miles a year or more. However, despite the cost advantages of natural gas fuel, the development of a national natural gas transportation network will be encumbered by high initial investment costs relative to the low operating costs for the incumbent oil-based network. Compared to the incumbent fuel, the lower cost of alternative fuel is an important element to commerciality, but is not the only driver to a successful transition. The costs of new infrastructure are also a significant variable to developing new networks.

To overcome the competitive hurdle posed by incumbent stations, our research finds that traffic volume is a more important success factor than the location of surplus natural gas supplies. The availability of cheap natural gas in locations such as Pennsylvania or Texas is less relevant than the overall density and volumetric flow of trucking. In other words, locations with stranded gas, that is gas that is located somewhere with insufficient access to possible buyers, are not necessarily the best locations for natural gas freight fueling businesses. Instead, we find that geographically dense and high volume freight corridors provide the most optimum locations for new investment in NGV fueling infrastructure, especially if coupled with higher than average retail diesel prices. Supportive state policies can also be influential if other conditions are prime. The best example of this is the state of California, which meets all of these criteria, including a robust freight corridor, high diesel prices compared to the rest of the country, and a carbon pollution credit market.

Our study shows that California's heavily trafficked Interstate 5 (I-5) corridor, which hosts almost all of the long-haul truck travel in the state, would provide investors with the most favorable commercial opportunity to initiate a concentrated profitable network of LNG fueling stations that might someday seed a possible expansion to a wider, national network.

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[24] Krupnick AJ, "Will Natural Gas Vehicles Be in Our Future? " May 2011. Issue Brief 11-06. Resources for the Future.

Because truckers have fewer options to travel outside route I-5, the initial costs for building a profitable NGV fueling network in the state are lower than in other parts of the country where multiple roads must provide dense station coverage. In addition, traffic flows on I-5 are robust compared to the national average, increasing the potential sales rate from any particular station location on the route. We calculate that an initial investment of under $100 million (under assumptions for a 12% return on capital) could be sufficient to start the launch of a dedicated network along I-5. However, in order for this investment to be effective, the market for LNG trucks must first reach 6,000 vehicles nationwide, or about twice current levels. Further, California is a potentially attractive location for a prospective natural gas transportation network because California-based fleet operators currently enjoy a 20% credit benefit under the Low Carbon Fuel Standard (LCFS). (Fossil natural gas currently has a 20% lower carbon score than diesel under the LCFS, although a regulatory proposal could shrink this percent reduction).

The other region that appears to have high enough demand to support early adoption of LNG as a trucking fuel is the Great Lakes area, which, like California, sees a high volume of traffic and experiences higher diesel prices. It is possible that a national network could evolve over time as more regionally profitable routes in California and the Great Lakes region proliferate outwards. Counter to popular thinking, the profitability of LNG stations is most tied to intensity of traffic flows and higher than average local petroleum prices than to ample availability of local natural gas, our modeling shows. These results paint a potentially positive picture for construction of infrastructure that might promote an easy transition from LNG to renewable natural gas in heavy trucking in the state of California as desired by state policy makers.[25]

California may have stronger interest in assisting the development of an LNG fueling network for heavy-duty trucking in the state – but only if vehicle efficiency and capture of production and distribution system leakage could be improved to add to environmental benefits. Still, the construction of an LNG refueling infrastructure system for heavy-duty vehicles would also enable the greater use of biogas, which might argue for state support if NGVs could be equal to or slightly better in their overall environmental performance than diesel. Consumption of biogas in transportation in California increased by an order of magnitude in one year jumping from 1.7 million gallons of diesel equivalent (dge) during the year beginning in Q3 2012 to 17.5 million dge the following year. During this time, biogas represented 4% of low carbon fuel credits generated for the state and has a substantial growth potential.

The construction of natural gas infrastructure would be enabling to biogas producers who would be assured that fueling networks would be available to commercialize their

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[25] Our independent academic research findings support the rationale for US Department of Energy efforts to create Interstate Clean Transportation Corridors and add new insights into the most economically optimum locations for such corridors. For example, see Stephanie Meyn (2012) Greener Alternatives for Transportation Corridors, Presentation to the US Department of Energy Clean Cities Program, West Coast Collaborative Partners Meeting. In 1996, similar ideas were presented by Bruce Resnik, on Alternative Fuels Trucking, NREL

production. California and neighboring states have a biogas resource base that is large enough to support between 10,000 and 30,000 LNG trucks, but further study is needed to determine what distant resources could be developed and imported profitably from other states and nearby countries. The California Biomass Collaborative, a University of California Davis-led public-private partnership for the promotion of California biomass industries, estimates that 32.5 million billion dry tons (bdt) of in-state biomass feedstocks could be available for conversion to useful energy[26] In particular, estimates for methane production from landfill gas are 55 bcf/year, 4.8 bcf/year for waste water biogas, and 14.6 bcf/year for biogas from manure sources. Similar biomass resources are located in states that border California or along routes for the transmission of natural gas to the state from major producing states.

We estimate that the methane potential from landfill gas in the Western states outside of California is 105 bcf/year based on existing and candidate landfills identified by the EPA.[27] Parker estimates an additional 100 million bdt/year of lignocellulosic biomass in the Western states which are roughly equivalent on an energy-content basis to the gasoline used by 14.5 million passenger cars a year. However, some of these in-state and external biomass sources are already committed to or could be used for the production of liquid biofuels or for dedicated power generation services to the businesses where they are co-located[28].

Barriers to Entry: High Capital Costs for New Infrastructure

Despite the cost advantages of a regional natural gas transportation network build-out, the development of a national natural gas transportation network will be encumbered by high initial investment costs relative to the low cost operations of the existing incumbent oil-based network. Thus, we find that commercial factors will not be sufficient to overcome the infrastructure capital and operational costs that must be considered in any competition with the widely disseminated, fully discounted incumbent infrastructure for diesel fuel all over the United States in a matter of just a few years.

Our analysis concurs with other alternative fuels research that demonstrates how the capital intensity of fueling station investments makes it difficult for new fuels to compete with incumbent oil-based fuels that benefit from mature, financially amortized distribution networks. The case of natural gas is more glaring than other promising fuels such as

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[26] Williams, R. B., Gildart, M., & Jenkins, B. M. (2008). An Assessment of Biomass Resources in California, 2007. CEC PIER Contract50001016: California Biomass Collaborative., (http://biomass.ucdavis.edu/files/reports/2008-cbc-resource-assessment.pdf)

[27] "Landfill Methane Outreach Program: Energy Projects and Candidate Landfills." US EPA, (http://www.epa.gov/lmop/projects-candidates/index.html)

[28] Parker, Nathan, Peter Tittmann, Quinn Hart, Richard Nelson, Ken Skog, Anneliese Schmidt, Edward Gray, and Bryan Jenkins. "Development of a biorefinery optimized biofuel supply curve for the Western United States." *Biomass and Bioenergy* (2010) (34), pp 1597-1607.

hydrogen or liquid biofuels because natural gas has as its starting point a substantial fuel cost discount compared to diesel, its incumbent competitor. Even though major corporations have begun investing billions of dollars to build infrastructure to feed natural gas into the U.S. trucking industry and expand the use of natural gas in fleets, natural gas' success as a transport fuel is by no means guaranteed.

Thus, a focused, regional approach that would lay the groundwork for expansion over a longer period of time would be most productive to tap the benefits of rising U.S. natural gas supply for transportation uses. Our scenario analysis shows that even a return to lofty diesel prices such as those seen in July 2008 would not significantly alter this conclusion because even this wider cost incentive does not create a sufficient economic environment to finance the wide gap needed for infrastructure capitalization. And a 50% government subsidy for LNG fueling stations similarly would not be effective in solving the problem of station unprofitability in many locations across the United States, our research shows.

Carbon Intensity and Air Quality Considerations of Natural Gas in Transportation

The benefit of natural gas on a net carbon intensity basis in transportation is less clear. In terms of climate pollution, tailpipe carbon dioxide emissions from burning natural gas in heavy-duty trucking applications are roughly one fourth to one third as compared to burning gasoline or diesel. [29]. But for spark ignition LNG trucks to match high-efficiency diesel trucks in life-cycle carbon intensity, methane leakage from the natural gas production and distribution system must be negligible. If the more efficient (and expensive) HPDI engine is used in LNG trucking, analysis shows, system methane leakage must be under 2.8% for natural gas to break even in carbon intensity. In addition, a large improvement in natural gas vehicle efficiency would be necessary for natural gas to compete effectively against future best-in-class diesel engines in life-cycle greenhouse emissions.

Generally speaking, natural gas-based fuels emit less particulate matter and sulfur components than diesel. Vehicle modeling research shows that a shift to LNG fuel can contribute a significant reduction in SOx tailpipe emissions as well as almost a full scale elimination in fine particulate matter in heavy-duty trucks. Regions with heavy use of diesel and bunker fuel (marine ECAS, ports, industrial sites, and roads with dense heavy-truck traffic or other non-attainment areas where diesel is heavily used) could experience substantial air quality improvements by switching to natural gas-based fuel. The scientific literature also suggests that aftertreatment technology is more important than the type of fuel used and, thus, this must also be taken into account for California to garner the optimum air quality benefits from a shift to natural gas in heavy-duty trucking. For example, diesel engines with particulate filters could produce lower levels of particulates than natural

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[29] Hengbing Zhao, Andrew Burke, Lin Zhu "Analysis of Class 8 Hybrid-Electric Truck Technologies Using Diesel, LNG, Electricity, and Hydrogen, as the Fuel for Various Applications" Proceedings of EVS27 Barcelona, Spain, November 17-20, 2013

gas engines not equipped with aftertreatment technologies, but when NGV engines are equipped with three-way catalyst technology they generally produce much lower particulate and SOx emissions than updated diesel engines. Similarly, NGV engines without aftertreatment have less ability to control formaldehydes and NOx pollution but with appropriate technology they could produce similar or lower levels than diesel[30].

The Case for Natural Gas: An Abundant, Domestic Fuel

A primary consideration for the adoption of natural gas as a key transportation fuel in the U.S. heavy-duty trucking sector is whether natural gas will remain in abundant supply, holding prices relatively low compared to oil-based fuels. U.S. gross natural gas production has risen from an annual average rate of 64.3 billion cubic feet per day (bcfd) in 2005 to 82.7 bcfd in 2013, driven primarily by momentous growth in production from shale from less than 4 bcfd to more than 31 bcfd. Natural gas supplies from the Marcellus formation in the U.S. Northeast have gained tremendous ground in the past year, altering historical patterns for oil and gas flows inside the United States and creating new opportunities.

In 2011, Advanced Resources International (ARI) estimated 1,930 trillion cubic feet (tcf) of technically recoverable resource for North America and 6,622 tcf globally, with over 860 tcf in U.S. gas shales alone.[31] Most recently, the U.S. Energy Information Administration (EIA) commissioned assessments from Intek in 2011 and another assessment from ARI in 2013. The Intek study estimated 750 tcf of recoverable shale gas resources in the U.S. Lower 48. ARI increased its U.S. shale estimate to 1,161 tcf, as part of a global assessment of shale resources of a world total of 7,299 tcf.[32] As more drilling has taken place, information about the size and economics of recoverable U.S. unconventional resources has improved. While concerns about sharp initial production decline rates have emerged, enhanced understanding about long term performance at fields and the closer distribution of infill drilling has increased optimism about the potential for improved recovery rates.

Figure 2. Shale Resources in North America[33]

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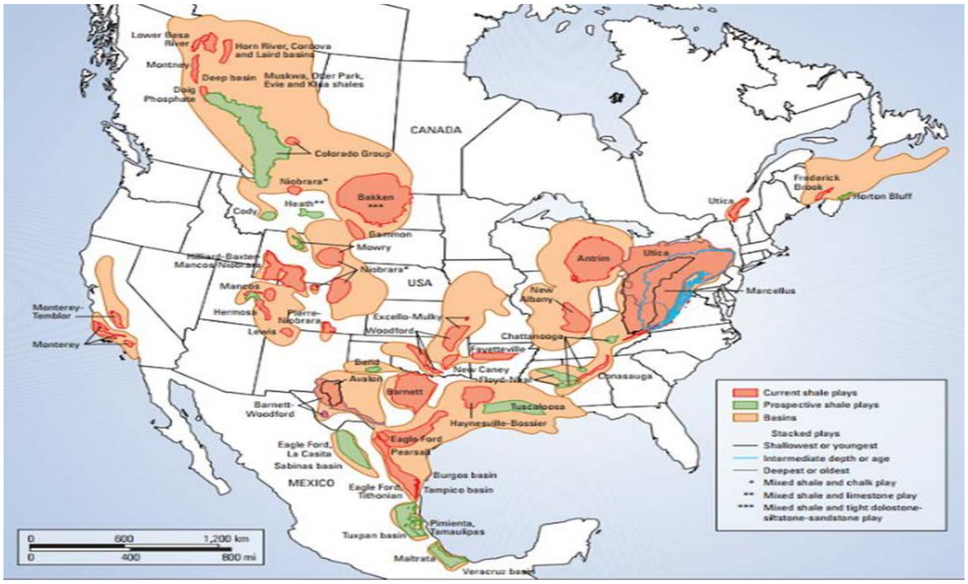
[30] Yoon S, Collins J et al, Criteria pollutant and greenhouse gas emissions from CNG transit buses equipped with three way catalysts compared to lean-burn engines and oxidation catalyst technologies, Journal of Waste Management, 2013 August, (8) 926-33

[31] "World Gas Shale Resources: An Assessment of 14 Regions outside the United States, a report prepared by Advanced Resources International (ARI) for the United States Energy Information Administration (EIA) April 2011.

[32] "A Review of Emerging Resources U.S. Shale Gas and Shale Oil Plays" Prepared by INTEK Inc. for US Energy Information Administration. July 2011.

[33] Source: Gallery of World Hydrocarbon Endowment & Shale Gas Resources, Al Fin Energy blog at http://alfin2300.blogspot.com/2012/03/gallery-of-world-hydrocarbon-endowment.html



Several organizations have studied the ARI, Intek and other assessments such as Rogner[34] and concluded that this large natural gas resource base will allow U.S. natural gas prices to remain relatively low for an extended period of decades, even if North American exports occur (barring a major unexpected disruption in global supplies). NERA Economic Consulting in a report prepared for the U.S. Department of Energy in 2012 analyzed multiple U.S. liquefied natural gas scenarios under EIA's high, low, and reference case for U.S. oil and gas resources. NERA's analysis found that average U.S. natural gas prices generally remain within the $4.00–$5.00 per thousand cubic feet (mcf) range, under most of the export scenarios studied and below $3.50/mcf under high resource scenarios for the study period to 2040.[35]

Another study by Rice University's Baker Institute, University of California, Davis, and Harvard University projects that U.S. Henry Hub spot prices will average $4.00– $6.00/mcf to 2030 under a status quo case where U.S. LNG exports average around 5 to 6 bcfd (Figure 2). Under a high export case of 12 bcfd, study researchers project that U.S. natural gas prices would be about $0.20 higher in the 2020s and $0.40 higher in the 2030s as compared to the status quo case.[36]

Figure 3. Henry Hub Price, 2000-2030, according to Rice Model Status Quo Scenario (Real 2010$)[37]

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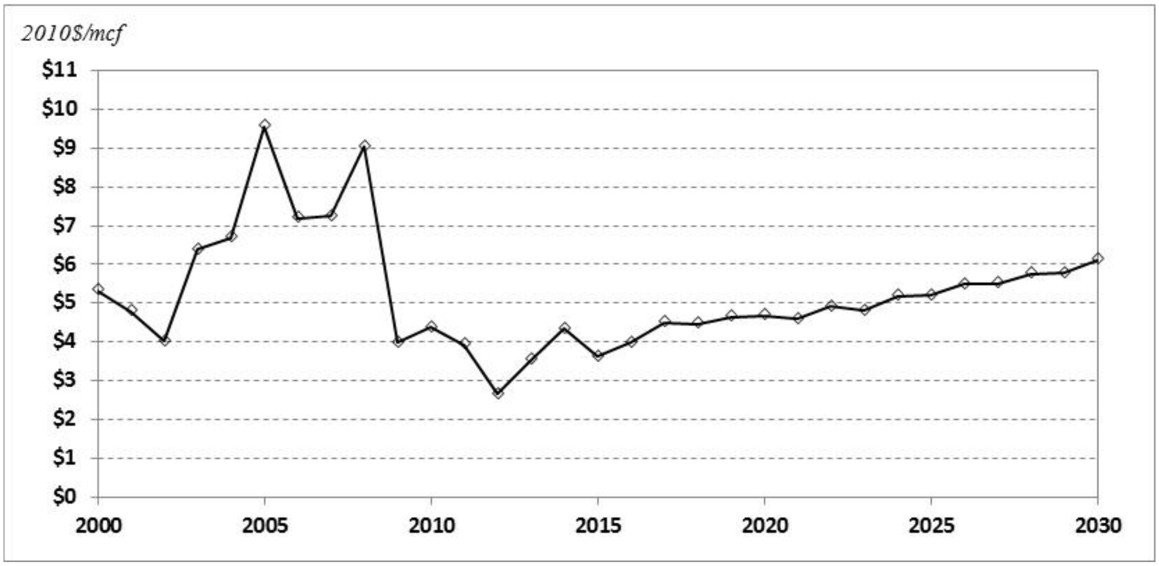
[34] H.H. Rogner, "An Assessment of World Hydrocarbon Resources" Annual Review of Energy and Environment, 1997

[35] NERA Economic Consulting http://www.nera.com/publications/archive/2014/updated-macroeconomic-impacts-of-lng-exports-from-the-united-sta.html

[36] Medlock, Kenneth, Amy Myers Jaffe, Meghan O'Sullivan, "The Global Gas Market, LNG Exports and the Shifting US Geopolitical Presence," Energy Strategy Reviews, Special Issue, Current and Emerging Strategies for US Energy Independence, December 2014

[37] Source: Baker Institute CES Rice World Gas Trade Model, vApr14 (Medlock). For much more detail on modeling approach and results see the CES working papers "U.S. LNG Exports: Truth and Consequence," 2012, available at



Medlock (2014) studies the average expected ultimate recovery (EUR), drilling costs and break even prices for key U.S. shales. He finds that there is an estimated 1060 tcf of shale gas resource recoverable across North America at prices below $6/mcf, and almost 1,450 tcf at prices below $10/mcf (Figure 3)

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http://bakerinstitute.org/research/us-lng-exports-truth-and-consequence; and “Natural Gas Price in Asia: What to Expect and What it Means,” 2014, available at http://bakerinstitute.org/research/natural-gas-price-asia-what-expect-and-what-it-means. Both are authored by Ken Medlock.

