

LNG AS A FUEL FOR DEMANDING HIGH HORSEPOWER ENGINE APPLICATIONS: TECHNOLOGY AND APPROACHES

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ABSTRACT

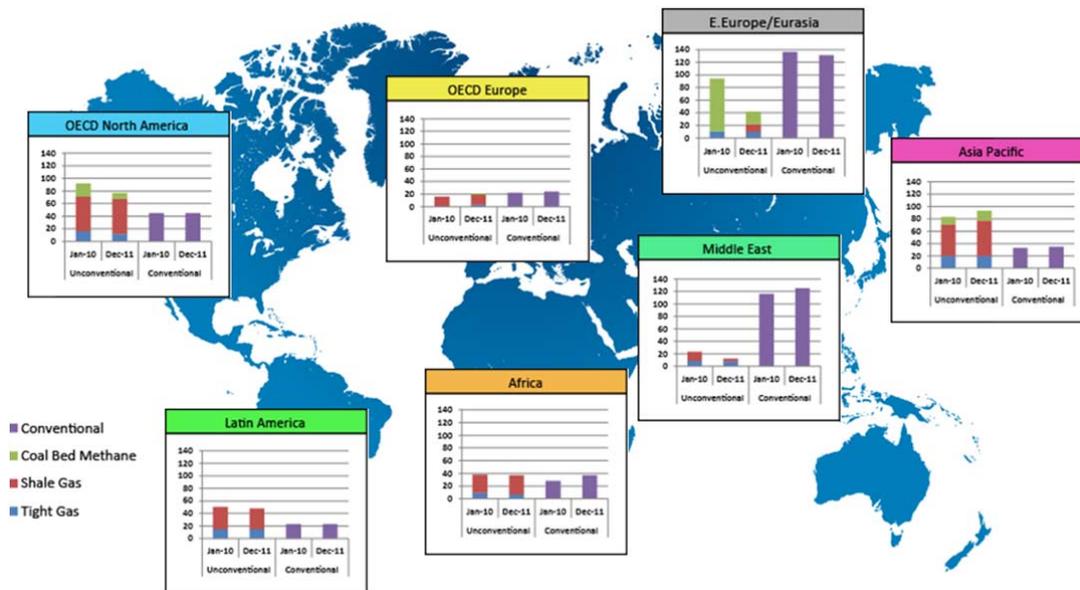
In addition to its successful on-road business, Westport is active in developing natural gas engine and mobile LNG fuel supply solutions for the high fuel-use sectors of rail, mining, marine and oil & gas. In this paper, Westport will describe some of the key challenges encountered and how Westport technology solutions under development are overcoming them to permit the rapid and widespread adoption of LNG as a fuel use in such demanding applications as mainline rail locomotives, mine haul trucks, tug boats and drill rigs. The paper will review the latest evidence for how Westport's proprietary High Pressure Direct Injection (HPDI) technology has been demonstrated to reduce emissions of nitrogen oxides (NO_x), particulate matter (PM), sulphur oxides (SO_x) and greenhouse gases (GHG) while retaining the diesel engine's favourable operating characteristics of high torque & power, transient response and efficiency.

INTRODUCTION

As natural gas fuel solutions become more widely available for heavy duty vehicle applications, the discussion around natural gas vehicles is switching from compressed natural gas (CNG) fuelled passenger vehicles to the opportunities for liquefied natural gas (LNG) fuelled trucks, locomotives and boats. This paper explores the technologies and approaches required to best leverage the opportunities for LNG, with particular focus on the demanding high horsepower engine applications such as mine trucks, locomotives, work boats and drill rigs.

BACKGROUND — SETTING THE STAGE FOR LNG IN TRANSPORT

A global revolution is beginning to take place for natural gas as a transport fuel. Widespread unconventional gas reserves mean this is not just a U.S. shale gas phenomenon. Figure 1 shows the global gas reserves around the world and how unconventional reserves have shifted the balance of natural gas supply. As these reserves are developed they promise to unlock an economical source of fuel for the transportation industry both domestically and as part of the global trade in LNG. Investment in natural gas transportation infrastructure in the U.S. and international markets is essential in the short term to advance the uptake for LNG for on- and off-road applications.



Source: IEA 2011 and 2012.

