ECONOMIC AND ENVIRONMENTAL BENEFITS OF NATURAL GAS FUEL FOR THE RAIL SECTOR IN CANADA

FINAL REPORT

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Preface

Under the Natural Gas Roadmap Implementation Committee, the Federal government, fuel utility and transportation industries have formed a Natural Gas Emerging Markets Working Group (Working Group) with the objective of investigating the potential for natural gas as a fuel in emerging markets for transportation in Canada. This Working Group is co-chaired by Natural Resources Canada (NRCan), Transport Canada and the Canadian Gas Association. This Working Group is undertaking a series of analytical projects to identify, evaluate and prioritize opportunities and barriers that relate to the adoption of natural gas in the areas of marine, rail and mine-haul transportation.

The Government of Canada is working towards moving to a cleaner transportation sector. The transportation sector represented 23 per cent of Canada's greenhouse gas (GHG) emissions in 2013 and is the second-largest contributor to GHG emissions in Canada, after the oil and gas sector. It is also a major source of air pollution (e.g. nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), volatile organic compounds (VOCs) and carbon monoxide (CO)). As part of its effort to support the transition to a cleaner transportation sector and reduce the sector's environmental impact, the Government of Canada has announced an economy-wide target to reduce GHG emissions by 30% below 2005 levels by 2030. Efforts may include such measures as the development of policies, regulations and standards to reduce emissions.

The rail industry in Canada has been actively working with the Government of Canada since 1995 to address the impacts of its activities on the environment through a series of voluntary agreements to reduce emissions. The most recent Memorandum of Understanding (MOU) is the 2011-2016 MOU concerning the emissions of GHGs and CACs from locomotives operating in Canada. This renewed agreement encourages RAC members in Canada to continue to voluntarily reduce the GHG intensity of their operations in-line with mutually agreed targets and to conform to U.S. Environmental Protection Agency (EPA) CAC emission standards until the *Canadian Locomotive Emissions Regulations*[1] are in force.

There are also efforts underway to reduce GHG emissions from the rail sector in the North American context. The Canadian and U.S. governments and the rail industry have been working together through the Regulatory Cooperation Council (RCC) to develop a Canada-U.S. voluntary action plan to reduce GHG Emissions from Locomotives, which would include measures to reduce GHG emissions. This initiative has included discussions on technical measures to reduce GHG emissions from locomotives including through the use of alternative fuels such as natural gas.

Historically, during the period of high oil prices, there has been interest from North American and rail operators around the world in natural gas fuel. For instance,

[1] See Canada Gazette Vol. 150 June 18, 2016: http://www.gazette.gc.ca/rp-pr/p1/2016/2016-06-18/html/reg4-eng.php

Burlington Northern railroad ran a pilot during the 1990s in its Powder River Basin coal service, and Union Pacific (UP) launched a multi-million dollar research program in 1992 together with Southwest Research Institute to pioneer advanced natural gas combustion systems [1]. Interest in natural gas waned over the next 20 years as oil prices subsided and technology was not matured sufficiently.

More recently, starting in 2011, Canadian National launched a research program with Westport Innovations and other collaborators to investigate advanced natural gas combustion systems for locomotives. This was driven by CN's desire to look for ways to improve operating efficiency and advance the company's sustainability agenda. Spurred on by this activity, both major locomotive OEMs commenced development of natural gas conversion kits for their locomotives. Primarily the focus has been on Liquefied Natural Gas (LNG), but there has also been some investigation of Compressed Natural Gas (CNG). BNSF has conducted much of the pioneering work to assess these technologies, but wider uptake has been relatively slow, with proponents citing a lack standards, particularly for the fuel tenders, as a reason for not adopting. To address this, the American Association of Railroads (AAR) set up a Natural Gas Fuel Tender Technical Advisory Group which has recently published for comment its first set of specifications and standards for LNG fuel tenders after 3 years of detailed deliberations. This represents an unprecedented level of engagement by railroads, suppliers and regulators not seen previously.

The opportunity presented by natural gas as a fuel for rail transportation merits further investigation with up to 27% reductions in greenhouse gas emissions reported as possible [2]. Although oil prices (and consequently diesel prices) are currently low, natural gas commodity prices have also fallen to all-time lows meaning that there is still a compelling financial case for using natural gas as a fuel if the locomotive conversion costs, fuel tender costs and fuel logistics can be addressed. A 30-50% savings in fuel costs have been reported [3] with the use of natural gas.