Figure 4. Estimated Expected Ultimate Recovery by Shale Play per Average Well by Location[38]

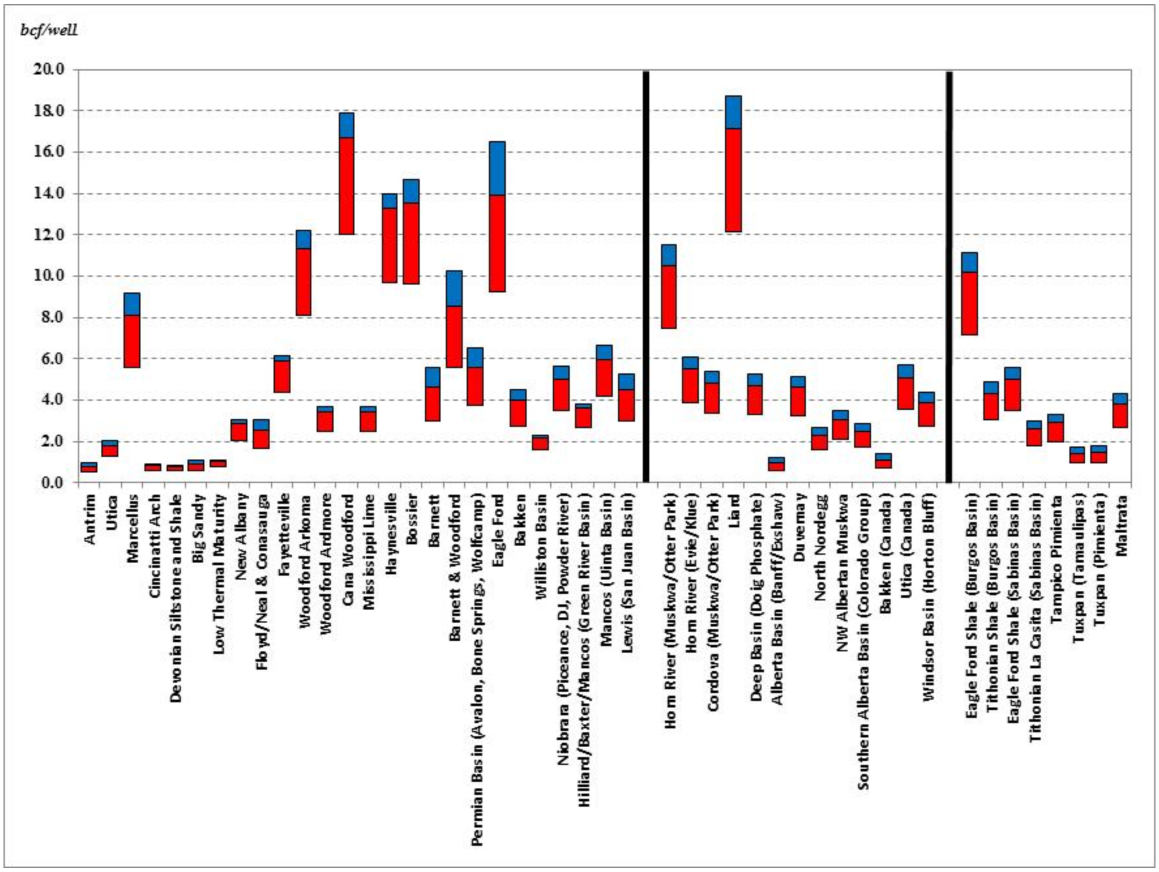

Figure 5 represents the average breakeven price by shale play in North America. Medlock (2014) concludes that about 246 tcf of the available resource at a breakeven price of under $6/mcf is in Canada, 111 tcf is in Mexico, and the remaining 656 tcf is in the United States. At prices under $10/mcf, 358 tcf is in Canada, 215 tcf is in Mexico, and 874 tcf is in the United States. Finally, Medlock notes that the total *technically* recoverable resource associated with Figure 5 is 1,844 tcf, where almost 400 tcf of the technically recoverable resource is commercially viable only if prices are at a minimum of $10/mcf.

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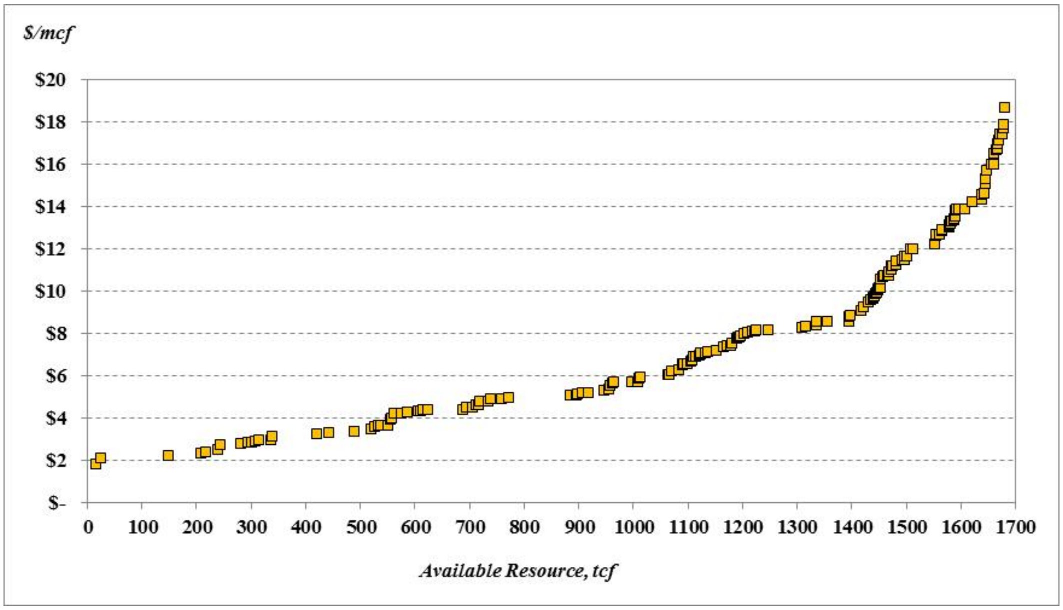
[38] Source: Baker Institute CES Rice World Gas Trade Model, Apr14 (Medlock)

Figure 5. North American Shale Gas Resource and Average Breakeven Price by Play.



The above analysis supports the notion that the North American natural gas resources have a relatively elastic supply curve at affordable prices. But natural gas' price attractiveness as a substitute for diesel fuel is also predicated on the durability of the sizable gap between relatively inexpensive natural price levels as compared to lofty oil price levels, and some uncertainty remains about long term trends for global oil prices. Rising tight oil resource development in North America combined with advances in automotive and other energy efficiency technologies are currently placing downward pressure on oil prices and could be part of a cyclical downturn,[39] but natural gas prices have also been declining of late. In recent months, spot prices of U.S. diesel have fallen roughly 25% while the price of U.S. natural gas has declined 30%. At present, the oil–natural gas differential available on futures markets is averaging around $9-$10/mmBTU equivalent from one year forward to three years forward. The long range derivatives differential is about $9.18/mmBTU equivalent cheaper. The possibility that natural gas prices could remain relatively affordable compared to diesel prices has increased interest in natural gas applications for transportation.

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[39] El-Gamal, Mahmoud Amin and Amy Myers Jaffe (2013) Oil Demand, Supply and Medium Term Price Prospects: A Wavelets-Based Analysis. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-13-10

The U.S. Freight Supply Chain and Potential for Natural Gas

Over 70% of all freight tonnage transported inside the United States moves by trucks. A high proportion of this movement of goods by trucks concentrates on the Interstate Highway system where some 2.5 million Class 8 heavy-duty vehicles carry 8.2 billion tons of goods a year. In addition, there are roughly 1.3 million medium-duty trucks in service in the United States[40]. Heavy-duty vehicles are defined as those in the highest weight class of 33,001 lbs. and over and include truck tractors, dump trucks, and cement trucks. Medium-duty vehicles are defined as service vehicles with weights of between 19,501 lbs. and 33,000 lbs., including a wider variety of trucks such as single-axle trucks, city transit buses and smaller truck tractors. Heavy-duty vehicle classes include classes 8B, (67%), 6 (14%), 8A (8%), 7 (5%), and Class 3 (1%).

The size of the U.S. diesel fuel market is approximately 41 billion gallons a year (excluding military). Heavy-duty vehicles represent about 62% of this market, with roughly 23-25 billion gallons per year demand coming from line-haul Class 8 trucks. Currently, there are only 9,500 truck stations in the United States that serve 1.5 million Class 8 trucks. Class 8 trucks use 30 billion gallons per year diesel consumption, the equivalent to 3.3 tcf/year natural gas or 10 to 15% of current U.S. natural gas consumption.

According to the EIA, annual demand for diesel fuel from freight trucks could rise to as much as 45 billion gallons under a business as usual forecast by 2025 or about double current use. Thus, the potential of natural gas to diversify the U.S. freight system away from oil is large.[41]

The heavy-duty trucking industry shifted from gasoline to diesel fuel after the 1970s oil crises in an effort to save money on fuel. The shift was slow in the 1950s but then ramped up quickly to 50% of the market after 10 years, and 100% of the market after the 1970s oil crises created competitive forces which gave firms switching to diesel fuel from gasoline a competitive advantage.[42] The rate of technology adoption is shown in Figure 6,[43] which represents the transition to diesel's share of new sales of Class 8 trucks in the United States starting in the 1960s.

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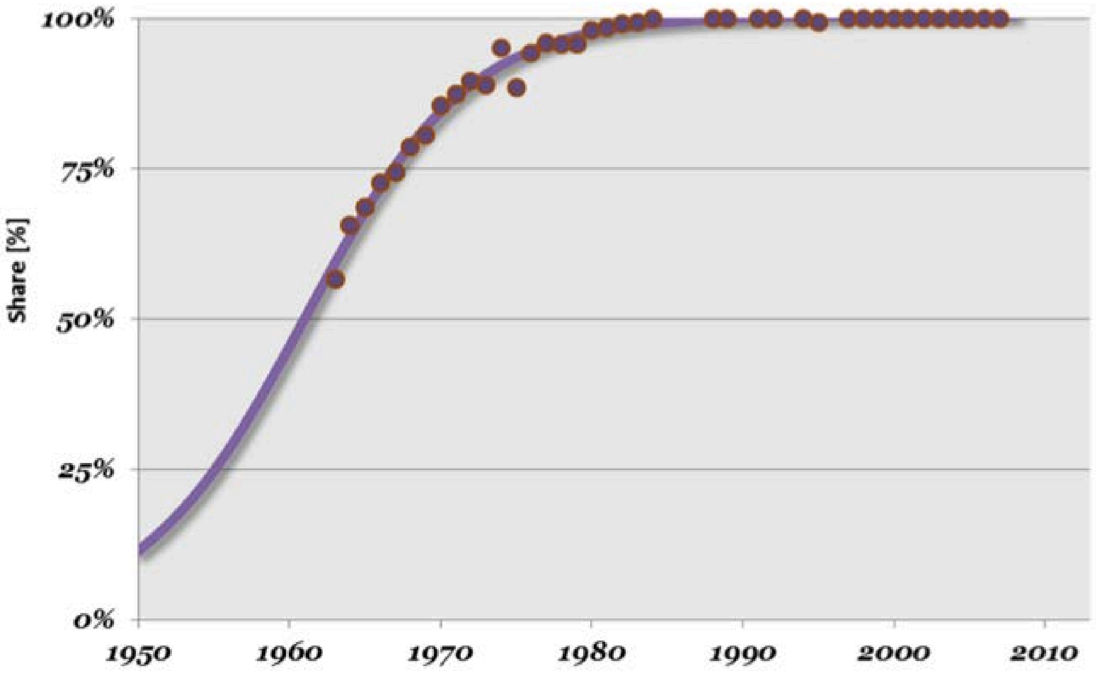
[40] http://www.afdc.energy.gov/vehicles/natural_gas.html

[41] In the U.S. the heaviest trucks consume an average of roughly 6.5 gallons per thousand ton-miles. However, fuel efficiency of the existing truck fleet varies by weight range, drive cycle and terrain. In 2014, the Cummins/Peterbilt team announced their fully-loaded class 8 truck achieved a fuel economy of 10.7 miles per gallon.

[42] LNG as a Fuel for Demanding High Horsepower Engine Applications: Technology and Approaches, Paul Blomerus 2012. Page 6.

[43] LNG as a Fuel for Demanding High Horsepower Engine Applications: Technology and Approaches, Paul Blomerus 2012. Page 6.

Figure 6. Percent of New Class 8 Truck Sales with Diesel Engines.



Because the turnover rate for new trucks for large fleets among first owners is relatively swift (i.e., three to four years) and natural gas is abundant and has seen a price advantage compared to diesel of between $1.50 and $2.00 a gallon over the last two years, there has been a growing interest in natural gas as a fuel for long distance trucking. In its report, "Energy 2020: Trucks, Trains and Automobiles," Citi projects that a shift to liquefied natural gas (LNG) for heavy trucking could eliminate 1.2 to 1.8 million barrels per day (mbd) of U.S. diesel demand by 2030 and 3.4 mbd globally.

At least two firms, Clean Energy Fuels, and ENN have begun building LNG fueling stations in the United States. There are currently 59 public LNG fueling stations and 42 private LNG fueling stations along routes from Los Angeles to Las Vegas, around Houston and around Chicago. The stations currently serve a fleet of 3,600 LNG trucks. California is the state with the largest number of LNG fueling stations, serving over 200,000 gallons a day, with local facilities in Tulare, Lodi, Fontana, Lost Hills, San Diego, Aurora and Ripon, among others. Zeuss Intelligence reports that there are 34 LNG supply plants with trailer loadout capable of producing about 3 million gallons of LNG a day[44]. The United States has over 800 CNG fueling sites of which a little under half are public.[45]

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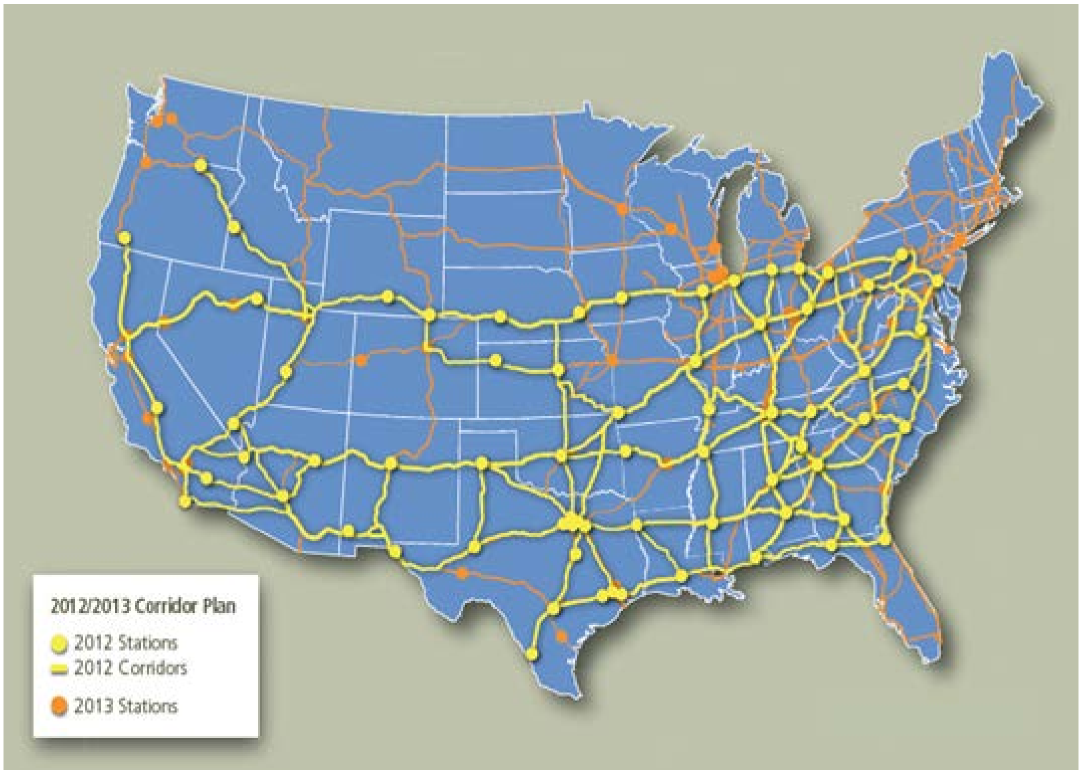
[44] Provided to authors by Zeuss Research consultants

[45] http://www.afdc.energy.gov/fuels/stations_counts.html

Clean Energy is the largest natural gas fuel provider in North America with over 330 natural gas fueling stations, serving 660 fleets and 25,000 vehicles. The company currently sells an average of 200 million gallons of CNG and LNG a year. The projected America's Natural Gas Highway (ANGH) by Clean Energy includes 150 natural gas stations spread out every 200–300 miles. Clean Energy says it is able to achieve a return on capital for fueling station investment and still pass on between $1.00–$1.50 a gallon in fuel savings to customers. Figure 7 shows Clean Energy's American Natural Gas Highway.

Figure 7. America's Natural Gas Highway envisioned by Clean Energy.



The company's business model is to line up with return-to-base segment shipping that is enabling a shift to LNG fuel. Increasingly, long distance trucking is changing from patterns where a single vehicle with a single driver transverses the entire country to a hub and spoke operation where more localized fleets handle part of a longer journey for modular containers.[46] This new transport paradigm means more trucks return to a local home base in the evening, not only improving the lifestyles of drivers but also creating more opportunities to fuel and maintain fleets from a home base. This emerging "relay race" supply chain model to daily regional operations with a home base is conducive to a shift to natural gas for fleets.