Figure 1: Global Gas Reserves

Demand for LNG as a transportation fuel is growing rapidly. LNG has several distinct advantages for transportation, and in particular for high horsepower engine applications:

1. **Increased range:** The increased energy density of this liquid fuel means that more fuel can be stored on the vehicle than with equivalent CNG fuel tanks.
2. **Rapid and economic refilling of fuel tanks:** LNG is a fluid that can be pumped with a high fuel flow rate that permit refueling at rates equivalent to current diesel refueling practices.
3. **Efficient pressurization of gas to be used with Westport™ HPDI engines:** high pressure direct injection (HPDI) technology promises to become a common solution for demanding high horsepower natural gas engine applications, as detailed in this paper. These engines require high pressure gas for injection into the cylinder, and pressurizing LNG is far more efficient than the equivalent process for CNG.

CNG will continue to dominate in passenger cars and return to base commercial vehicles such as buses, refuse trucks and delivery trucks where either the small fuel volumes with long hold times or slow overnight filling make CNG the more attractive option. Even so, the widespread availability of so-called LCNG stations that are able to rapidly and economically generate large volumes of high-pressure CNG to fill vehicle tanks using an LNG pump instead of a costly and inefficient compressor will mean that an increasing share of the CNG market will be served by LNG raw material.

The attractive economics (up to 50% savings in the U.S.) from domestically liquefied or imported LNG as an alternative to diesel represent a compelling reason to consider this fuel switch.¹ But it is not just the pure fuel price differential that encourages current high horsepower diesel engine users to evaluate LNG. The clean-burning properties of natural gas mean that criteria emissions regulations (where these are in place) are more easily met by natural gas engines. Diesel-powered engines require much more complex and costly pre- and after-treatment solutions to achieve the same levels of regulated emissions. In some cases, the cost differential between a fully compliant diesel-powered vehicle with all its aftertreatment equipment and its natural gas powered equivalent may be negligible. There is also a growing emphasis on criteria emissions, particularly oxides of nitrogen (NOx) and particulates, in traditionally unregulated markets such as China and

¹ Cost savings vary due to the divergent prices for LNG in various markets. For example in Europe, savings may approach 20-30%.

India where air quality concerns are driving the adoption of clean-burning fuels, in particular natural gas, for transportation of goods and passengers.

The greenhouse gas (GHG) emissions reductions offered by natural gas as a fuel is well-publicized. Not only are GHG emissions rapidly becoming part of the regulated emissions profile, but industries such as petroleum and mining are actively monitoring and reducing their GHG emissions. This shift is due to several factors, including corporate or community commitments, maximizing the monetary position in voluntary markets (via offsets and other mechanisms), and improving operational and energy efficiency. These industries traditionally consume vast quantities of diesel due to demanding high horsepower engine applications that extract and transport fossil fuels.

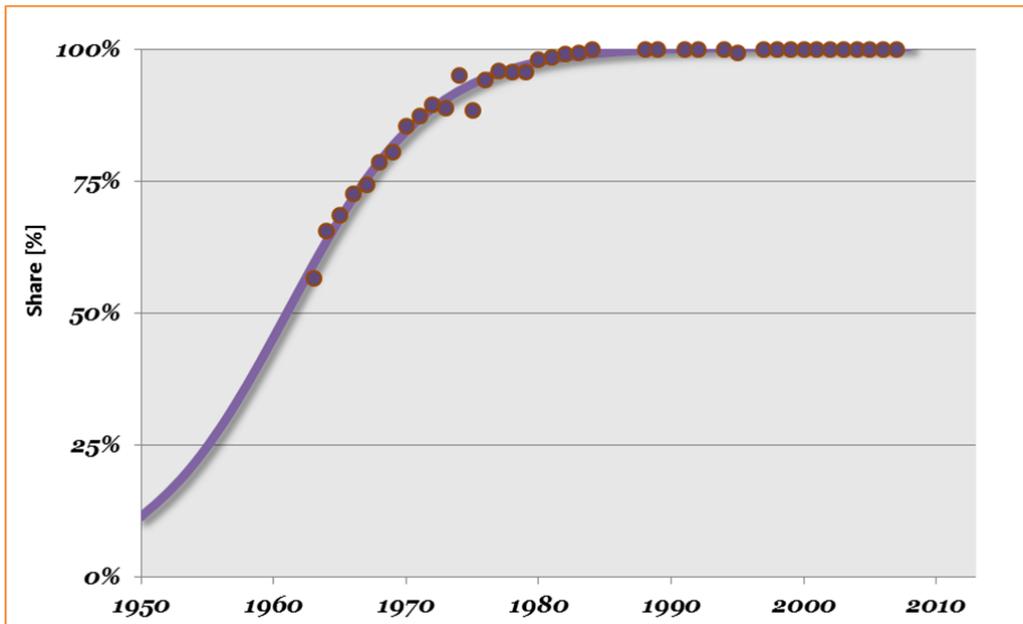
Finally, the strategic importance at both country and company levels of a diversified portfolio for transportation fuel should not be underestimated. The decoupling of natural gas and oil prices – which has begun in North America and is beginning to move into other markets – means that reliance on both oil and natural gas commodities will provide companies with an attractive natural hedge against commodity price fluctuations, and offers national and energy security advantages for governments.

RAPID FUEL TRANSITIONS — THREE HISTORICAL CASES

Given all these advantages, one might anticipate the transition to LNG as a fuel for high horsepower application to be very rapid. But significant barriers exist, particularly because of the extremely demanding nature of these applications. To understand how the transition to LNG fuel is likely to occur, it is instructive to examine historical examples of how market segments have shifted from using one fuel to another. These transitions follow the typical “s-curve” and undergo surprisingly rapid transitions. In the face of a radically altered customer value proposition, the march of change would seem to be unstoppable once it gets started.

Example 1: The transition from gasoline to diesel trucks

Diesel trucks are commonplace in our daily life and it seems as though they have always been there. But it was not always the case. In the 1950s and 60s the trucking industry in North America and around the world underwent a complete upheaval as more efficient engines that could burn the more plentiful and low-cost diesel fuel became available for the truck market. Figure 2 shows that the market share of diesel trucks grew from 10-15% in 1950 to 100% by the 1980s. Even though diesel powered trucks cost more and were heavier than gasoline powered trucks, the economic case provided by the increased productivity and lower fuel costs was overwhelming.



Source: MacKay & Co., & Wards Auto Group

Figure 2: Diesel's share of new sales of Class 8 trucks in the U.S.

Example 2: The rise of combined cycle natural gas power plants

Recently, an even more rapid transition is taking place in the electricity generation industry, from coal to natural gas. That natural gas overtook coal as the predominant electricity generation fuel in the U.S. last year was widely reported in the industry.² How did this situation arise and why was all this natural gas generating capacity built long before the recent low natural gas price advantage? The 1978 *Powerplant and Industrial Fuel Act* prohibited new natural gas power plants and industrial applications due to energy security concerns, while encouraging alternative electricity generation sources such as coal and nuclear. By the time the relevant sections were repealed in 1987, oversupply and attractive natural gas prices prevailed.³ At the same time, during the 1980s, technological advances took place in the thermal efficiency of large scale combined cycle gas turbine (CCGT) power plants.⁴ These two factors combined caused a surge in natural gas fired power generation. As demonstrated in Figure 3, within a period of 14 years the natural gas share of new U.S. power plant construction went from 6% in 1986 to 96% in 2000.

² U.S. Energy Information Administration, "Monthly coal- and natural gas-fired generation equal for first time in April 2012," Today in Energy (July 6, 2012): available at <http://www.eia.gov/todayinenergy/detail.cfm?id=6990>.

³ U.S. Energy Information Administration, "Repeal of the Powerplant and Industrial Fuel Use Act (1987)": available at http://www.eia.gov/oil_gas/natural_gas/analysis_publications/ngmajorleg/repeal.html.

⁴ Lothar Balling, Heinz Termuehlen, and Ray Baumgarnter, "Forty Years of Combined Cycle Power Plants," Energy-Tech Magazine, ASME Power Division Special Section (October 2002): available at http://www.energy-tech.com/uploads/17/02/10_ASME.pdf.