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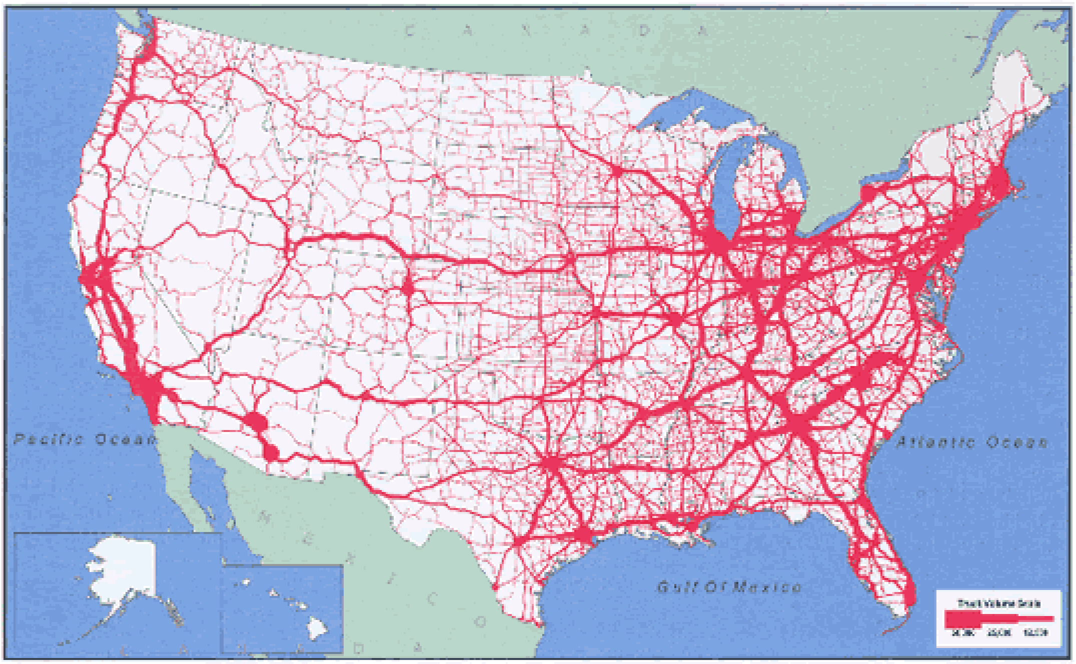
[46] For more details on this phenomenon and its potential to enable LNG as a trucking fuel, see Alan J. Krupnick, Will Natural Gas Vehicles Be in Our Future? Resources for the Future Issue Brief 11-06

Some U.S. trucking corridors have heavier traffic than others and may therefore be better suited for a shift to natural gas than less traveled routes. Among the highest traveled trucking corridors I-5 in California; Milwaukee to Chicago; upstate New York, New York City and New Jersey; Dayton, Ohio to Cincinnati; routes around the Kansas City region; Chicago to Indiana; Dallas to Houston and Orlando to Tampa. Routes such as I-5 in California where truckers have fewer alternative routes to choose from offer the best potential for alternative fuels because they can support a dedicated network with the highest chances that the majority of trucks will pass a particular station. As might be expected, several of these highly trafficked routes also tend to have the highest diesel prices in the nation. Diesel prices averaged 9% to 10% above the national average in New York and Pennsylvania in 2013. Diesel prices in Ohio, Michigan and New England average about 5% above the national average, while California, Delaware and Maryland prices are 2% above the national average and Indiana prices are 3% above the national average.

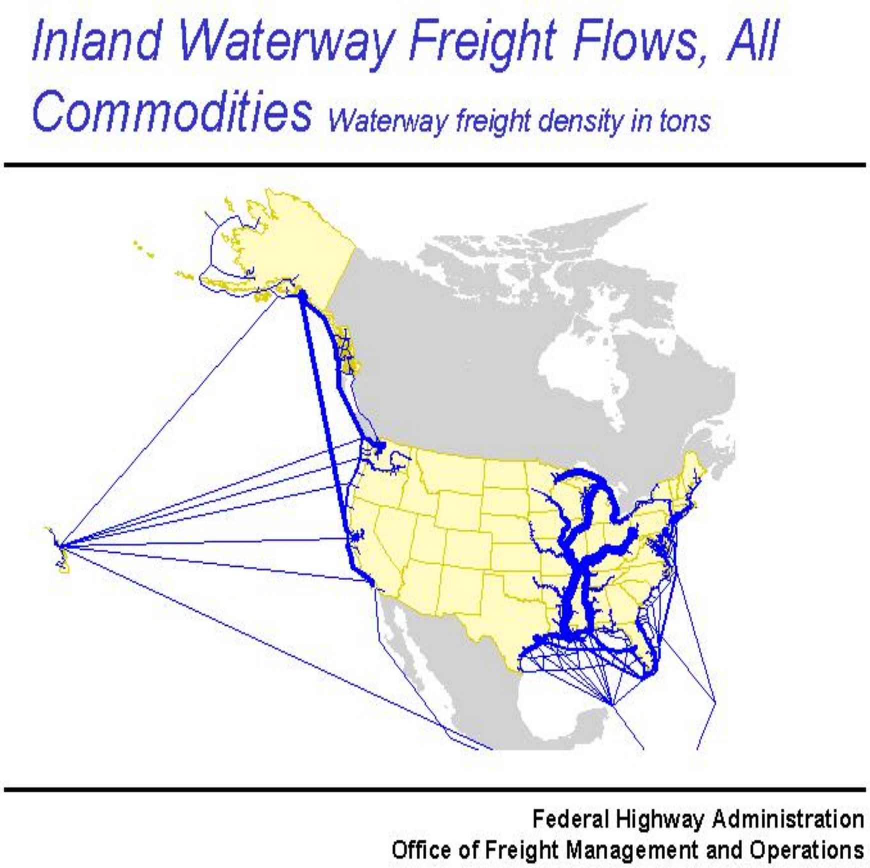
Figure 8 shows the concentration of trucking traffic on U.S. interstates with thickness of dark red shading representing those routes with the heaviest truck traffic flows. As the figure shows, California and the Great Lakes region are among the heaviest flows in the United States and therefore may have the highest potential for a new fuel.

Figure 8. Concentration of Truck Traffic.



This concentration of truck traffic in the U.S. supply chain to certain regions complements the patterns of movements of goods by ship as shown in Figure 9.

Figure 9. Waterway Freight Density. [47]



Barriers to Commercial Adoption of Natural Gas in Long-Distance Trucking

Vehicle cost

Despite some recent gains in network development, natural gas faces the same chicken-egg problem as other alternative fuels. Two major commercial barriers exist. The first commercial barrier is that LNG trucks cost significantly more than diesel trucks. The cost varies depending on the actual model. The components that add to cost are the engines, which can be either compression ignition (CI) or spark ignition (Si), and the natural gas onboard storage systems, which can be either CNG or LNG.

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[47] http://www.ops.fhwa.dot.gov/freight/Memphis/appendix_materials/lambert.htm

Ignition in the Ci engines requires injection of a small amount of diesel fuel although the engine is operated on natural gas. As shown in Table 1, the cost of the CI engine is far more expensive than a diesel engine at a $25,000–$30,000 premium. The Si engine is only $1,000–2,000 more expensive than the diesel engine of the same displacement but performs at a significantly lower rate of fuel efficiency. The fuel economy of trucks using the dual-fuel CI engines are close to those using a diesel engine, while the fuel economy with the Si natural gas engine is about 10-20% less than with the diesel engine

The cost ($/dge) of storing natural gas as LNG is 20–25% higher than storing it as CNG, but offers some advantages in lighter volume and weight. For the same size storage unit, the range using LNG will be twice that of CNG due to differences in energy content per an equal volume of each fuel. The longest range will be attained using a LNG CI truck because of the higher fuel economy of the dual-fuel CI engine and the higher energy density of the fuel. However, as indicated in Table 1, the differential cost of the LNG CI truck will be higher than that of the CNG Si unit due to higher cost of both the dual-CI engine and the LNG storage. .

The least expensive NGV option would therefore be CNG storage and Si engines. Using the cost values in Table 1, for a range of 700 miles, the cost of a CNG Si truck would be $7,900 lower than the LNG CI truck. The CNG Si truck would carry a price premium of $36,298 over a diesel truck. The more efficient CI model with the LNG storage would have a premium of $44,168.

Table 1. NGVs range, fuel economy and cost differentials respect to diesel.

Vehicle	Range (miles)	Fuel economy (mpdge)	Engine Cost ($)	Storage Cost ($)	Incremental cost to OEMs ($)	Incremental cost to Consumers ($)
Diesel	900	5.6	9,000	1,000	0	0
LNG Ci	700	5.4	20,000	35,200	45,200	67,800
LNG Si	570	4.4	10,000	35,000	35,500	38,200
CNG Ci	370	5.4	20,000	15,000	25,400	38,100
CNG Si	300	4.4	10,000	15,000	16,500	24,500

Cost of the refueling infrastructure

The second barrier is that LNG and CNG fuel cannot leverage existing filling station equipment but requires a new set of fueling apparatus.[48] Across the United States, there is a mature, robust distribution network for diesel fuel and gasoline. There are 59,739 diesel fueling stations and 156,065 gasoline stations in the United States and 2,542 truck stops where fuel is readily and conveniently available. This translates on average to about 20 truck stops for every 400 miles of Interstate freeway.

Despite attractive fuel cost differentials and freight customers' interest in cleaner transportation fuel options, the trucking industry has to date been reluctant to take the plunge on expensive equipment upgrades to natural gas.

The logistics sector operates on thin margins and tight schedules, and fueling station density is a critical issue. LNG trucks are dedicated vehicles, meaning they must have LNG station coverage that enables their full range of operations. But the penetration rate of LNG along major highways with the highest flows of goods by heavy-duty truck represents less than 0.1% of the national market. This presents a chicken and egg problem in transitioning to a significant market share for LNG trucks.

Drivers need to stop to refuel as infrequently as possible and natural gas' reduced density of fuel means more time-consuming stops for fueling. The distance to a vehicle maintenance technician with natural gas vehicle repair skills is also a consideration for a trucking route. For long-haul shippers, natural gas stations must be provided along routes every 300–400 miles, whereas diesel fuel stations can be spaced over 1,000 miles apart. Natural gas stations must be available along the entire route for it to be viable for truck fleets to shift to NGVs. To date, despite the strongest market for commercial truck sales in almost a decade, momentum towards the use of natural gas in long-distance heavy-duty truck fleets has been waning.[49] At present in the United States, there are only a few major shipping routes that have full coverage for LNG fueling (Figure 10).

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[48] It is possible to reduce some of the land and facilities cost by locating natural gas fueling infrastructure contiguous to traditional truck stops as has been done in some limited locations, but the cost of the fueling infrastructure itself remains a barrier.

[49] Bob Tita "Slow Going for Natural Gas Powered Trucks" *The Wall Street Journal*, August 25, 2014

Figure 10. Existing Public and Private LNG Stations. [50]

A core issue blocking the construction of a comprehensive national network for natural gas fueling is the capital intensity of new fueling station investments which have to compete against sales outlets of incumbent fuels whose distribution networks are fully depreciated. In effect, natural gas' price discount would have to be large enough to cover both the high capital costs for building out new stations and higher operating costs for LNG fuel as illustrated below in Figure 11.

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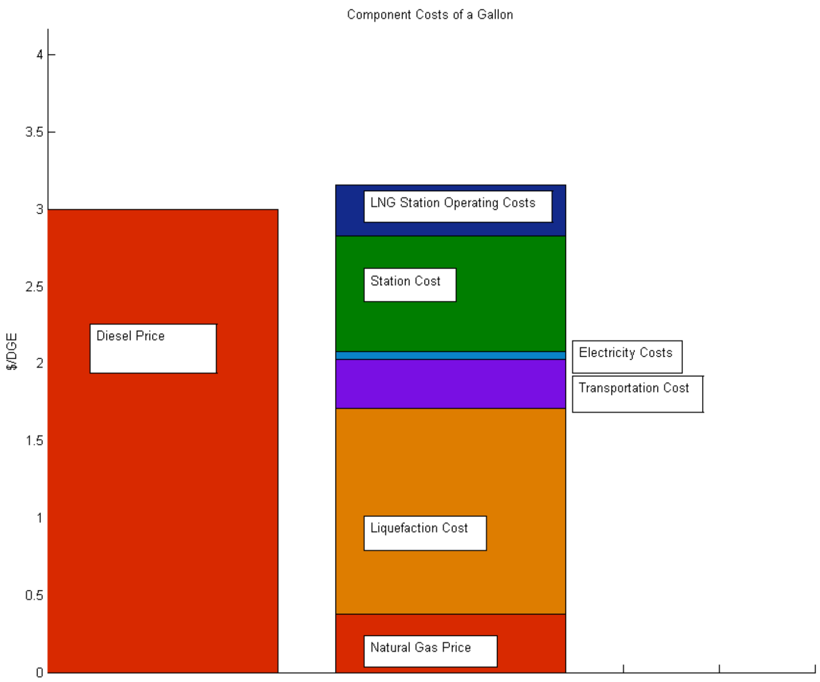
[50] http://www.afdc.energy.gov/locator/stations/

Figure 11. Diesel Prices Vs Natural Gas and LNG infrastructure costs.



The level of vehicle turnover and the prolific network of incumbent diesel fueling venues across the U.S. highway system limits the transition rate for alternative fuels and means that a new, alternative fuel must offer the same convenience at a lower cost. Otherwise, governments must provide public incentives to investors to provide new stations for an alternative fuel. Thus, the conversion of heavy-duty fleets to a new fuel is unlikely to take place rapidly because only 200,000 to 240,000 new vehicles come on the road each year. At present only 14% of fleets operate any vehicles on alternative fuels.[51]

Still, the annual turnover rate for heavy-duty trucks is a relevant factor in the pace at which a shift to natural gas is likely to penetrate the heavy-duty sector. The high turnover rate for heavy-duty trucks means that steady demand for new trucks could be a facilitating factor to the development of a natural gas network for heavy-duty fueling. The market for new heavy-duty trucks in the coming years will be substantial. Between 2014 and 2025 roughly 2.7 million new trucks will be purchased – or 76% of the total fleet in 2025, creating a ready market for natural gas vehicles, if commercial incentives are evident.

Building on work by the US National Petroleum Council (2012), our independent assessment shows that the cost benefit of natural gas as a direct fuel is most compelling for heavy truck fleets whose vehicles travel 120,000 miles a year or more, given a diesel price

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[51] Alt Fuels: Beyond Natural gas. Fleet Owner Magazine. April 8, 2014. http://fleetowner.com/running-green/alt-fuels-beyond-natural-gas

of $4/gallon, $2.45/dge for LNG, and $2.34/dge for CNG[52]. We find that greater use of natural gas in the heavy-duty sector could potentially lower the cost of U.S. freight supply chains and thereby enhance U.S. competitiveness and energy security. In particular, we find that while natural gas vehicles can be more expensive upfront than conventional diesel powered medium- and heavy-duty vehicles, the fuel savings can produce attractive payback for natural gas fleet owners in less than three years.

The breakeven fuel prices for LNG and CNG are shown in Table 2 for the various truck designs. The results indicate that, from a fuel cost perspective, CNG is more favorable than LNG, but the range of CNG vehicles is much shorter than LNG vehicles. From the engine perspective, the economics of the CI dual fuel engine is more favorable using either CNG or LNG even though the CI engine is initially more expensive.

Table 2. Breakeven fuel prices for NGVs by technology/storage configuration and payback period based on total annual mileage.

Vehicle	2 yr./120k miles	3 yr./60k miles	3 yr./160k miles
LNG-Ci (dual fuel)	$2.60	$1.80	$3.20
LNG-Si	$2.21	$1.85	$2.60
CNG-Ci (dual fuel)	$3.50	$3.20	$3.80
CNG-Si	$3.00	$2.80	$3.30

The results in Table 2 indicate that trucks with an annual mileage greater than 120,000 miles traveled per year provide a favorable payback period for a shift to natural gas of less than three years. Note that the base price of diesel fuel for this calculation was $4/gallon. If the breakeven price is greater than the price of the fuel, the economics of that case is favorable. Trucks travelling more than 120,000 miles per year are responsible for just over 38% of the all truck miles in the United States.

At present, most fleets that are considering LNG fuel are looking at the trucks with the Si engine, which is less expensive than the dual-fuel compressed ignition engine (with a diesel pilot) (*i.e.* HPDI model). The advantage of the HPDI truck is that the vehicle operates at similar efficiency as a diesel engine even adjusting for energy content differences between the two fuels. Even though the more efficient HPDI engine would provide better economic and environmental performance, there is a disconnect between the public policy and economic objectives of a fuel switch. Right now, the dual-fuel engine is not commercially available in large numbers and it sells at a premium price. We believe that this barrier would have to be eliminated for key states, such as California, to embrace natural gas as a direct fuel. The manufacturer of the dual fuel engine, Westport, has so far not announced any immediate plans to mass produce it. Westport Cummins, a 50-50 joint venture between

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[52] Zhao H, Burke A, and Zhu L. Analysis of Class 8 Hybrid-Electric Truck Technologies Using Diesel, LNG, Electricity, and Hydrogen as the Fuel for Various Applications. EVS27. Barcelona, Spain. November 17-20, 2013. For other industry-based background on the issue, see The National Petroleum Council (2012), Advancing Technology for America's Transportation Future: Fuel and Vehicle Systems Analyses: Natural Gas Analysis.

Westport and Cummins, is the manufacturer of most of the Si natural gas engines. With a Si truck, the driver needs to refuel more often, which costs time, or requires larger storage capacity, which reduces cargo space. In terms of fuel storage, CNG systems are also less costly than LNG systems. But natural gas as CNG has lower energy density, thus for a given range, a NGV will require more storage space if using CNG than if using LNG. Costs for storage units and other components are expected to be reduced over time, as more industry players enter the market in the U.S. and China.

CNG trucks are generally less expensive than LNG trucks but at present are only available with the less efficient Si engines. Both lower energy density and lower engine efficiency contribute to making CNG fueled vehicles require even more frequent refueling than LNG trucks. The CNG refueling process is also more time consuming than LNG refueling. This means that, for long trips, the added initial cost for the LNG HPDI technology provides a more attractive long run payback than the higher operating costs of operating based on a CNG vehicle once downtimes are taken into account. This is another reason the Ci engine will become attractive if/when it becomes commercially available.

Infrastructure Modeling Approach

To analyze the potential for an expansion of natural gas into the heavy-duty sector and its widespread use across the country's major trucking routes, we take into consideration the barriers and constraints described above and consider the incentives that must exist or be created in order to propel natural gas as a key fuel in the U.S. freight system. To study the conditions under which either LNG or CNG fuel could be commercial in U.S. long haul trucking, we create a modeling framework that utilizes spatial mapping of existing major Interstate highways, trucking routes, key fueling routes for fleets and heavy-duty trucks, and fueling infrastructure for CNG for fleet operation and LNG for long-haul trucks to make infrastructure planning decisions. Spatial network theory and network analysis is utilized to generate all of the spatial information that is needed to calculate the most profitable trucking corridors to establish LNG infrastructure.[53]

Our spatial optimization model is designed to determine the most profitable transportation networks and locations for natural gas flows into transportation markets in California and nationally using spatial infrastructure data and comparing costs for transportation of natural gas by source, distribution method, and other market development variables through mathematical optimization. Our modeling work builds on a body of academic literature undertaken in the study of hydrogen fueling in the United States and only very limited study of the long haul duty NGV market. [54]

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[53] Allen Lee, 2014. Locating LNG Refueling Stations for US Freight Trucks Using a Flow-Based, Range Limited Facility Location Model integrated with GIS and Supply-Chain Optimization. Transportation Research Board. National Academies. January 2014

[54] As discussed by Dagdougui, the approaches for planning and designing the hydrogen supply chain can be classified as follows: 1) optimization methods (most prominent); 2) geographic information systems (GIS) based methods; and 3)

We compare the economics of natural gas transportation from supply site to refueling stations either via pipeline or truck, using data on existing natural gas pipelines and transmission systems and highway system to determine through the model solution the most profitable locations of refueling facilities. This comprehensive assessment tool is aimed to simulate the potential volumetric capacity for the natural gas transportation market in the United States, as well as optimal location of new and existing fueling facilities.

Our study considers where and when infrastructure should be deployed over a 20-year time horizon in order to satisfy demand along major trucking routes or corridors. To address both spatial and temporal dynamics, we develop a multistage mixed-integer linear programming model to optimize the process of building and operating LNG liquefaction and distribution facilities. We consider both transitions to using more LNG in the heavy-duty vehicle sector or alternatively to build a mix LNG infrastructure and CNG refueling networks that would compete against the incumbent fuel, diesel, in high volume markets. For more details about our methodology, please see the appendix to this paper.

Modeling Results and Policy Analysis

Base case scenario

To date, despite the strongest market for commercial truck sales in almost a decade and a historic gap between low natural gas prices and high oil prices, America's natural gas highway is struggling to take hold.[55] Our analysis confirms this trend and finds that only certain regional markets have sufficient traffic density in combination with higher diesel prices compared to the U.S. national average to give investors a sufficient return on capital to incentivize station construction without government intervention.
Our regional analysis, under 0.2% LNG market penetration, shows that California and the U.S. Great Lakes/Northeast regions, which have a relatively high level of demand and

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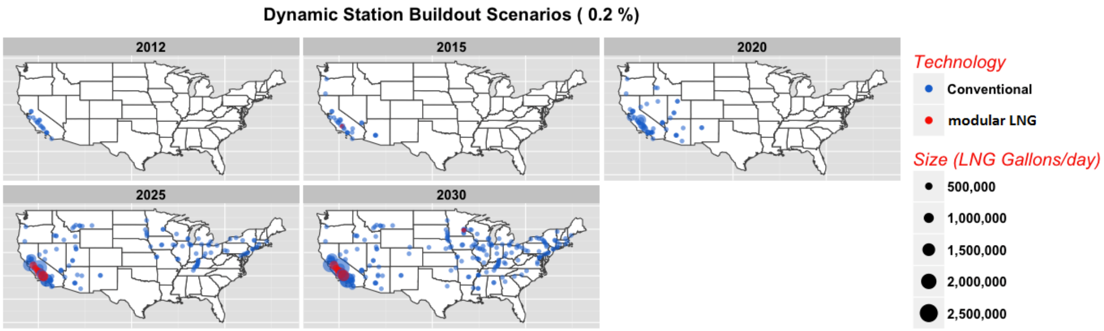
scenario dependent transition models[54]. There are a small number of studies that combine the strengths of a national energy system optimization approach with a spatially explicit infrastructure optimization approach. Stachan et al. described an integrated approach linking spatial GIS modeling of hydrogen infrastructures with an economy-wide energy systems (MARKAL) model's supply and demand[54]. Parker et al. used an annualized profit maximization formulation to study the optimal distribution network for bio-waste to hydrogen[54]. Previous research on natural gas as an alternative fuel has often focused on evaluating the cost effectiveness of natural gas to achieving environmental goals in transportation.Yeh provides a review of several national markets. This literature has focused mainly on light duty, transit and refuse vehicles applications, while only a few include long haul trucking applications. Rood Werpy concludes that high costs, limited refueling infrastructure, and uncertain environmental performance constitute barriers to widespread adoption of natural gas as a transportation fuel in the US[54] but, in another substantial contribution to the literature, Krupnick finds that the move from a long-haul route structure to a "hub and spoke" structure could facilitate the development of natural gas refueling infrastructure in the highway system.

[55] Bob Tita "Slow Going for Natural Gas Powered Trucks" *The Wall Street Journal*, August 25, 2014

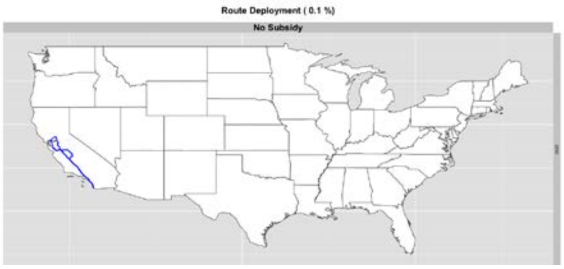
traffic density, have the greatest commercial potential at present and could play a key role in the network development, as shown in Figure 12.

Figure 12. Dynamic LNG station buildout scenarios under a 0.2% market penetration.



The following diagrams show the optimal network build-out for California under today's penetration rate of 0.1%, or where about 6,000 LNG trucks would be in operation across the United States. A detailed map of the California build-out network is found in Figure 13.

Figure 13. Trucking route deployment across the under current 0.1% market penetration.



Our results indicate (Figure 14) that for the California network to operate profitably under the optimal configuration, conventional station technology of the smallest capacity should be deployed.

Figure 14. Dynamic LNG station build out scenarios under 0.1% market penetration.

The regional analysis contrasts with the outlook for a national network. At today’s level of market penetration of only 0.1% of the heavy-duty trucking fleet operating on LNG fuel, investors are unlikely to see a large enough fuel switchover to earn a commercial 12% return on capital in building a significant national LNG truck-fueling network until the year 2030. Our analysis finds that the majority of natural gas fueling stations along U.S. Interstate routes would be unprofitable if built under current market conditions (see appendix for detailed analysis).

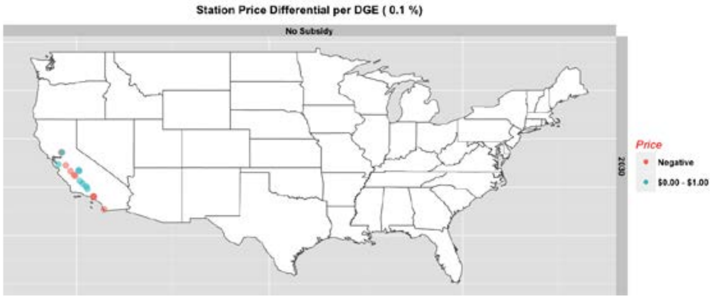
In summary, the natural gas cost advantage at present is not sufficiently large enough to launch a national network based on commercial market forces. Rather, we find that it would take roughly 15 years for fuel demand to rise sufficiently and additional technological learning to take hold before lower station equipment costs and higher rates of trucking demand would support construction of a comprehensive American natural gas highway. Although a network of LNG stations is currently in place in several locations, our analysis would suggest that many of those stations will have difficulty sustaining profitable operations.

The Potential Role of California as a Regional Launching Base for a National Network

We also tested whether the more profitable regional networks, such as the one in California, could lay the groundwork for expansion over time to a more comprehensive national network. Our results indicate that support for regional pilot programs in California and/or the Great Lakes region would hasten the development of America’s natural gas highway and lower the cost of implementation in the long run.

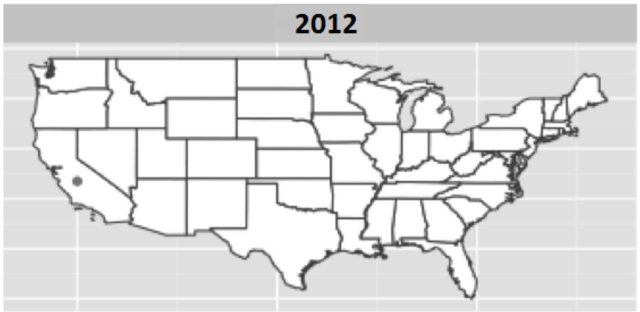
Figure 15 shows the price difference for each built station for California. Notice that still not all stations are potentially profitable, but as long as the routes as a whole are making profit, the profits from highly desirable locations will offset losses at stations experiencing less traffic, allowing the entire route to receive a 12% rate of return on capital. As discussed above, the lower volume stations are necessary to ensure trucks have sufficient coverage to travel the entire route and use only LNG fuel.

Figure 15. Dynamic LNG station price difference per diesel gallon equivalent under 0.1% market penetration.



California is a unique investment opportunity because it has a solitary main trucking artery that means truckers do not have the desire to branch out into alternative routings. This limits the number of stations that need to be provided to ensure that truckers have the full coverage needed to use LNG vehicles. We calculate that the costs to provide dedicated coverage for LNG across California are relatively low at under $100 million, were the number of LNG trucks on the road in the United States to double from 3,000 currently to 6,000. More specifically, it would cost roughly $10 million to construct all the LNG stations show in Figure 15 in our model year 2012, and roughly $80 million to construct all the micro-LNG liquefaction plants in Figure 16 in our model year 2012. Given this result, it is surprising that integrated oil companies do not see such a network as a profitable way to comply with California's Low Carbon Fuel Standard.

Figure 16. LNG liquefaction plant build out scenarios under 0.1% market penetration.



California already has several LNG fueling stations, including two at the Port of Long Beach. The California example demonstrates that station investors should be looking first and foremost for high volume routes where truckers have fewer routing options than in other parts of the country. It also confirms the corporate strategy being undertaken by fuel providers and truck manufacturers to focus marketing efforts on large corporate fleets where a couple of large early adopters could make a limited route such as California's I-5 a commercially viable, cost-effective place to introduce LNG as an alternative fuel. We find that comparable investments in the U.S. Mid-Continent would not pan out as commercially attractive without substantially higher initial investment levels. To launch a successful national network of LNG stations, where the industry would be making profit as a whole, would be prohibitively expensive in the billions of dollars, far more than might be reasonably considered by the federal government or a small number of commercial investors.

Our analysis would suggest that companies should first establish limited networks in California and the Great Lakes region in making investments in natural gas fueling infrastructure because these regions offer the highest potential concentration of fleets' adoption that could realistically direct a sufficient number of trucks to create a profitable network of stations. Eventually, a natural gas station network could extend beyond these initial LNG hotspot markets. The concept that a handful of large fleets could commit to substantial purchases of LNG trucks in a particular regional market finds evidence in today's commercial climate. For example, UPS ordered about 700 natural gas tractors in 2013, showing the viability of getting adoption of the additional trucks via a fleets purchasing model. A California network receives an extra financial boost from the existence of a liquid carbon pollution market that qualifies credits for natural gas fuel use.

Alternative Scenarios

To test the sensitivity of the profitability of a national network to the number of trucks on the road, we analyze a scenario where double the current number of trucks would be operating with LNG fuel. We compare our modeling results against four case study scenarios: 1) a 50% subsidy to station costs (or the equivalent of a 50% cost breakthrough) under current levels of demand; 2) a 50% subsidy to station costs (or the equivalent of a 50% cost breakthrough) under 100% higher levels of demand than currently seen; 3) a high diesel price scenario where regional diesel prices are at peak levels seen in 2008; 4) a high diesel price scenario where regional diesel prices are at peak levels seen in 2008 and under conditions of 100% higher demand than currently seen. Table 3 summarizes our results.

Table 3. Summary of Results by Scenario.

	0.1% Initial Penetration Rate			**0.2% Initial Penetration Rate**		
	Summary	**Route Completion 2015**	**Route Completion 2030**	**Summary**	**Route Completion 2015**	**Route Completion 2030**
No Subsidy	Network only builds in California.	0%	2%	Network begins in California and extends Eastward. Northeast and Great Lakes regions begin construction in 2025.	3%	55%
50% Subsidy	Network begins in California and extends eastward.	2%	6%	Network begins construction in California, Arizona and Nevada. Construction in the Great Lakes begins in 2015.	28%	76%
High Diesel	Network begins in California and extends eastward.	0%	6%	Network begins in California. East and West coasts connected in 2015.	69%	77%

We discuss these scenario results in more detail below:

Alternative Scenario 1: U.S. Natural Gas Fueling Networks Under a Doubling of LNG Trucks

To test the sensitivity of the profitability of a national network to the number of trucks on the road, we analyze a scenario where double the current number of trucks would be operating with LNG fuel. Figure 17 shows the location and configuration of LNG refueling network. Figure 18 shows the distribution of profitable stations over time under a 0.02% market penetration case. Not surprisingly, optimum station build-out patterns favor the regions with higher heavy trucking traffic flows (California, Midwest and the Great Lakes routes (Wisconsin-Illinois region, Kansas City region, Nashville, Dayton/Cincinnati, upstate New York) as well as areas with high diesel prices (California, New York, Ohio, and the Mid-Atlantic). Figure 19 (plants) micro LNG liquefaction plants also show strong favoritism in California, Midwest, and Mid-Atlantic/New England areas.

Figure 18 shows the respective price differentials by station and there appears to be a direct correlation between high station densities regions, like the ones described above and competitive LNG prices when compared with diesel prices. High volume routes in Texas and Florida lag other regions as early adopters. In the case of Texas, low diesel prices may be a contributing factor. Florida lacks a high volume route into the state, despite a large flow of traffic exiting from its ports.

Figure 17. Dynamic LNG station build out scenario under 0.2% market penetration.

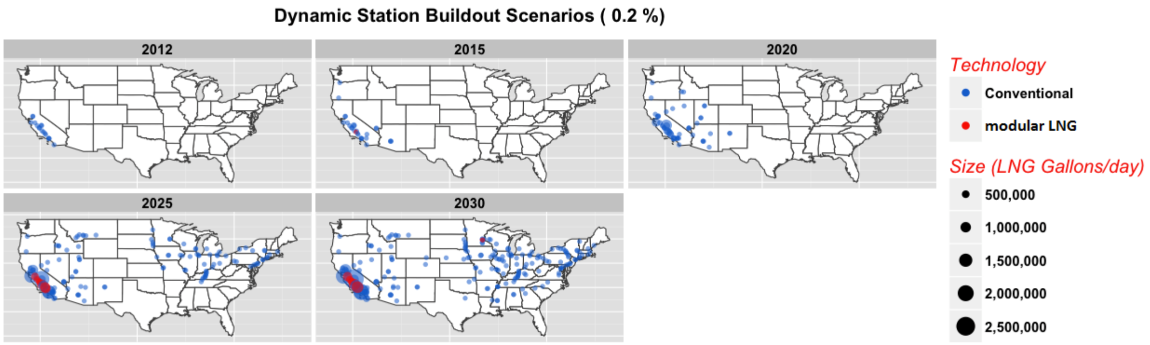


Figure 18. Dynamic LNG station price difference per diesel gallon equivalent under 0.2% market penetration.

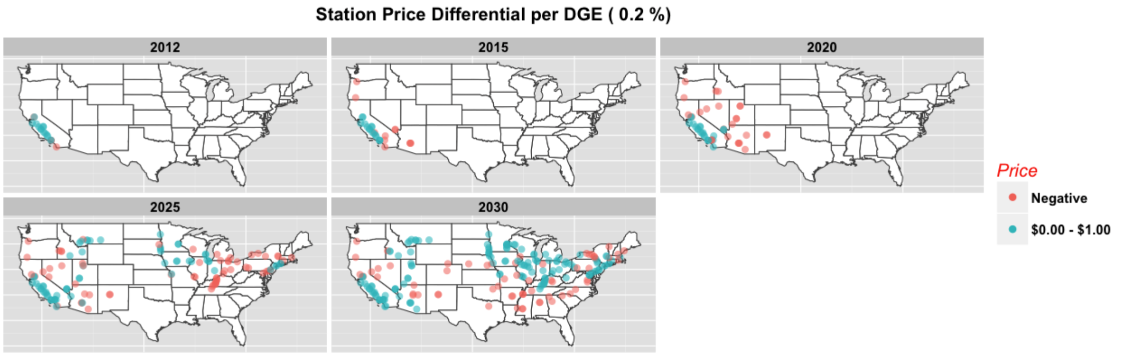


Figure 19. LNG liquefaction plant build out scenarios under 0.2% market penetration.

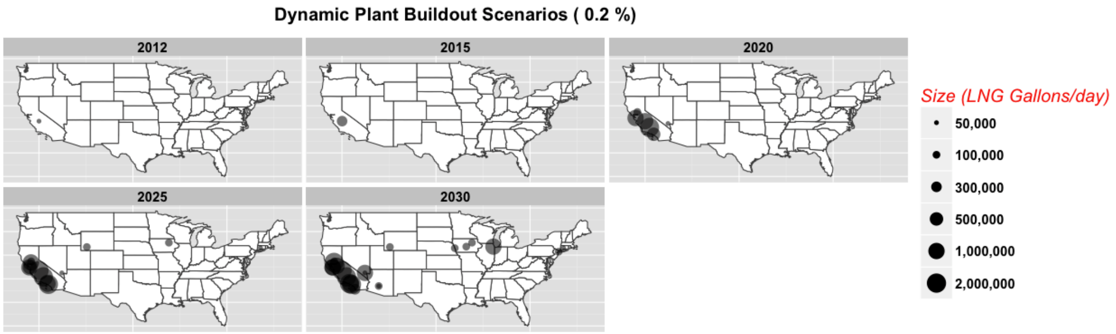
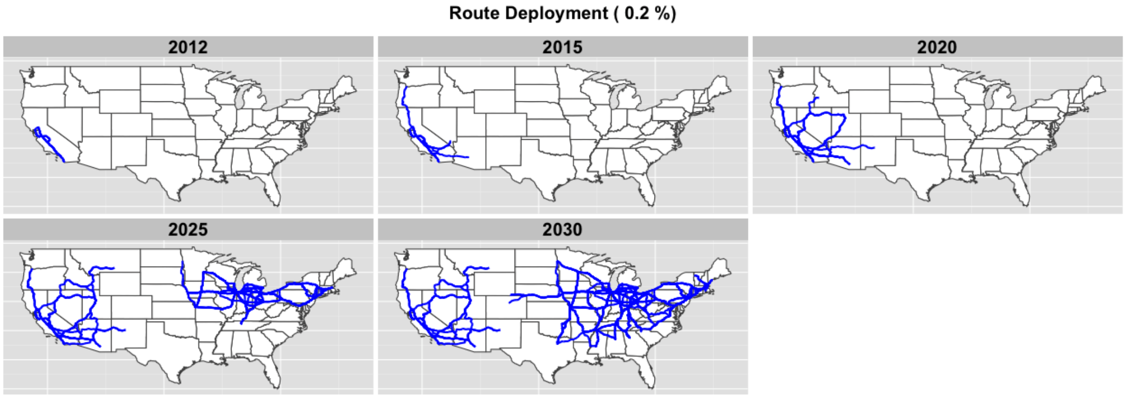


Figure 20. Trucking route deployment under 0.2% market penetration.



California's heavy density of both liquefaction plants and LNG stations can potentially serve as a launching point for a broader network of stations over time. Figures 17-20 reveal our results for how the network might develop based on solely commercial factors over time, starting in California under the 0.02% scenario where the market contains 6,000 LNG trucks in operation.

Our results reveal some interesting commercial dynamics to the temporal aspects to technology choices. Conventional technology is highly favored over small-scale, modular LNG technology small-scale modular LNG technology as can be seen in Figure 17. This is mainly due to the very high upfront cost of the LNG box technology but also because some conventional stations and liquefaction plants are partially financed already. In this process, early on, micro-LNG plants, which provide an economy of scale benefit to fuel providers, are built near these high demand seeded areas and remain concentrated in these areas even in later years. In order for small-scale, modular LNG technology to be competitive with conventional stations, they will require a faster technology learning rate or a subsidy.