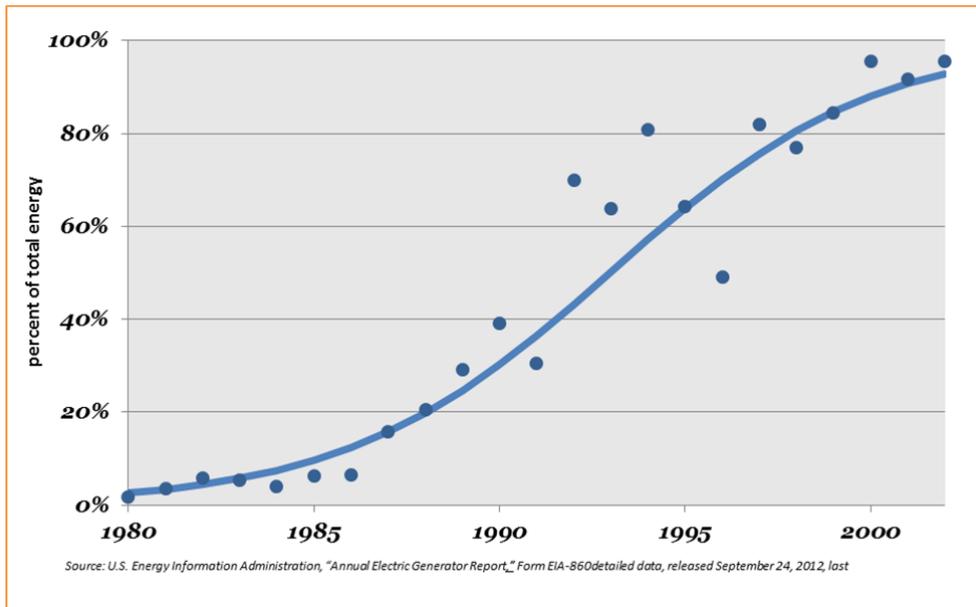


Figure 3: Natural Gas share of new power plant constructed in the U.S. currently operating

Example 3: The transition from steam to diesel trains

The final example is perhaps the most rapid of all. Figure 4 shows the transition from steam locomotives to diesel locomotives for North American railroads. This curve should not be confused with those for Figures 2 and 3, which are market share of new build equipment. The data in figure 4 show the absolute share of locomotives active in hauling freight and passenger trains. Despite having been the dominant form of rail motive power just a decade before, steam locomotives were almost completely removed from service by 1960. In less than 20 years, the largest rail freight network in the world completely replaced all of its main motive power and fuelling infrastructure. The impetus for this was the overwhelmingly compelling saving of greater than 50% on a cost per mile basis of the vastly more efficient diesel-electric locomotive – a nearly five-fold efficiency advantage over its steam predecessor which could only manage 6% thermal efficiency.

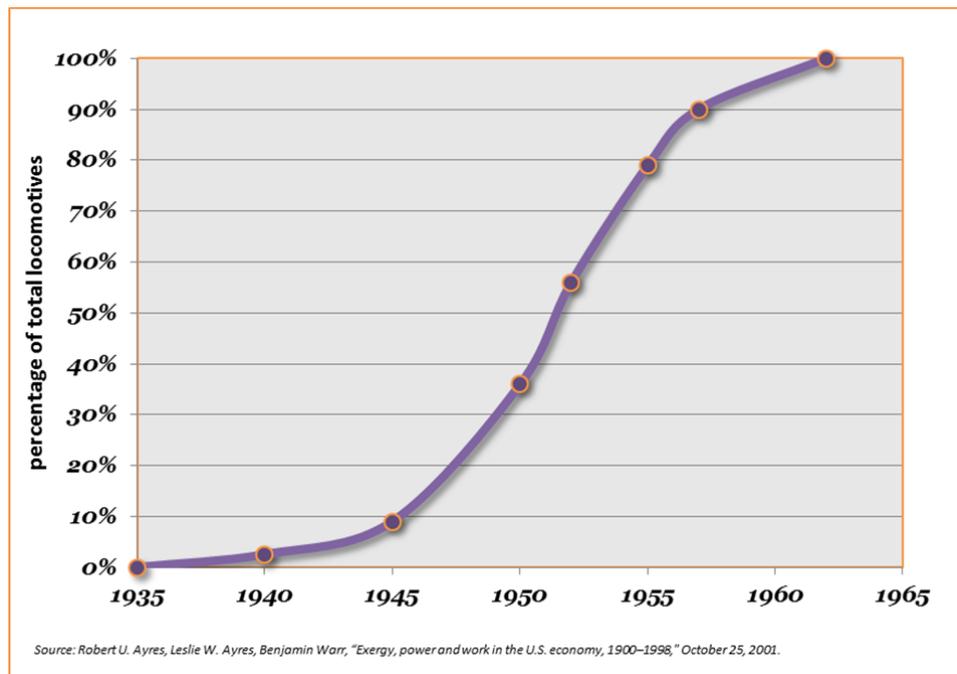


Figure 4: Diesel Powered Locomotives, North America

The fundamental observation from these three examples is the importance of the technology solution in initiating the s-curve transition. It is not sufficient to simply have a plentiful supply of low-cost fuel: to enable a shift there must be a technology solution that can robustly and efficiently transform that fuel into useful work.