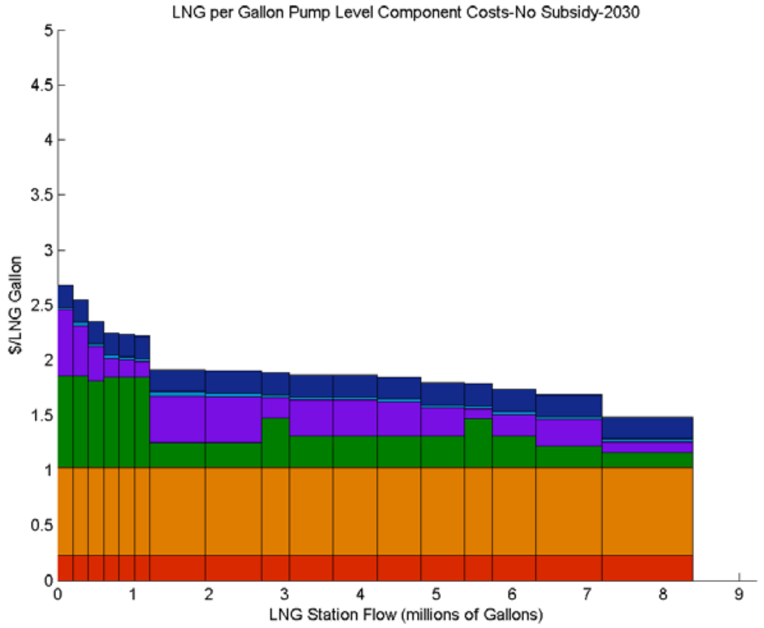
Alternative Scenario 2: Subsidy Scenarios

Using a case study approach, we study what level of investment is needed to get past the chicken-and-egg problem of station coverage sufficiently that new investment becomes sustainably profitable. Under current market conditions, we find that it is unlikely that national policy intervention of federal truck subsidies or federal station subsidies would be cost effective.

On a national basis, investors would have to be willing to build substantial facilities at a loss until those facilities reached a market concentration of over 2% to 3% of market share even under a scenario where they receive a 50% subsidy on station costs. Such a subsidy would be prohibitively expensive, in the billions of dollars. A core element of this result is the capital intensity of new fueling station investments which have to compete against sales outlets of incumbent fuels whose distribution networks are fully depreciated. In effect, natural gas' price discount would have to be large enough to cover both the high capital costs for building out new stations and higher operating costs for LNG fuel.

We do not find this result surprising because an alternative fuels station adoption cost gap exists between fuel/system operations costs for incumbent ample diesel stations that are already amortized, and the high cost of new LNG fueling infrastructure. Figure 21 demonstrates the large cost advantage the existing diesel fueling system has over LNG, even with the large discount in the underlying natural gas as compared to diesel fuel prices.

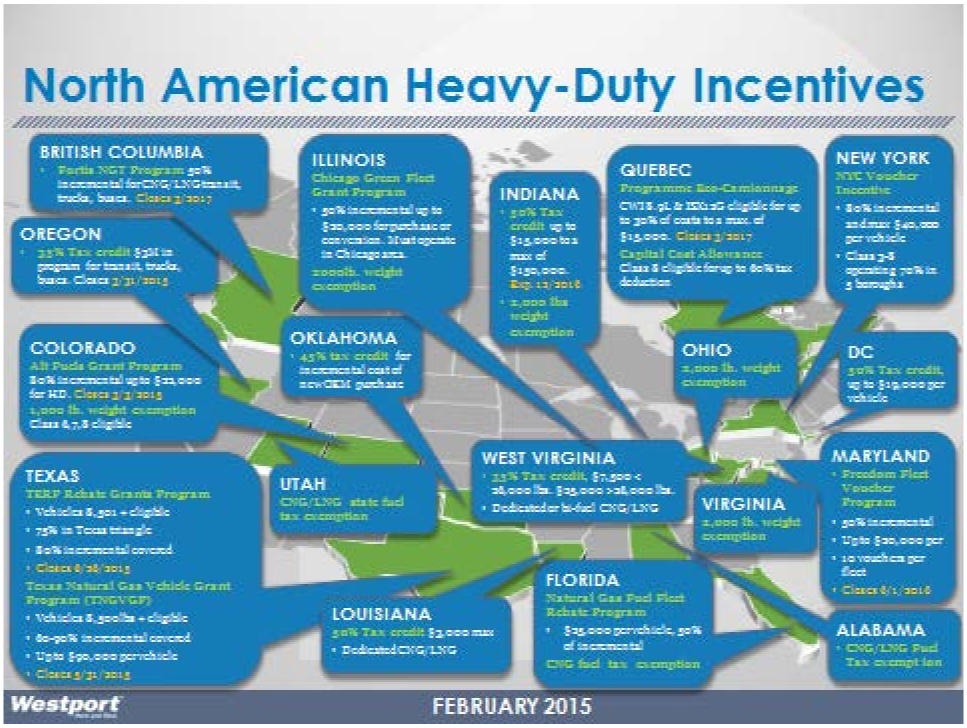
Figure 21. LNG delivered cost by station flow volume.



To date, U.S. states that have implemented programs to support natural gas as a transport fuel have provided incentives or subsidies either on vehicle purchases or retrofits or on station costs.

Figure 22 shows the range of policies used to stimulate natural gas vehicles in the United States. A number of states are offering incentives to support the expansion of natural gas as a transportation fuel. Pennsylvania, home to the rich Marcellus Shale gas basin, recently announced the Natural Gas Development Program that would provide $20 million over three years to convert or acquire heavy-duty vehicles that run on CNG and tailored the Alternative Fuel Infrastructure Grant to support mid duty vehicles conversion and fueling infrastructure financing through the Alternative and Clean Energy Fund. The state of Oklahoma, in another example, instituted a 75% subsidy on CNG fueling stations in 2012 as part of its goal to facilitate the use of natural gas in commercial vehicles. Figure 22 provides a view of available state incentives.

Figure 22. State incentives applicable to natural gas vehicles. [56]



Station Subsidy Scenario Results

When we test the robustness of our results against a 50% discount on the cost for LNG fueling stations, we find that only the profitability of a California network is greatly enhanced, with almost all stations in the state yielding a positive margin greater than $1.00. The results indicate that the carbon credit currently provided to natural gas fuel under California's current climate policies should be helpful in enabling a commercially profitable natural gas network in the state. The analysis also shows that a 50% subsidy would allow a large expansion of LNG liquefaction plants after 2025 as cumulative demand accrues over time.

A 50% reduction in station costs is not sufficient for the modeling solution to result in a build-out of a national LNG network in the next few years, indicating that the existing station costs for either traditional or small-scale, modular LNG technology are prohibitively expensive to allow investors to realize a typical rate of return on capital of 12% given limitations on the speed to gear up LNG truck demand.

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[56] Westport.

Truck Subsidy Scenario Results

We also consider an intervention where either the cost of natural gas fuel trucks falls dramatically or government subsidizes truck purchases. There is some indication that natural gas fuel truck tanks manufactured in China could cost up to 60% to 70% less than those currently manufactured in North America. We find that a doubling of the current penetration rates for LNG trucks can have significant impacts on future LNG network development. These results mimic reality and support the suggestion that policy intervention will be needed to get a national LNG network off the ground. The familiar question of whether it is more effective to reduce station prices or support higher LNG truck demand by subsidizing the vehicles is debatable. Our analysis suggests either option could influence market development. Directionally, scenarios analysis indicates that the market might be slightly more sensitive to a lowering of truck acquisition costs than to station construction costs since our scenario analysis indicates that a doubling of existing truck penetration rates would have a larger impact on network expansion than a 50% station cost subsidy.

Our scenarios also show that policy choices could influence the competition between LNG supply technologies. Generally speaking, in the early stages of natural gas fueling network buildout, conventional technology of plant and traditional fueling station technology is the least cost technology for early infrastructure implementation. Since the static model incorporates existing infrastructure, the network build out from regions that benefit from the highest densities such as California, Texas, the Midwest, and East Coast with stations connecting east and west. As penetration rates rise, the number and sizes of stations also increases in these locations but new stations emerge in other markets as well, notably Florida. The Mid-Continent remains less dense but routes become more abundant with greater station connections between the U.S. East and West Coasts. LNG modular technology starts to be deployed on high traffic routes, mainly in California, once the network gets to 3% concentration, as shown in Figure 23.

Figure 23. Static LNG station build out scenarios.

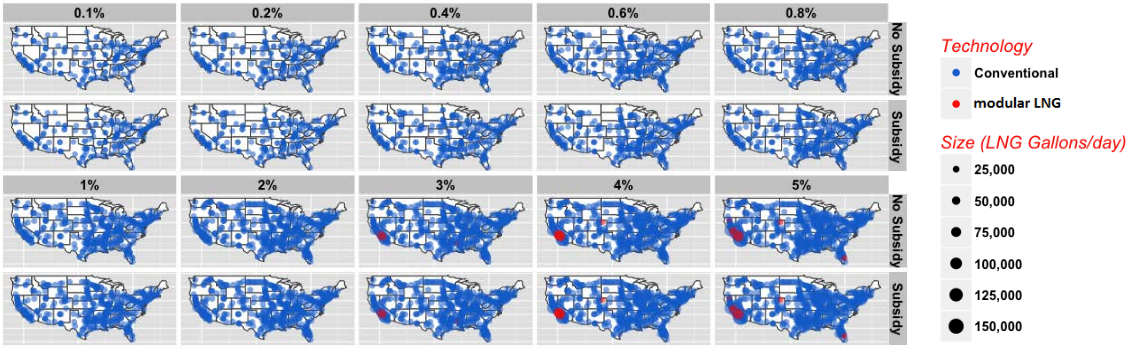
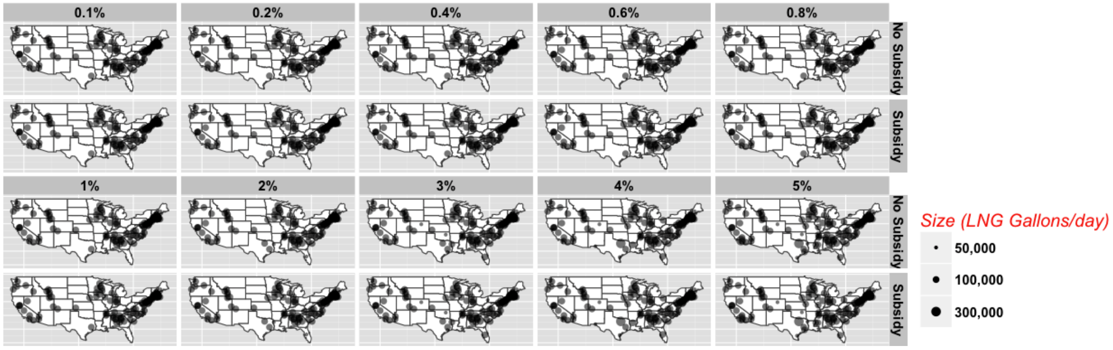


Figure 24 depicts the location build-out for micro-LNG plants under various rates of market penetration. The main visible difference in the 50% subsidy scenario is that small-scale, modular LNG technology gets built much earlier on, suggesting that the higher cost of that technology is a barrier and lowering its costs would enable the network to build faster.[57]

Figure 24. Static LNG plant build out scenarios.



Alternative Scenario 3: High Oil Price Scenario

U.S. diesel prices are currently declining as supply surpluses in global markets have put pressure on oil prices overall. But geopolitical factors could reverse this trend, raising the possibility that someday higher oil prices could potentially enhance the profitability of LNG as a trucking fuel. Using the modeling simulation, we test whether an increase in

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[57] The reason the subsidy favors LNG box technology is that small-scale, modular LNG technology does not require an intermediate step. It directly converts gas to liquid, whereas the conventional pathway requires additional unsubsidized infrastructure (i.e. a liquefaction plant for conversion). In other words, the entire LNG pathway is contained inside a small scale modular technology, but a conventional station is only one component of its pathway. Thus, when small-scale, modular LNG technology gets a 50% reduction, it reduces the cost of the entire pathway but when a conventional station gets a 50% subsidy, its pathway is only partially subsidized. Components of the conventional pathway like the liquefaction plants and trucking costs are not factored in, only the capital deployed towards the stations gets the advantage of the subsidy so the percentage of the system capital that is subsidized is lower than the 50% enjoyed by each modular small scale unit. Thus, despite economies of scale for conventional technology, a 50% station subsidy favors small-scale, modular LNG technology development.

diesel prices while natural gas prices remain constant would be a sufficient condition to propel a higher level of station network construction. We find that even at higher oil prices, which creates a wider differential between the fuels is still not sufficient to overcome the alternative fuels adoption cost gap and seed initial development of an entire national network for natural gas fueling.

But under the high diesel price scenario and a U.S. fleet of 6,000 trucks (i.e. double today's level) price differential density plots for this scenario reveal stronger impetus for network development and coverage, notably in Texas and Florida, when compared to other scenarios. This high oil price scenario also results in a notably strong transcontinental density of stations connecting the eastern United States with the west.

High Oil Price Scenario Results

Our analysis indicates that significantly higher diesel prices in certain states creates an adequate threshold to promote broader LNG adoption in key hotspot locations, whereas a 50% station subsidy scenario results in a more sparsely populated network that is stretched too thinly across the nation. Under the high diesel, 6,000 truck penetration rate scenario, local hotspots develop regionally and eventually expand to nearby regions, which initially aren't experiencing as much development. Figure 25 (build-out, 0.2%) also suggests some very interesting station technology implications. Under the no subsidy, high diesel scenario, small-scale, modular LNG technology fills in network connections in the U.S. Mid-Continent (Heartland & Mountain regions) since overall traffic volumes are lower, and therefore don't support the scale economies of a larger scale hub and spoke mini-LNG plant infrastructure system.

Figure 25. Dynamic LNG refueling station build out scenarios under 0.2% LNG market penetration rate.

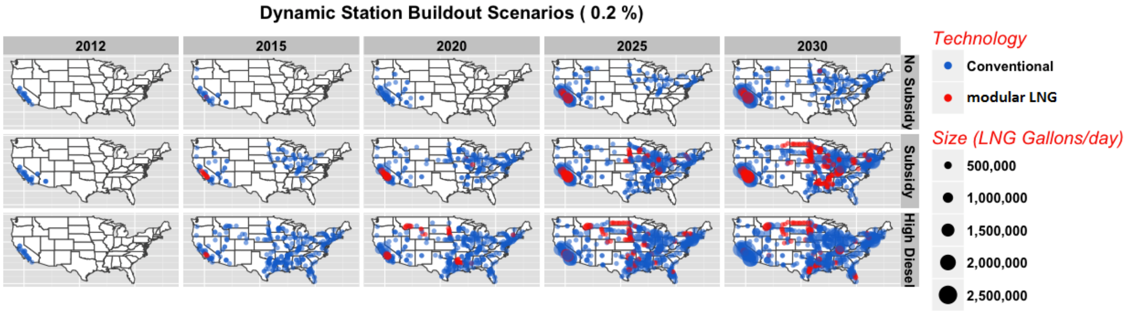


Figure 26. Dynamic liquefaction plant build out scenarios under 0.2% market penetration rate.

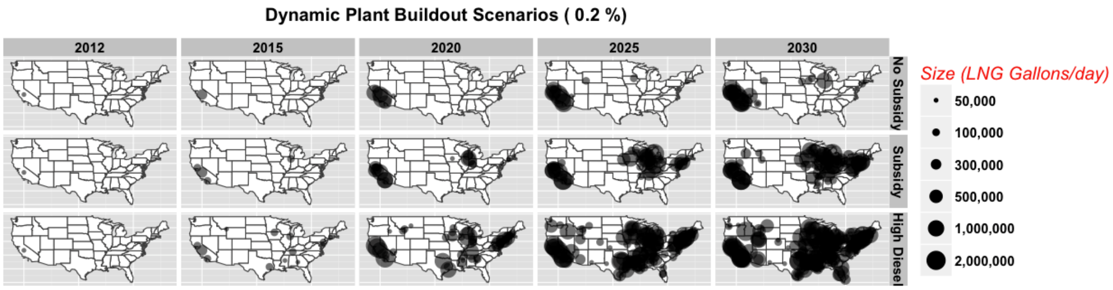
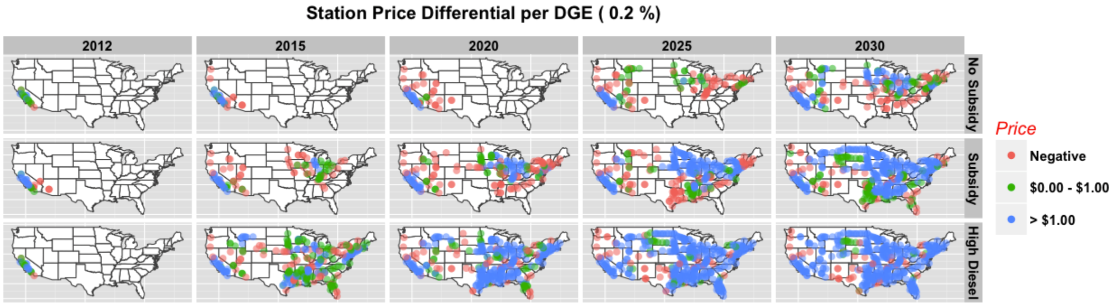


Figure 27. Dynamic LNG-Diesel price spread under 0.2% LNG market penetration ($/gde)



CNG as an Alternative to LNG Fuel

We test our results against a scenario where CNG stations are available as an alternative technology. Kuby has found that early adopters of CNG light duty natural gas vehicles may be willing to refuel more frequently and farther from home than gasoline drivers, but more so on work-based trips and less on home-anchored trips[58]. In another study, Kelley and Kuby find CNG users favored refueling CNG along routes used frequently rather than closer to their homes[59,60]. Both studies suggest CNG is more appealing for commercial applications than for passenger vehicles. This matches with findings by the Boston Consulting Group that suggests that CNG vehicles will likely continue to replace high-mileage, low-fuel economy vehicles and work by Christopher Knittel that CNG vehicles

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[58] M. Kuby, L. Lines, R. Schultz, Z. Xie, J.-G. Kim, and S. Lim, “Optimization of hydrogen stations in Florida using the Flow-Refueling Location Model,” Int. J. Hydrogen Energy, vol. 34, no. 15, pp. 6045-6064, Aug. 2009.

[59] Kelley S and Kuby M. On the Way or Around the Corner? Observed Refueling Choices of Alternative-Fuel Drivers in Southern California. Journal of Transport Geography December 2013. 33:258-267.

[60] Kuby, Michael, Scott Kelley, and Joseph Schoenemann. Spatial Refueling Patterns of Alternative-Fuel and Gasoline Vehicle Drivers in Los Angeles. Transportation Research Part D – Transport and Environment December 2013. 25:84-92.

offer long term cost advantages. [61] The Boston Consulting Group study finds that conventional petroleum fuel stations will only add CNG refueling when they find a fleet partner and that manufacturers that offer both vehicle and refueling station technology are necessary to boost CNG adoption[62]. Rosenstiel et al. find that, in Germany, a monopoly of service stations at motorways, is one of the most prominent market failures inhibiting the development of a functioning market for NGVs[63].