TECHNOLOGICAL INNOVATIONS IN NATURAL GAS VEHICLES

To advance the proposition that a technology solution is essential for the transition of high horsepower engines, we examine some natural gas vehicle examples that have already taken place and/or are in the process of influencing the transition of a segment of the market to natural gas fuel. Westport has a track record of developing such technology solutions, working alone and in concert with its original equipment manufacturer (OEM) partners. These solutions already have, or are in the process of, revolutionizing the customer experience, and represent the enablers of the rapid transitions illustrated above.

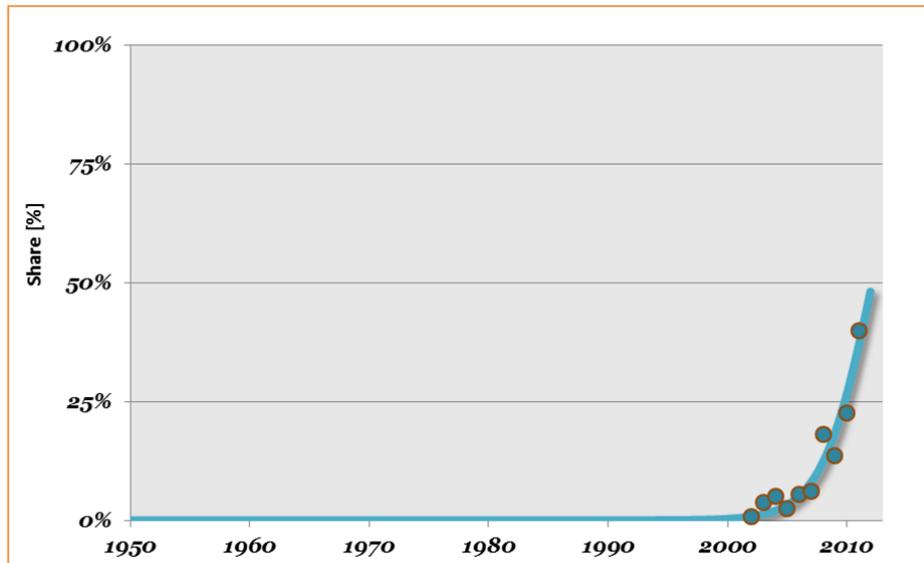
Example 1: Clean Combustion Solution for Natural Gas Refuse Trucks

The Cummins Westport ISL G spark ignited natural gas engines use Stoichiometric combustion with cooled gas exhaust recirculation (EGR) and a three-way catalyst (TWC). This technology was developed to meet the stringent 2010 U.S. Environmental Protection Agency (EPA) emission requirements and was introduced with the ISL G in June 2007.

The cooled-EGR system takes a measured quantity of exhaust gas and passes it through a cooler to reduce temperatures before mixing it with fuel and the incoming air charge to the cylinder. Stoichiometric combustion in combination with cooled-EGR creates the ideal combustion process with the chemically correct mixing of fuel and air, offering increased power density and thermal efficiency. It also reduces in-cylinder combustion temperatures and creates an oxygen-free exhaust, which then enables the use of a TWC to control oxides of nitrogen (NOx) emissions.

When deployed with natural gas, this combustion and aftertreatment system presents a compelling alternative to best available diesel aftertreatment systems for refuse trucks to meet stringent emissions standards. The market penetration of natural gas engines in the refuse sector in the U.S. has been dramatic. Figure 5 illustrates this rapid transition, showing that the market share of natural

gas refuse trucks climbed from less than 10% to nearly 50% within three years of release. Leading fleets such as Waste Management and Republic Services (which together comprise 50% of the U.S. market⁵) have publicly stated that the majority of their new truck purchases will be fuelled by natural gas.