Because CNG technology is less expensive on a supply chain per gallon basis than LNG and it can be built profitably at smaller scales, we find that CNG becomes an enabling technology in the development of broader natural gas fueling infrastructure. CNG stations can be profitable at smaller sizes than LNG and can supplement LNG networks with LCNG (liquefied-compressed natural gas) optionality to help station owners optimize revenue streams from access to natural gas feedstock. Figure 28 shows how CNG quickly becomes a competing technology to LNG in long distance trucking at the 0.2% market penetration scenario as demand for natural gas fuel develops in California and beyond, especially under scenarios where station subsidies are offered or diesel prices are high.

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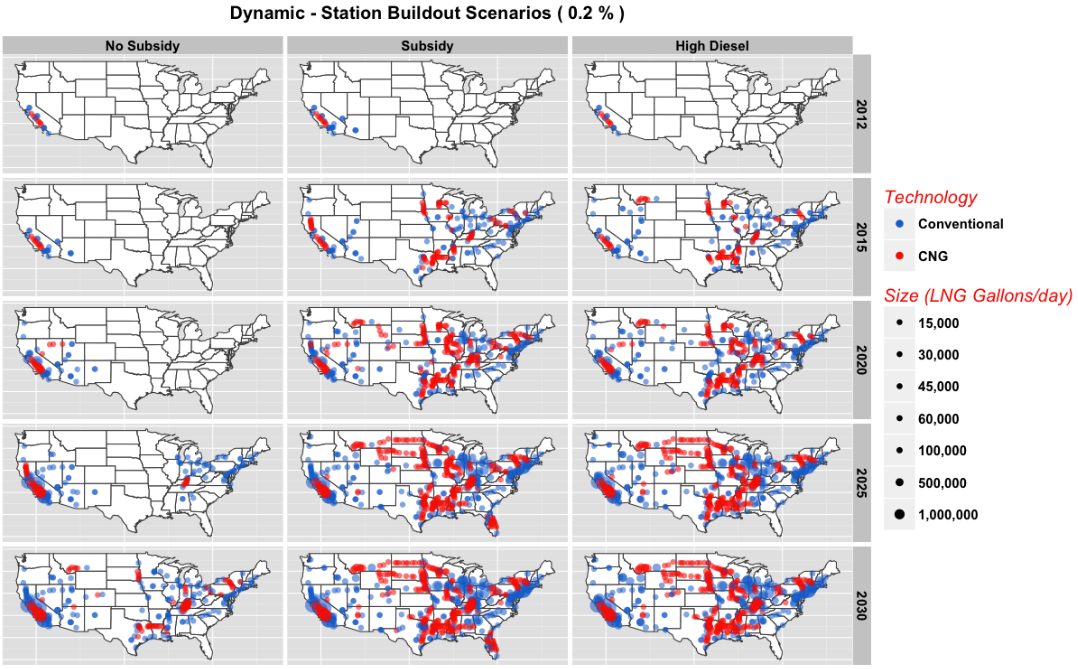
[61] Nath R, Aubert G, Dewar A. A Realistic View of CNG Vehicles in the U.S. The Boston Consulting Group. June 16, 2014; Christopher Knittel, Leveling the Playing Field for Natural Gas in Transportation, Hamilton Project discussion paper, Brookings Institution

[62] Mosquet X, Devineni M, Mezger T, Zablit H, Dinger A, Sticher G, Gerrits M, and Russo M. Compressed Natural Gas. A Potential Bridge Technology? The Boston Consulting Group. July 6, 2011.

[63] Rosentiel DP, Heuermann DF, Husig S, Why has the introduction of natural gas vehicles failed in Germany? Lessons on the role of market failure in markets for alternative fuel vehicles. Energy Policy. Volume 78, March 2015, Pages 91–101

Figure 28. Dynamic CNG and LNG station build out under 0.2% market penetration rate.



Our results suggest that to best promote an alternative fuel into heavy-duty trucking, such as LNG, focus should begin on the highest volume freight routes such as California and the upper Midwest and then eventually commercial factors will encourage investment to branch out to other hotspot regions such as the Mid-Atlantic.

Our findings have interesting implications for California where fuel providers can earn carbon pollution credits under the LCFS and cap and trade systems. We find that if LNG could get to a limited penetration of 0.2% of the heavy trucking market, a commercial network in California could get off the ground. A subsidy in the form of carbon credits (natural gas currently is valued at a 20% savings to diesel under the LCFS) will help this process along. The state of California is currently investigating whether a build-out of natural gas fueling infrastructure across the state would facilitate higher use of renewable biogas as a low carbon transport fuel. Our initial analysis would confirm that this pathway may prove viable if the state’s network of natural gas fueling infrastructure could reach a minimum threshold. Another source of LNG fuel could come from LNG export terminals built in the northern United States to export natural gas to Asia. We do not consider this source of LNG fuel for this study but it could be a subject of future research. However, as will be discussed at length below, technological and process improvements for the natural gas supply chain would have to be made for fossil natural gas to meet California’s long term climate goals as a low carbon fuel.

Business Models for Advancing Natural Gas in Transportation

Business Model A

Private companies Clean Energy Fuels and ENN have begun building commercial fueling stations for LNG and CNG for use in long distance trucking. The business model for these stations is to seed the network with a minimum number of cross-country stations while simultaneously soliciting large trucking fleet owners and operators to switch a portion of their operations to natural gas fuel.

Clean Energy is the largest natural gas fuel provider in North America with over 330 natural gas fueling stations, serving 660 fleets and 25,000 vehicles. The company currently sells an average of 200 million gallons a year of CNG and LNG. Clean Energy says it is able to achieve a return to capital for fueling station investment and still pass on $1.00 to $1.50 a gallon in fuel savings to customers. The company's business model is to line up with return-to-base segment shipping for LNG fuel. In its presentations, Clean Energy says it engaged with trucking companies to determine optimal station locations; however, not all stations currently in operation are profitable and the momentum for its America's Natural Gas Highway has slowed some in the last year.[64]

Clean Energy's initial efforts received some support from Oklahoma Gov. Mary Fallin's initiative to promote natural gas in transportation in the state and beyond. To promote the use of natural gas in transportation, Oklahoma brought together original equipment manufacturers (OEMs), station providers and natural gas producers to create a coordinated effort that would overcome chicken and egg infrastructure issues, at least for CNG networks in the state. The state orchestrated bulk government purchasing orders of natural gas vehicles from the major automakers at a discounted level while offering a 75% station cost subsidy to station developers in exchange for a commitment to construct a credible number of fueling stations. There are currently close to 30 natural gas fueling stations in Oklahoma.

By the same token, ENN also has begun its efforts in Utah, which similarly had a state-sponsored program to enhance the use of natural gas vehicles. In February 2009, then Gov. Jon Huntsman announced that Utah would increase the state's NGV fueling infrastructure,[65] the state offered incentives to drivers to offset the higher price for the NGV vehicle and Questar offered financing and lease programs to customers to support the economics of the conversions. As a result, Utah has 99 natural gas fueling stations, public and private, many of which are located along primary highway corridors to support the fuel requirements of heavy-duty trucks.

Several national fleets are deploying natural gas trucks, including: Cisco, Pepsi, Walmart, Frito-Lay, HEB, Trimac Transportation, Truck Tire Service Corporation (TTS), Verizon,

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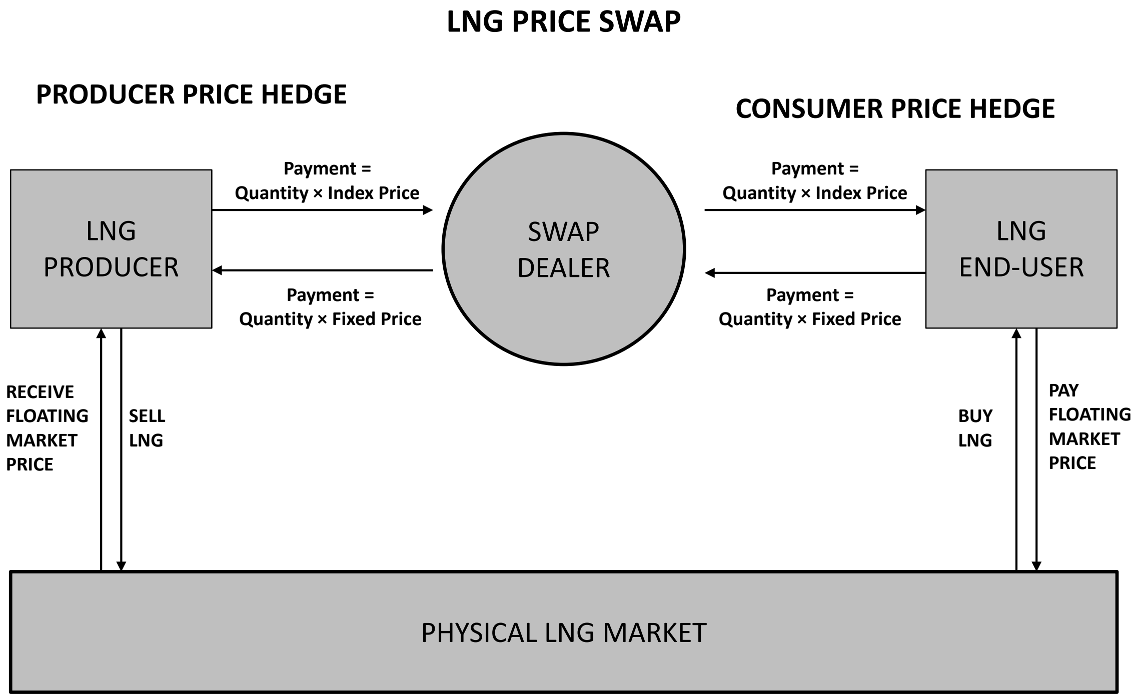
[64] Bob Tita "Slow Going for Natural Gas Powered Trucks" *The Wall Street Journal*, August 25, 2014
[65] Press Release, Office of the Governor of Utah, February 12, 2009

UPS, AT&T, Food Lion, and Ryder. One consideration for fleet truck owners is that vehicle turnover typically takes place within five years, at which time trucks are then sold to secondary and tertiary markets in the United States and Mexico. The economics of conversion to natural gas must therefore take into account resale value of the vehicle as well as lower operating costs but current rapid paybacks and the gradual emergence of buyers in the secondary market is driving more companies to consider natural gas fuel. Fleet owners also worry that supply chains for natural gas vehicles are not yet sufficiently high to avoid higher maintenance costs than traditional diesel vehicles and knowledge of the vehicle among trained maintenance workers is also lower, again potentially leading to higher fixed operating costs. Finally, fleet managers remain concerned that the gap between oil and natural gas prices will not remain at currently wide levels, adding an element of price risk.

While there have been some instances of local and state governments providing subsidies for trucking fleet owners to shift to natural gas vehicles, it seems unlikely that sufficient public funds into the billions of dollars will become available to offer incentives to truck owners to create sufficient demand to get the national long-distance natural gas fueling infrastructure to a tipping point. Instead, natural gas marketers may have to consider alternative business models such as the utilization of derivatives and swaps instruments.

At present, the oil–natural gas differential available on futures markets averages $9.50-$9.57/mmBTU from one year forward to three years forward. The eight-year long-range differential indicates natural gas is $9.18/mmBTU cheaper. Under swap arrangements, a financial intermediary could offer fleet owners a financial contract that locks in the purchase of the spread between natural gas and oil that is currently available in derivative markets. At the same time, the intermediary can offload the risk of the contract through an equal and opposite sale of the spread to a natural gas producer, who might be concerned that natural gas prices will fall relative to oil over time if surpluses continue to develop in North America and globally. By engaging in a swap arrangement, the fleet owner can guarantee that the margins needed to ensure the payback for a shift to natural gas vehicles are sustainable even if the price of oil were to fall over time.

Figure 29. LNG price swap process.



Business model B.

Another business model is for LNG providers to consider parallel investments in LNG for ships as an anchor to create demand that would support investment in LNG trucking infrastructure emanating in ports and expanding beyond them. One critical driver toward LNG adoption could come from the regulations which designate emission control areas (ECAs). ECAs regulate the emissions of sulfur and nitrogen oxides. Over time these regulations will become stricter requiring alternatives to the present fueling systems. In addition the ECA regulations specify varying emissions requirements depending on the distance from certain shorelines. The North American ECA specifies stricter emissions limits within 200 nautical miles of the shoreline. Given the strict North American ECA, some shipping companies are investigating adopting LNG for shipping trips that spend a significant amount of time near the North American shore, such as trips from the Los Angeles region to Seattle or Alaska. The Port of Tacoma will soon lease land to build an LNG bunkering facility. The Totem Ocean Trailer Express Company operates ships between the Tacoma and Alaska posts and plans to retrofit 2 ships for LNG operation. The decision was driven by the ECA requirements.

However, the cost to either purchase new LNG ships or retrofit ships to LNG is significant. Given the long turnover rates, typically 30 years or longer, relatively few ships require replacement at any given time. The same chicken-and-egg issue relevant to LNG trucks acts as a barrier for LNG shipping adoption. Both LNG bunkering terminals and ships must be installed or purchased to make the decision to adopt LNG (see appendix for additional discussion of costs for alternative means of compliance). Thus, like trucking, there are many uncertainties about the pace and scale of marine adoption of LNG fuel, making it difficult for investors to rely on port demand to serve a major anchor for developing the U.S. natural gas heavy-duty network system over the next five to ten year time frame.

Environmental Performance Analysis

As discussed, natural gas can provide benefits as a trucking fuel in terms of fuel costs and energy security. It has also been shown to play a substantive role in limiting certain kinds of air pollutants. For the California market, fuels are also judged by their carbon intensity and currently natural gas qualifies as a low carbon fuel under the LCFS for light-duty vehicles. For heavy-duty applications, the carbon intensity of natural gas is mostly affected by upstream and in vehicle leakage and by fuel efficiency of the vehicle. In this section, we discuss particulate matter, oxides of nitrogen (NOx) and carbon emissions

Particulate matter and Nitrogen Oxides

Particulate matter

EPA estimates that heavy-duty vehicles currently contribute more than 60% of the total particulate matter (PM) emissions from on-road vehicles. Mobile emissions themselves constitute 4 and 6% of the total PM2.5 and PM10 emissions, respectively, in the US. In California, mobile sources constitute 21% of total PM2.5 and 40% of total PM10[66]. According to California Air Resources Board (ARB) diesel engines and equipment rank as the 8th and 9th highest contributors[67] to PM2.5. State regulation requires diesel trucks and buses that operate in California to be upgraded to reduce emissions and to be completely replaced by 2010 or later models progressively between 2015 and 2023. The regulation applies to nearly all privately and federally-owned diesel fueled trucks and buses and to privately and publicly owned school buses with a gross vehicle weight rating (GVWR) greater than 14,000 pounds[1].

In diesel technology, particulate matter is effectively controlled with filters, but filters, like any other emission control devices add cost and require maintenance. A shift to natural gas is an alternative to installing filters because natural gas fuel typically emits less PM and sufur oxides (SOx, which are PM precursors) than diesel without aftertreatment. A shift to natural gas fuel can contribute a significant reduction in SOx tailpipe emissions as well as an almost a full-scale elimination in fine particulate matter in heavy-duty trucks. Regions with heavy use of diesel and bunker fuel (marine ECAS, ports, industrial sites, and roads

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[66] State and County Emission Summaries
http://www.epa.gov/cgi-bin/broker?_service=data&_debug=0&_program=dataprog.state_1.sas&pol=PM25_PRI&stfips=06

[67] Amendments Approved in April 2014 http://www.arb.ca.gov/msprog/onrdiesel/onrdiesel.htm

with dense heavy-truck traffic or other non-attainment areas where diesel is heavily used) can achieve substantial air quality improvements by switching to natural gas-based fuel.

However, the scientific literature suggests that engine type, aftertreatment technology, idling patterns, and drive cycle are more important than the type of fuel used, and thus this must also be taken into account for California to garner the optimum air quality benefits from a shift to natural gas in heavy-duty trucking. For example, diesel engines with particulate filters could produce lower levels of particulates than natural gas engines not equipped with aftertreatment technologies, but when NGVs are equipped with three-way catalyst technology, they produce generally much lower particulate and NOx emissions than do older NGVs without updated technology[68].

Nitrogen oxides

On-road mobile sources is the top contributor to NOx in the U.S.[69] In California, heavy-duty vehicles contribute to more than 30% of all nitrogen oxide (NOx) emissions from on-road vehicles[70]. NOx is an ozone precursor. The San Joaquin Valley and the South Coast air basins in California both surpass the federal ozone standard of 75 parts per billion (ppb)[71]. Heavy-duty on-road diesel vehicles are the largest source of NOx emissions in both these areas.[72] NOx emissions from heavy-duty trucks are limited federally to 0.2 grams NOx per brake horsepower-hour (bhp) for model years 2010 and later.

A 2009 survey of heavy-duty truck drivers at points of entry into California showed that non-California-registered trucks concentrated in the air basis that were having air quality issues[73]. Thus, the regulation applied to all trucks that operate in California even if they are not registered in California.

Strategies to comply with NOx standards include the use of alternative fuels. Biodiesel, blends of diesel with fuels made from plant oils, animal fats and waste oils have gained some attention, but studies find combustion of biodiesel blends results in slightly higher

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[68] Yoon S, Collins J, Thiruvengadaem A, Gautam M, Herner J, Ayala, A, (2013) "Criteria pollutant and greenhouse gas emissions from CNG transit buses equipped with three-way catalysts compared to lean-burn engines and oxidation catalyst technologies, Journal of Air Waste Management Association, 63 (8) 926-33; Also Chandler, Eberts, Melendez, (2006) finds roughly 20 to 25 percent greenhouse gas emissions reductions for CNG transit buses compared to diesel in 2004 engine models.

[69] EPA. Part III Environmental Protection Agency 40 CFR Parts 50 and 58 Primary National Ambient Air Quality Standards for Nitrogen Dioxide; Tuesday, February 9, 2010
Final Rule. Federal Register http://www.epa.gov/ttn/naaqs/standards/nox/fr/20100209.pdf

[70] Facts About On-Road Heavy-Duty Vehicle Programs http://www.arb.ca.gov/enf/hdvip/onroad_hdtruck_factsheet.pdf

[71] http://www.epa.gov/air/criteria.html

[72] Sokolsky S, Silver F, Pitkanen W. "Heavy-duty truck and bus natural gas vehicle technology roadmap". July 2014.

[73] Lutsey N. Assessment of out-of-state truck activity in California. Transport Policy Volume 16, Issue 1, January 2009, Pages 12–18

NOx emissions than combustion of ultra-low sulfur diesel (ULSF), with variability across the different engine models tested[74].

Natural gas can be used as alternative fuel for trucks. Academic studies generally agree that natural gas engines can achieve lower emissions than diesel trucks of the same efficiency primarily due to fundamental fuel properties and in-cylinder combustion modifications[75]. For example, in a study at West Virginia University (WVU) on trucks using a portable heavy-duty chassis dynamometer, LNG trucks averaged 80% less NOx emissions, but extent of reductions varied across natural gas engine manufacturers[76]**.** The WVU portable laboratory was also used to test trucks and buses using Caterpillar dual fuel natural gas (DFNG) engines; it also found reduced NOx but the extent of NO_x reduction was dependent on the type of test cycle used[77].