Source: Westport

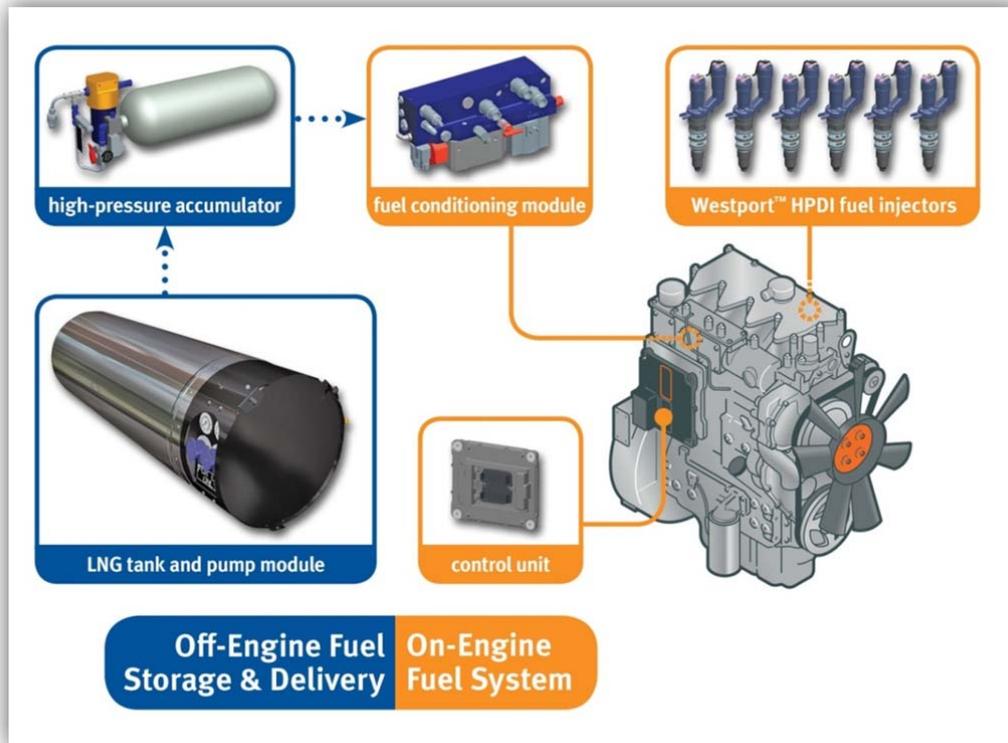
Figure 5: Natural gas share of natural gas refuse truck sales in the U.S.

Example 2: Westport HPDI Natural Gas Engine Technology for Heavy Haul Trucking

Traditionally, it had been accepted that natural gas engines lacked the torque necessary to haul the heaviest loads for on-road trucking. This changed with the release of the Westport 15L natural gas engine which provided class-leading emissions and performance while maintaining the same horsepower and torque as the equivalent diesel fueled engine. The union of Westport high pressure direct injection (HPDI) natural gas technology and the proven Cummins ISX long block, provided operators with the power and torque required to haul North America's heaviest loads – gross combined weights of over 80,000 lbs.

The Westport 15L engine, featuring Westport HPDI technology, uses natural gas as the primary fuel, along with a small amount of diesel as an ignition source, or “liquid spark plug.” Westport HPDI engines retain diesel-cycle operation with up to 95% replacement of diesel fuel (by energy) with natural gas, and is illustrated in Figure 6.

⁵ Ben Steverman, “Waste Management: Trashing a Merger?,” Bloomberg Businessweek (July 15, 2008): available at <http://www.businessweek.com/stories/2008-07-15/waste-management-trashing-a-merger-businessweek-business-news-stock-market-and-financial-advice>.



Source: Westport

Figure 6: Westport HPDI natural gas fuel system for heavy haul truck engines

Since its initial release in PACCAR's Peterbilt and Kenworth trucks in 2009, uptake has been rapid, with over 800 trucks already in service with customers. Due to this early success, other major OEMs have begun to adopt the same technology solution. Most recently, Volvo North America has announced a 13L engine which also deploys the Westport HPDI technology aimed at the same heavy haul truck market⁶. Heavy haul trucking is now positioned on the foot of the s-curve and analysts project 50 to 100% annual growth rates in the period 2013 – 2015.⁷

Example 3: Westport LNG Tank System for Regional Haul/Vocational Trucking

Current industry standard systems require two LNG tanks to operate effectively with larger spark ignited (SI) engines, and require warm (saturated) LNG. Warm LNG fuel systems offer less range than those with cold (unsaturated) LNG, and are more prone to methane leakage when the vehicle is left to stand for a significant period of time.

The Westport LNG Tank System overcomes this by offering a low pressure version of the LNG pump to guarantee fuel delivery. Where two traditional pressure transfer LNG tanks may have been required to provide sufficient fuel flow to the engine, now only one LNG tank is required. This represents a dramatic cost reduction opportunity where range requirements demand only one tank. A third benefit of this approach is that it enables SI and dual fuel engines to use cold LNG for improved energy storage density, range and ultimately commonality in fuel conditioning at dispensing stations. Successfully establishing cold LNG as the standard for all natural gas fuel systems types will help the supply chain lower the cost of components (due to increased usage of

⁶ Brandon Borgna, "Volvo Trucks Details Comprehensive 'Blue Power' Natural Gas Strategy for North America," news release (May 18, 2012): available at http://www.volvotrucks.com/trucks/na/en-us/news_and_events/news_releases/layouts/CWP.Internet.VolvoCom/NewsItem.aspx?News.ItemId=123985&News.Language=en-gb.

⁷ Frost and Sullivan, "Strategic Analysis of North American Class 6-8 Natural Gas Truck Original Equipment Manufacturer". (March 20, 2012): available at <http://www.frost.com/sublib/display-report.do?id=N8CF-01-00-00>

these common components). This represents an advance from today's marketplace where separate components are required for provision of cold and warm LNG on a vehicle. The system is illustrated in Figure 7.



Figure 7: Westport LNG Tank System for Spark Ignited Engines in Regional Trucking

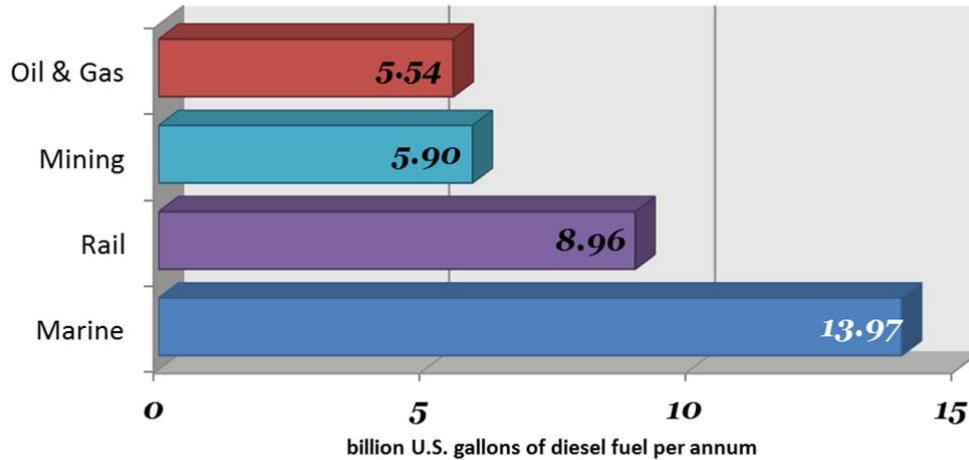
Compared to existing CNG options, a single 150 gallon Westport LNG Tank System takes the place of three standard CNG tanks, lowering fuel storage costs, reducing overall vehicle weight by approximately 600 pounds, and reducing refueling times. The new Westport LNG Tank System will be available in 120 and 150 gallon capacities, is optimized for spark ignited (SI) engines and begins shipping in mid-2013. The 120 gallon or 150 gallon single-tank systems can run for approximately 350 to 450 miles, respectively, on cold (unsaturated) LNG fuel. Those ranges double for dual-tank configurations.

APPLYING THESE INNOVATIONS TO HIGH HORSEPOWER

These technology solutions have been instrumental in advancing the on-road natural gas market both in North America and internationally.⁸ But what are the equivalent technologies and approaches that might be applied to demanding high horsepower engine applications?

Mobile high horsepower engine applications such as mine trucks, locomotives and drill rigs consume very large amounts of diesel fuel, and have remained resistant to transitioning to natural gas. Together, the marine, rail, mining and petroleum industries burn more than 30 billion gallons of diesel fuel annually (4.2 billion mmBTU), largely in high horsepower, high performance diesel engines. The breakdown by industry is presented in Figure 8. If converted to LNG, these applications would use approximately 80 million tons per annum or half the global LNG export capacity in 2007. This figure solely covers diesel, and does not incorporate the large marine segment currently burning heavy fuel oil.

⁸ The surge in natural gas fuelled trucks in China powered by Weichai Westport engines is a good example.