Despite efforts, NOx attainment in the California basins is proving evasive. CARB adopted in December 2013 optional ultra-low nitrogen oxides (NOx) emission standards for diesel truck engines, with funding opportunities are available via programs such as the Carl Moyer Program[78]. Under these new optional rules, there are three new levels of optional certification corresponding to reductions respect to the current federal standard of 50%, 75%, and 90% (i.e., 0.1 g/hp-hr, 0.05 g/hp-hr, and 0.02 g/hp-hr respectively).

Natural gas blended with hydrogen could meet the more restrictive NOx levels, even without aftertreatment, according to engine dynamometer tests at the University of Central Florida/Florida Solar Energy Center on and Sandia National Laboratories[79], but according to a study by West Virginia University Center for Alternative Fuel, Engines and Emissions (CAFEE), aftertreatment is necessary in order to achieve very low NOx[80] if pure natural gas fuel is used.

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[74] Venkata NG. 2010 Exhaust emissions analysis for ultra low sulfur diesel and biodiesel garbage truck. Master's Thesis. The University of Toledo

[75] Korakianitis T, Namasivayam A.M., Crookes R.J. "Natural-gas fueled spark-ignition (SI) and compression-ignition (CI) engine performance and emissions. Progress in Energy and Combustion Science Volume 37, Issue 1, February 2011, Pages 89–112

[76] Weaver, C., Turner, S., Balam-Almanza, M., and Gable, R., "Comparison of In-Use Emissions from Diesel and Natural Gas Trucks and Buses," SAE Technical Paper 2000-01-3473, 2000, doi:10.4271/2000-01-3473.

[77] Norton, P., Frailey, M., Clark, N., Lyons, D. et al., "Chassis Dynamometer Emission Measurements from Trucks and Buses using Dual-Fuel Natural Gas Engines," SAE Technical Paper 1999-01-3525, 1999, doi:10.4271/1999-01-3525.

[78] http://www.arb.ca.gov/msprog/onrdiesel/onrdiesel.htm

[79] Hoekstra, R., Van Blarigan, P., and Mulligan, N., "NOx Emissions and Efficiency of Hydrogen, Natural Gas, and Hydrogen/Natural Gas Blended Fuels," SAE Technical Paper 961103, 1996, doi:10.4271/961103.

[80] Yoon S, Collins J, Thiruvengadam A, Gautam M, Herner J, Ayala, A, (2013) "Criteria pollutant and greenhouse gas emissions from CNG transit buses equipped with three-way catalysts compared to lean-burn engines and oxidation catalyst technologies, Journal of Air Waste Management Association, 63 (8) 926-33; Also Chandler, Eberts, Melendez, (2006) finds roughly 20 to 25 percent greenhouse gas emissions reductions for CNG transit buses compared to diesel in 2004 engine models.

However, NOx control technology can produce a fuel efficiency penalty, which is counterproductive to the new EPA/NHTSA CAFÉ-like regulations for trucks[81], which require more aggressive fuel economy. Lower efficiencies mean more CO2 is emitted per mile. Thus, there is the concern that NOx goals can hinder efforts for fuel economy improvement in what it is sometimes referred as the NOx-GHG tradeoff in diesel engines

The diesel engine is optimized to either reduce NOx or maximize efficiency, but both goals are antagonistic from an operational point of view. NOx formation is maximized at peak temperature. In diesel engines, a strategy to reduce NOx consists of introducing cooled exhaust gas that is also lower in oxygen reducing the production of NOx. However, the lower temperature produces less effective combustion and thus more CO2 and PM. PM pollution can be controlled with filters, but higher CO2 emissions can still remain problematic. This has been brought to public attention after the recent VW scandal, by which it has been discovered that the car manufacturer used a defeat devise to operate diesel engines differently under test conditions (to produce low NOx) and road conditions (to provide the maximum fuel efficiency)[82].

An alternative to diesel with three way catalysts (3WC) is natural gas engines with selective catalytic reduction (SCR). However, the extent of NOx reductions also depends on the driving cycle. ARB found that SCRs realized reductions of 75% NOx reductions during cruise and transient modes, but no NO_x reductions during idle[83]. This could be due to the fact that catalysts require at least 200°C before significant NOx reduction is achieved. This temperature is not maintained right after engine start, during idling or even at low speeds[84], thus possibly explaining why real emissions have been found higher than predicted by emissions models used in certifications[85,86]. As scientific knowledge improves, more studies are being conducted to test operating parameters such as coolant temperature, fuel temperature, percent fuel, engine speed are important in determining exhaust emissions in trucks. Vehicle model, age, aftertreatment technology, and driving cycle can be as or more relevant factor than fuel type (ie natural gas or diesel) used in determining NOx emissions.[87]

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[81] EPA/NHTSA CAFÉ standards for trucks: Phase 1 (10-23% reduction in fuel consumption required model year 2014-2018) and Phase 2, which will be announced 2015, will be more stringent.

[82] Volkswagen: The scandal explained. Nov, 4th 2015 http://www.bbc.com/news/business-34324772

[83] Dinh Herner J., Hu S., Robertson W.H., Huai T., Collins J.F., Dwyer J.F., and Ayala A. "Effect of Advanced Aftertreatment for PM and NO_x Control on Heavy-Duty Diesel Truck Emissions" *Environ. Sci. Technol.*, **2009**, *43* (15), pp 5928–5933"

[84] Venkata NG. 2010 Exhaust emissions analysis for ultra low sulfur diesel and biodiesel garbage truck. Masters Thesis. The University of Toledo

[85] Weaver, C., Turner, S., Balam-Almanza, M., and Gable, R., "Comparison of In-Use Emissions from Diesel and Natural Gas Trucks and Buses," SAE Technical Paper 2000-01-3473, 2000, doi:10.4271/2000-01-3473.

[86] http://researchplanning.arb.wagn.org/files/Activity_Data_HDD_SOW-20666.pdf

[87] Idling regulations restrict trucks from idling more than five minutes or idling in school zones and some technologies such as an auxiliary power unit (APU) or direct-fired heater (DFH) can be used to increase temperature and reduce NOx emissions at idling. APU and DFH have been shown to reduce NOx by 89% and 99% respectively. Emissions tests from Class 8 over-the-road tractors on a chassis dynamometer showed emissions from Idle and Creep Modes were found to be variable due to varying auxiliary loads on the engine, according to Air Resources Board-sponsored truck activity programs. Engine control unit (ECU) or on board data (OBD) loggers can help with maintenance, but more importantly they could be used to improve characterization of certification models. CalHEAT Truck Research Center

For both goals of low NOx and low carbon emissions to be met will require advances in turbocharging technology, such as inertia reduction, aerodynamics and bearing improvements- and other technologies[88] relevant to both natural gas and diesel engines- might be necessary[89].

Greenhouse gases

In terms of climate pollution, tailpipe emissions from burning natural gas in heavy-duty trucking applications will produce between two-thirds and three-fourths the emissions of burning gasoline or diesel[90], but there are other issues that affect the well-to-wheels carbon intensity of natural gas in transportation. The variables that impact the environmental performance of natural gas include the level of methane and carbon dioxide venting and leakage from upstream production methane emissions from fuel distribution and processing; and methane emissions from the vehicle.

Existing Studies on Climate Performance of Natural Gas as A Transportation Fuel

The question of whether natural gas is better than diesel from the climate point of view has been tackled by several researchers and agencies.

For the Low Carbon Fuel Standard (LCFS), the Air Resources Board (ARB) produces a point estimate that best represents all fuel used in the state. It is calculated using the CA-GREET, which is a version of GREET developed by Argonne National Lab (ANL) where adjustments are made for efficiency, distribution distances, and upstream petroleum emissions that reflect the state averages rather than national averages. The LCFS calculation is designed to create a representative a point estimate but does not reflect the variability derived from different drive cycles, vehicle engines, classes of vehicle and other on road factors.

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at CALSTART in a roadmap prepared for The Southern California Gas Company suggests optional ultra-low NOx standards could focus on emission reduction technologies problem areas, such as thermal management of NOx emission reduction technologies. Characterize heavy-duty truck activity profiles (e.g., duty cycles, starts and soak time) for different vocational uses to identify operating conditions relevant to SCR function. Evaluate emission test cycles to represent SCR relevant operating modes. Post-combustion after-treatment technology such as optimized catalysts and improved conversion efficiencies, can be employed on natural gas engines to further reduce emissions of NOx and CO2. July 2014 Heavy duty truck and bus natural gas vehicle technology roadmap, Prepared by Steven Sokolsky, Fred Silver, and Whitney Pitkanen.

[88] Reducing the Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: First Report. The National Academies Press, Washington, DC

[89] Arnold, S., Balis, C., Jeckel, D., Larcher, S. et al., "Advances in Turbocharging Technology and its Impact on Meeting Proposed California GHG Emission Regulations," SAE Technical Paper 2005-01-1852, 2005, doi:10.4271/2005-01-1852.

[90] Zhao et al. 2013

ARB's LCFS carbon intensity number reflects a weighted average for a fuel based on the state's current mix of applications (transit, taxis, trucks) rather than a single application. Currently, the LCSF calculation does not specifically represent the greenhouse gas emissions from long haul trucking . Rather it is a value that represents collectively the applications that have been early adopters of natural gas in the state, mostly transit buses and other fleets. For this reason, the ARB calculations are not comparable apples-to-apples to scientific literature that specifically studies long haul, heavy-duty natural gas trucking.

The LCFS value is revised periodically. In the original LCFS lookup tables calculate gasoline, diesel, CNG and LNG at a carbon intensity of 95.86, 94.71, 68, and 72.38 gCO2e/MJ (not EER adjusted) respectively[91]. In more recent public hearings, ARB is considering a modification to 98.38, 98.03, 75.56, 80.42 g/MJ (not EER adjusted) or 100.53, 102.76, 88.29, 96.19 g/MJ respectively if EER adjusted[92]. Depending on what report is used and compared with diesel natural gas provides a carbon reduction of 12 or 28%, based on revisions in the case of CNG, and 24% or 6% in the case of LNG.

There are differences between the LCFS numbers and those estimated by other studies. Different parameters and different approaches contribute to the variability in the results. ARB does use CAGREET, which is structurally equivalent to GREET, to simulate the natural gas pathways, so any difference in natural gas estimates between ARB results and others who use GREET is due to parameter variability (i.e., parameter uncertainty[93]). However, ARB models upstream petroleum emissions with OPGEE rather than GREET or CAGREET. For this reason, in addition to potential parameter uncertainty, differences might arise from differences in the modeling approach for petroleum (i.e., model uncertainty).

Since life cycle carbon intensity is an abstract property that cannot be measured with a physical instrument (unlike temperature which can be measured with a thermometer), it is impossible to tell which modeling approach is more accurate. Each model will have strengths and shortcomings. Since there is not "true" physical emissions testing value that can be used to validate the life cycle approach, no one model can be scientifically proven to be better, and the different results produced with the two models must be treated as the result of both parameter and model uncertainties.

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[91] http://www.arb.ca.gov/fuels/lcfs/121409lcfs_lutables.pdf

[92] http://www.arb.ca.gov/fuels/lcfs/lcfs_meetings/040115_pathway_ci_comparison.pdf

[93] Data can be varied (e.g., regional differences) or uncertain (we can't estimate). However, the term "parameter uncertainty" is often used in modeling to reflect both uncertainty and variability in data, and that is the meaning used in this paper.

Another important point is that the LCFS analysis is designed to measure the life cycle carbon intensity of the fuel itself and not the operation of specific vehicles or applications. Thus, the LCFS number is given in gCO2e/MJ. Unless otherwise noted, this metric does not reflect the relative efficiency of the alternative vehicle. Sometimes this metric is specified as EER-adjusted. The Energy Efficiency Ratio (EER) is the relative gain or penalty in energy efficiency between incumbent and alternative engines. Fuels used in spark ignition engines must factor in a fuel efficiency penalty of about 10% when compared to fuels used in compression ignition diesel engines. In heavy duty trucking natural gas burns in spark ignition engines and substitutes diesel, which is burned in efficient compression ignition engines, thus an EER of 0.9 typically applies. In taxis it substitutes gasoline, and since both gasoline and natural gas are burnt in spark ignition engines, the EER is 1, which is the same as to say that no EER adjustment is necessary. Given these differences, in its most recent reports, ARB has shown recently both EER-adjusted and non EER-adjusted numbers.

Beyond the calculations made under the LCFS, several academic institutions have endeavored to study the life cycle greenhouse gas emissions performance of long distance heavy duty trucks using natural gas fuel. One such peer-reviewed scientific study on heavy-duty trucks by the Environmental Defense Fund (EDF) and Columbia University, find that "*converting heavy-duty truck fleets (to natural gas) leads to damages to the climate for several decades*". Instead of using static 20y or 100y global warming potentials (GWP) that most researchers and agencies use, the EDF- Columbia University study uses radiative forcings of each greenhouse gas as a function of time. In other words, this research shows the time it takes for a fleet conversion to natural gas to offset the shortcoming of emitting more short-lived methane with the long term benefit of emitting less CO2. The researchers find that the immediate release of methane is material and that only on a very long dated basis is it appropriate to conclude that natural gas is a preferred fuel to diesel given the relative inefficiency of natural gas vehicles and the higher emissions damage of methane compared to CO2 in the short run. After some period of time, 72 years (CNG) and 90 years (LNG) in the case of the SI NGV trucks and 51 years in the case of the HPDI truck (LNG), a climate benefit occurs as the initial warming created by methane dissipates and the benefits of lower CO2 emissions are reaped.

The EDF-Columbia University study assumes relative efficiencies of the SI and high performance direct injection (HPDI), a compression ignition natural gas engine, are 13% and 5.5% lower than diesel respectively. They consider the difference in the engine efficiencies of natural gas 8.9L and 11.9 L spark ignition (SI) engines and include a 15L HPDI engine technology that, to the date of this report, is still not marketed. Due to uncertainty related to relative engine efficiencies, the study conducts a detailed sensitivity analysis of this parameter. For methane slip (i.e., methane from the vehicle) this study uses is 4.2 gCH4/mi for HPDI and 2.6 g/CH4 for the SI. Another parameter in this study that creates variation from other studies are assumptions about upstream methane leakage rates and methane emitted in the vehicle which are calculated based on national averages and therefore will vary from any studies specifically on California based studies.

Another study by Carnegie Mellon University (CMU) offers probabilistic ranges rather than point estimates in order to account for the variety in fuels and transportation systems. The CMU study includes the addition of payload differences, and researchers model new vehicles rather than the fleet of vehicles currently existing in the market. The study uses a probabilistic approach in which probabilistic distributions of input parameters are created from a variety of data sources. Thus, instead of using one value for methane leakage, their probabilistic approach shows a right skewed distribution of natural gas upstream emissions, justified by the existence of a few super emitters. For the WTW emissions, in addition to the variability in feedstock systems, they include variability in vehicles and fuel options. Significantly, the scientists conclude that "f*or Class 8 tractor-trailers and refuel trucks, none of the natural gas pathways provide emissions reduction per unit of freight-distance moved compared to diesel trucks*"[94]. When compared with petroleum fuels, CNG and centrally produced LNG emissions increased by 0-3% and 2-13%, respectively.

These studies demonstrate that there is a wide variability in conclusions when comparing natural gas to incumbent fuels. As discussed, much of the variety arises from variations of data and of methodology. We also contribute to the scientific debate by utilizing Argonne's GREET 2014 model and testing the same the questions. In this paper, we do not intend to focus attention on specific carbon intensity values, because we understand the uncertainty associated with one point estimate. Rather, we consider scenarios around an initial point estimate to understand the dynamics of the system, and to provide policy-makers an understanding of how the different factors affect directionality and uncertainty of results. Other than endorsing one fuel type or the other, we intend to show the sensitivities for the use of the specific natural gas application in long-haul trucking to provide additional information for policy analysis. This effort is not intended to be compared to the methodology of the Low Carbon Fuel Standard which, as discussed, applies to the fuel only and not the application of the fuel in specific vehicles, drive trains and/or applications.

Additional Sensitivity Analysis on Natural Gas Greenhouse Gas Life Cycle

In our analysis, we utilize GREET 2014[95] and assume national averages of methane leakage of 1.14%[96] to test scenarios for the life cycle carbon intensity of natural gas versus diesel fuel in the operations of various kinds of engines used in class 8 vehicles for long distance trucking. In one scenario case where the more efficient HPDI engine is used in long distance trucking using LNG fuel, we find system-wide methane leakage from natural gas production and distribution cannot exceed 5% for natural gas to break even in carbon intensity as compared to diesel engines (Figure 30). For a scenario where LNG trucks are

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[94] Tong F., Jaramillo P., Azevedo I.M.L. (2015) Comparison for Life Cycle Greenhosue Gases from Natural Gas Pathways for Medium and Heavy-Duty Vehicles. Environ. Sci. and Tech. 49, 7123-7133.

[95] Rood Werpy M., Santitni D., Burnham A., and Mintz M., Argonne National Laboratory "White Paper on Natural Gas Vehicle: Status, Barriers, and Opportunities" September 2009 which found that in-use emissions reductions varied by region, fuel composition and engine configurations. The authors conclude that light duty natural gas vehicles can offer up to a 15 percent reduction in greenhouse gas emissions

[96] Dominguez-Faus, R. The Carbon Intensity of C8 NGV trucks. Working paper.

equipped with the less efficient spark ignition engine, we calculate that methane leakage would need to be eliminated entirely for natural gas to match the carbon intensity of more efficient diesel engines (Figure 30). At any given leakage rate, the HPDI is always much more favorable than the spark ignition engine. This analysis demonstrates that it is more effective, in life cycle terms, to increase vehicle efficiency than to reduce upstream methane leaks.

Our scenario sensitivity analysis also examines how natural gas is stored (i.e., compressed vs. liquefied) and finds this is material to climate outcomes. Using these scenarios and applying them to class 8 vehicles using CNG fuel instead of LNG fuel, we find that upstream methane leakage impacts CNG more than LNG[97]. CNG requires distribution via leaky natural gas local pipelines to the refueling stations where it is compressed, whereas LNG is transported as LNG from LNG plant to refueling station by truck. For the reasons discussed above, we do not find carbon pollution advantage in cases where a combination of less-efficient Si engine is combined with CNG storage technology, including under conditions where upstream methane leakage is wholly eliminated.