Source: UN Energy Statistics Database, Westport analysis

Figure 8: Global diesel consumption in demanding high horsepower applications

Individual vehicle fuel consumption in these markets can be substantial, making the business case for switching to natural gas highly compelling. The largest mine trucks can each consume over 400,000 gallons (1.5 million liters) of fuel annually. An inland waterway tow boat pushing a fully loaded barge consumes 7,000 gallons in a single day and a single land-based drill rig can consume even more.

These markets are highly concentrated geographically and by customer. For example, 95% of the 10 billion gallons of diesel fuel consumed annually by rail locomotives is confined to North America, Europe, Russia, India and China. Nearly half of this is by the seven Class I railroads in North America. In resource extraction, a handful of global multinational mining companies own the majority of the 20,000 largest mining trucks in the world. And petroleum exploration and production is controlled by an even smaller number of global multinationals.

Despite the compelling economics and the concentrated markets, these mining, rail, marine and petroleum applications have thus far proved almost impervious to LNG as a fuel, for reasons largely specific to the demands of each sector:

- Early attempts to use LNG fuel for **rail** locomotives in North America failed despite several well-funded demonstration projects because the engine technology was either immature or could not provide the required power demanded by modern locomotives.
- More recent attempts to utilize LNG as a fuel for **oil and gas** exploration and production in both the U.S. and China have met with limited success. Engines equipped with dual fuel conversion kits struggle to sustain diesel replacement rates of over 50%. When pure-gas SI engines are deployed, these need to be combined with wasteful load grids to manage the power fluctuations demanded from the engine, creating inefficiencies of up to 50%⁹.
- In the **marine** segment there has been some uptake of LNG-fuelled vessels for ferries and platform support vessels, though widespread uptake is limited by the responsiveness of current gas engine technologies. For instance, passenger ferries and ship-handling tugboats rely on the previously-unmatched ability of diesel engines to maneuver by rapidly applying power.

⁹ Source: Brian R. Murphy, "Natural Gas Fuel Options for Modern Drill Rigs", Paper presented to World LNG Fuels Conference 2013, (January 21 - 23, 2013). Houston TX.

- In **mine** trucks, the onboard storage requirements of large quantities of LNG fuel coupled with the extremely demanding engine duty cycle required to climb out of enormous open pit mines has meant that very few have even attempted to put forward a solution using LNG.

UNLOCKING THE POTENTIAL OF NATURAL GAS FOR HIGH HORSEPOWER

This is about to change. Westport and Caterpillar have begun development of commercial products which tackle the most challenging and highest fuel burn applications namely the North American mainline freight rail locomotive and the large mining truck illustrated in Figure 8. The two companies are co-developing the engine and fuel system for these applications deploying the Westport HPDI engine technology that has been proven in the North American heavy haul truck market. Westport is also developing rail tender car solutions for the new locomotives that promise to provide extended range and operational flexibility.



Caterpillar 795 Large Mining Truck



EMD SD70 Locomotive

Source: Caterpillar

Figure 8: Caterpillar 785 Large Mining Truck and EMD SD70 Locomotive

These products promise the same performance and efficiency as the diesel engine powered vehicles they replace. They will not compromise the response to transient loads and will not de-rate the engine – the full torque and power will be available to the operator whenever needed. Retrofitting existing equipment with OEM-supplied and warranted kits will mean that the transition promises to be as fast, or faster than the steam to diesel transition illustrated above. With more cost effective emissions aftertreatment solutions, the price differential is likely to be insignificant when compared to the substantial operating cost savings available.

Engine testing is already underway and vehicle prototypes will not be far behind. Once these most demanding applications have been proven, other market applications will naturally follow, many of which use the same engines:

- **In rail:** global mainline rail and shunting locomotives
- **In mining:** smaller haul trucks and other mining equipment such as shovels, dozers and scrapers
- **In marine:** tugs, ferries, platform support vessels and inland waterway push boats
- **In petroleum:** drill rigs, workover rigs and fracturing engines

Other related industries such as construction will soon follow.

CONCLUSION

Given the technology solutions under development and the advantageous economics of LNG fuel, we predict a rapid transition to LNG as a fuel for these most demanding high horsepower engine applications. The demand on the global LNG infrastructure, both domestically and import/export will be significant. An additional 40 mmtpa of liquefaction will be required in global LNG production just to support a 50% market penetration of the high horsepower market which, based on historic projections, will take place within the next 10-15 years.