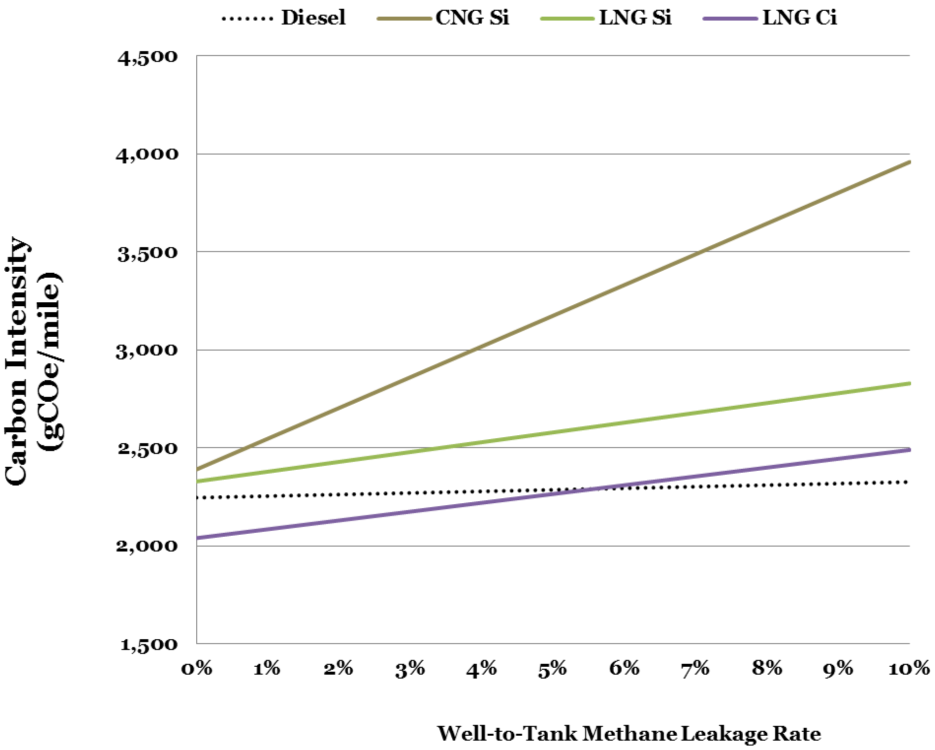

Figure 30. 100-year carbon intensity (gCO2e/mile) of C8 diesel and natural gas under different leakages rate. Dashed line represents diesel, brown line is CNG on a Si

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[97] These results are based on national natural gas supply chain assumptions. In California, results can be different due the lower leakage in the pipeline infrastructure and the higher energy efficiencies in upstream processes.

engine, green line is LNG on a Si engine, and purple is LNG on the HPDI model. The crossing of NGV lines with diesel line indicates breakeven leakage rates.

Figure 31 compares the contribution in grams of CO2 per mile to the 100 year carbon intensity (CI) of diesel and three configurations of NGV Class 8 trucks, given a base case with leakage rate of 1.14%, 6.3 gCH4/mi for spark ignition and 3.6 gCH4/mi for compression ignition, and a 0.9 EER for spark ignition engines, and 1 for the compression ignition. This comparison reveals that the high-efficiency HPDI Ci engine using LNG is the best performing vehicle-storage technology combination that would provide a beneficial carbon reduction with respect to diesel under the currently accepted Environmental Protection Agency (EPA) official methane leakage rate of 1.14%.

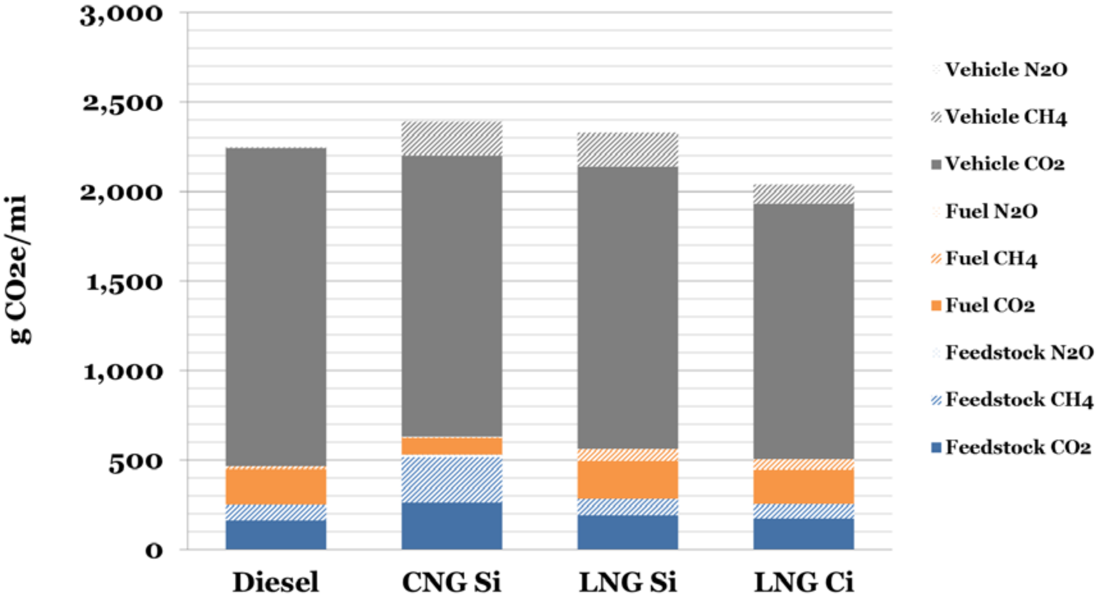

Figure 31.Carbon intensities of diesel and natural gas vehicles under baseline conditions. The graph shows the contribution of the different greenhouse gases and **life cycle segments to well-to-wheels Carbon Intensity of Diesel. Blue indicates emissions from feedstock procurement, Orange indicates emissions from conversion of feedstock to fuel, and Grey indicates vehicle emissions. Solid box refers to CO2 and stripped box refers of CH4. Percentages in parenthesis show change respect to diesel.**

Technologies exist for industry to curb upstream methane leakage significantly. In 2012 EPA ruled that all new oil and gas wells must use green completions beginning in 2015. The rule only applies to existing or modified wells, and affects an estimated 13,000 wells every year. While originally designed to control smog-contributing pollutants, green completions are also able to control methane emissions at oil and gas production sites. A study by the Environmental Defense Fund (EDF) found that a large number of operators are using these best practice technologies already.[98] According to official estimates, between 2012 and 2015, when green completions were only voluntary, methane emissions were reduced by 16%, despite the increase in oil and gas production. Technologies exist to bring wellhead methane leakage to zero. However, these technologies only reduce leakage at field operations. Additional technologies will be required to eliminate leaks at processing facilities, transmission lines and local distribution pipelines which can often be leakier.

EPA is now in the process of drafting methane-specific regulations to be issued sometime in 2016. The new regulations will apply to new and modified infrastructure, and will potentially cover production and distribution operations, not just drilling. According to EPA estimates, the new regulations could achieve reductions of methane leaks in natural gas and oil systems of 40% to 45% by 2015, using 2012 as baseline.

Still, our scenario analysis suggests that the largest potential improvements in the carbon intensity of NGVs running on fossil natural gas will come from gains in natural gas vehicle efficiency. As discussed above, NGVs equipped with HPDI engines compare favorably to diesel if leakage is below 5%. Using the same parameters, we find that NGVs using HPDI engines (5.36 miles per dge) would provide an 8% reduction in carbon emissions compared to diesel. Under very high methane leakage rates of 3% or higher, under our modeling parameters, a Si engine (4.8 miles per dge) would produce no significant benefits and in fact, would create significant increases in carbon emissions compared to operations of high efficiency diesel engines. It is possible that the carbon intensity of natural gas fuel could be lowered, especially by co-mingling fossil natural gas supplies with lower carbon intensity renewable natural gas from bio-waste sources or hydrogen.

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[98] http://www.edf.org/methaneleakage; also see A R Brandt et al, (2014) Science Vol 343, “Methane Leaks from North American Natural gas systems,”

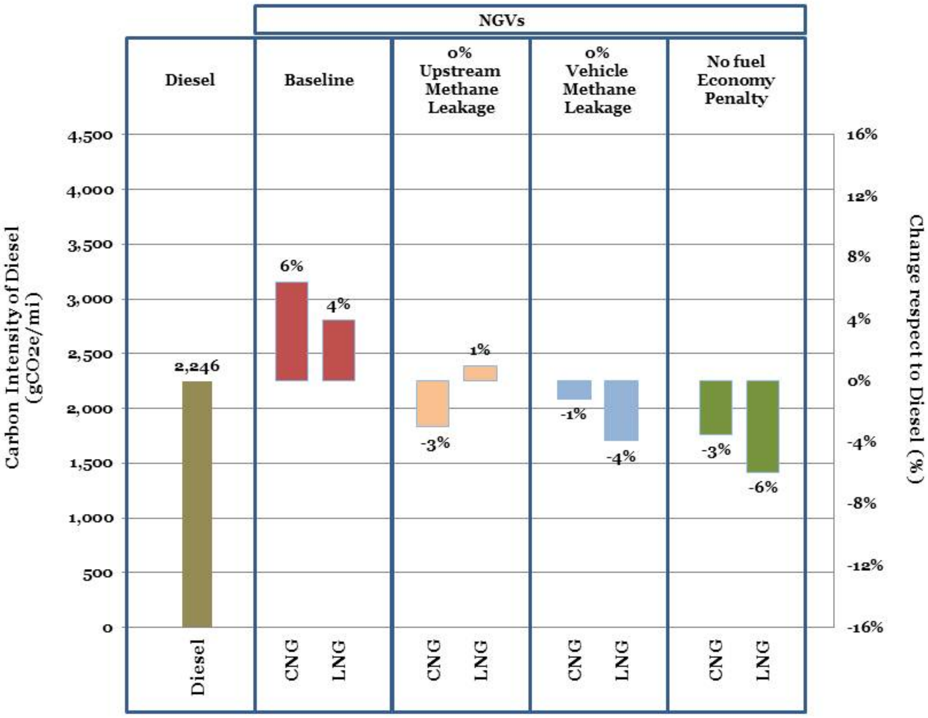

Figure 32. Figure 3. Difference (%) in carbon intensity between NGVs and Diesel vehicles under baseline and alternative scenarios.

Figure 3 shows the difference between the carbon intensity of NGV trucks and the baseline diesel truck according to simulations using Argonne's 2014 version of the GREET1 life cycle assessment model and different assumptions of methane leakage and vehicle fuel economy (baseline indicates a 10% fuel economy penalty in Si and no penalty for HPDI).

Our analysis suggests that improving efficiencies in vehicle engine and during upstream processes can be more effective at reducing the carbon intensity of natural gas in transportation than a strategy based in controlling methane leaks alone.

Conclusions and Implications for Policy

The deeply entrenched incumbency of oil-based fuels and their well-established infrastructure distribution provide a formidable barrier to the transition to alternative fuels. Even for a fuel such as LNG, which currently enjoys a deep cost discount to diesel, establishing a competitive fueling network will be challenging. Moving LNG into the heavy-duty trucking fleet could prove the most pliable of the options for fuel-switching based on commercial factors. That is because the turnover rate for Class 8 vehicles is fairly rapid compared to other kinds of vehicle stocks (three years, for example, compared to 10 to 14 years for light-duty vehicles) and vehicle ownership tends to be concentrated in large corporate fleets whose vehicles have high miles utilization per year and who can scale up more quickly than individual vehicle owners to shift vehicle technologies.

But large fleet owners will not be willing to make investments in alternative fuel vehicles unless they are assured of dedicated fueling station availability for their entire travel route. Thus, our scenario analysis suggests that the best way to promote an alternative fuel, such as LNG, into the heavy-duty trucking sector would be to focus initially on the highest volume freight routes such as California and the upper Midwest and then eventually commercial factors will encourage investment to branch out to other hotspot regions such as the Mid-Atlantic.

Trying to build from scratch a well-covered national network is not the most optimal approach to establishing a LNG highway, at least in the early stages. Instead, it may be beneficial to first establish limited networks in California or the Great Lakes region because these regions could benefit most from a high concentration of fleets adoption to add realistically a sufficient number of trucks to create a profitable network of stations. Eventually, a natural gas station network could extend beyond this initial LNG hotspot market.

Conceptually, focusing on a handful of large fleets that could commit to substantial purchases of LNG trucks in a particular regional market makes commercial sense and is consistent with the current commercial climate. For example, UPS ordered about 700 natural gas tractors in 2013 alone, showing the viability of getting adoption of the additional trucks via a fleets purchasing model.

Policy makers at the federal level have expressed an interest in promoting natural gas as a transport fuel in commercial fleets as a means to promote energy security, given abundant, domestic natural gas supplies that are located in geographically diverse locations. North American natural gas fuel is also expected to remain less expensive than oil-based fuel, opening the possibility of more cost-effective supply chains that can better compete with international markets. Finally, a push for natural gas into transportation will ensure that domestic producers have a ready domestic market for their gas to prevent supply overhangs from threatening profitability and associated job growth. However, to best utilize natural gas into U.S. trucking, policy makers need to consider both commercial realities in the market as well as ways to improve the environmental performance of natural gas as a direct fuel.

Successful public-private partnerships have already been utilized in some U.S. states such as Oklahoma to promote a switch to CNG vehicles for government work fleets. Policy makers can consider whether a pilot project federal-state partnership for LNG trucking could benefit the U.S. natural gas industry while at the same time promoting alternative fuel goals. The United States' recent commitment to reduce greenhouse gas emissions 25% to 28% from 2005 levels by 2030 includes stringent regulation of methane emissions, venting and flaring from U.S. domestic oil and gas production. Any shift to natural gas fuel would have to be considered in this context.

The question of what hotspot to select for a pilot project for natural gas vehicles is a complicated one. Our analysis would suggest that high access to natural gas supplies is less important than the density of freight miles traveled on local highways. Optimum station build-out patterns favor the regions with higher heavy trucking traffic flows (California and the Great Lakes routes (Wisconsin-Illinois region, Kansas City Region, Nashville, Dayton/Cincinnati, upstate New York) as well as areas with high diesel prices (California, New York, Ohio, and the Mid-Atlantic). Small scale micro LNG liquefaction plants also show strong favoritism in California, Midwest, and Mid-Atlantic/New England areas.

At present, the California natural gas heavy-duty trucking network receives an extra financial boost from the existence of a liquid carbon pollution market that qualifies credits for natural gas fuel use. California currently offers fuel providers carbon pollution credits under the LCFS and cap and trade systems. We find that if LNG could get to a limited penetration of 0.2% of the heavy trucking market, a commercial network in California could get off the ground. A subsidy in the form of carbon credits (fossil natural gas currently has a 20% lower carbon score than diesel under the LCFS) will help this process along. But the California Air Resources Board is considering regulations that will lower the credit available to natural gas fuel

Still, interest in natural gas as a trucking fuel should not be rejected out of hand as the state of California is also investigating whether a build-out of natural gas fueling infrastructure across the state would facilitate higher use of renewable biogas as a low carbon transport fuel. Our initial analysis would confirm that this pathway may prove viable if the state's network of natural gas fueling stations could reach a minimum threshold.

Several companies are currently investing in natural gas fueling infrastructure in the state of California, and there are many major commercial fleets that are operating in the state and could profitably switch to natural gas or biogas fuels. This starting base means that the cost of building an optimal natural gas fueling system in the state is relatively inexpensive compared to the cost of building fueling infrastructure for some of the other alternative fuels.

Since the commercial costs are low for a federal/state collaboration promoting a public-private partnership that would utilize natural gas and low carbon biogas fuel in California, the development of a natural gas fueling network there could support the expansion of natural gas as a fuel in other contiguous markets over time and eventually support the build-out of a national natural gas network across the U.S. highway system. This would suggest that federal government support for California's efforts to build alternative fuels infrastructure would be justifiable as a means to promote domestic natural gas markets in the short term and to enable a faster transition to low carbon biogas over the longer run.

Participating station investors could be expected to achieve a rate of return to capital of 12%, making the network commercially sustainable once built. The experience of the state of Oklahoma with natural gas fueling is instructive. The state brought parties together simultaneously to organize orders for the vehicles and commitments to build the fueling infrastructure under a single initiative receiving some state funding and calibrated so that stations and vehicle purchases appeared simultaneously.

The construction of natural gas infrastructure would be enabling to biogas producers who would be assured that fueling networks would be available to commercialize their production. California and neighboring states have a biogas resource base that is large enough to support between 10,000 and 30,000 LNG trucks, but further study is needed to determine what distant resources could be developed and imported profitably from other states and nearby countries. The California Biomass Collaborative, a University of California Davis-led public-private partnership for the promotion of California biomass industries, estimates that 32.5 million billion dry tons (bdt) of in-state biomass feedstocks could be available for conversion to useful energy[99] In particular, estimates for methane production from landfill gas are 55 bcf/year, 4.8 bcf/year for waste water biogas, and 14.6 bcf/year for biogas from manure sources. Similar biomass resources are located in states that border California or are along routes for the transmission of natural gas to the state from major producing states.

We estimate that the methane potential from landfill gas in the Western states outside of California is 105 bcf/year based on existing and candidate landfills identified by the EPA.[100] Parker estimates an additional 100 million bdt/year of lignocellulosic biomass in the Western states which are roughly equivalent on an energy-content basis to the gasoline used by 14.5 million passenger cars a year. However, some of these in-state and external biomass sources are already committed to or could be used for the production of liquid

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[99] Williams, R. B., Gildart, M., & Jenkins, B. M. (2008). An Assessment of Biomass Resources in California, 2007. CEC PIER Contract50001016: California Biomass Collaborative., (http://biomass.ucdavis.edu/files/reports/2008-cbc-resource-assessment.pdf)

[100] "Landfill Methane Outreach Program: Energy Projects and Candidate Landfills." US EPA, (http://www.epa.gov/lmop/projects-candidates/index.html)

biofuels or for dedicated power generation services to the businesses where they are co-located[101].

Other states besides California might be amenable to a pilot program for LNG trucking but many locations that have already embarked on limited investments such as Utah might find it difficult to promote sustainably commercial expansions that will link quickly to sufficiently high traffic networks. Thus, as the federal government seeks partnerships for natural gas fuel investment, it will want to consider venues such as the upper Great Lakes and Mid-Atlantic that also have the potential to contribute biogas inputs and also have highly identifiable heavy freight routes that could support a high volume trucking fleet for LNG or CNG powered vehicles.

National or state efforts to work with vehicle manufacturers to promote best in class engine efficiency and commitment to production would also be a critical component of any successful initiative to promote natural gas adoption into the heavy-duty sector. Our research suggests that improved efficiency of natural engines and reducing methane leaks from the vehicle are key to ensure environmental benefits. Such an effort needs to be consistent with emerging climate policies that are currently being implemented, such as carbon reduction efforts like those in the state of Colorado, which is seeking to eliminate methane leakage from oil and gas production, or recently announced plans by the White House in January 2015 of a draft federal methane regulation by the summer of 2015.

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[101] Parker, Nathan, Peter Tittmann, Quinn Hart, Richard Nelson, Ken Skog, Anneliese Schmidt, Edward Gray, and Bryan Jenkins. “Development of a biorefinery optimized biofuel supply curve for the Western United States.” *Biomass and Bioenergy* (2010) (34), pp 1597-1607.