In the context of the background set out above, this report under NRCan Contract 3000631959 aims to evaluate the environmental and economic benefits of natural gas in the rail sector. The objective is to estimate the economic benefits of using natural gas as a fuel for locomotives in Canada, to evaluate where gaps exist in current research on environmental benefits and make recommendations for addressing the gaps that are found.

Executive Summary

Natural Gas as an alternative fuel to diesel in the rail industry presents a major opportunity for economic benefit to Canada and the Canadian rail sector under the right conditions. The opportunity is concentrated in the mainline freight locomotives that burn the majority of fuel (87%) and emit the majority of CAC and greenhouse gas (GHG) emissions.

The source of the opportunity is a price gap between diesel and natural gas that has opened since 2011 and looks certain to be sustained based on current Canadian National Energy Board (NEB) and U.S. Energy Information Administration (EIA) forecasts.

The analysis performed in preparation of this report suggests that if rail diesel remains over 80c/L, then 40-50% savings in fuel cost can be achieved by converting existing locomotives to run on a blend of natural gas fuel and diesel using OEM supplied conversion kits, leading to a favourable business case. To achieve these savings, large fleets of locomotives need to be converted and refuelled at centralized refuelling depots with new co-located liquefaction plants. Carbon pricing is unlikely to affect the business case decision, even at $50/tonne.

A major investment is required in liquefaction and locomotive equipment, estimated at $2.8 billion for the highest potential mainline freight locomotive population of 1,420 locomotives identified in this report.

30% average reduction in NO_x and 88% reduction in PM are predicted if all locomotives were converted from their current tier status as of 2014 to the best available OEM-provided natural gas conversion kit.

Initial dual fuel technologies being deployed do not reduce GHGs, however advances in engine technology currently under development by both major OEMs do have the potential to reduce GHG emissions. Further R&D is required.

An unprecedented level of activity focused on natural gas for rail is taking place in the U.S. with locomotive OEMs, railroads, railcar manufacturers, the AAR and regulators all involved. Although CN conducted a pilot project in 2013 – 2015, there is currently very little activity in Canada.

Canada could take a leading position by focusing research, development and deployment on the technologies and policies required to ensure natural gas for rail has both an economic benefit *and* environmental (GHG) benefit.

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Section 1: Overview of the Rail Sector

1.1 Industry Structure

Canada's railroad industry transports $280 million worth of goods and 75 million passengers each year [4]. Figure 1 shows the breakdown in revenues from freight, passenger and other sources and demonstrates that the vast majority (90%) of activity is focused on freight movement with over $13 billion of revenue in 2015.

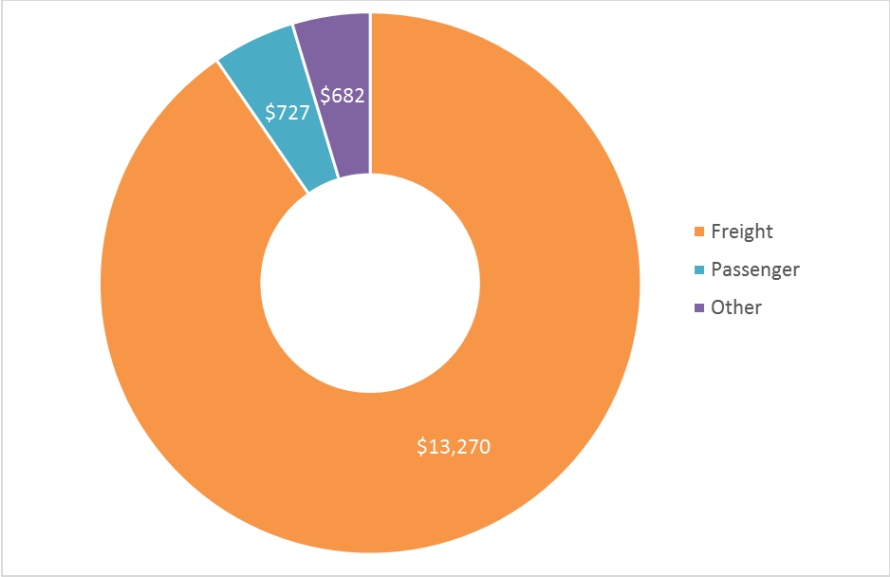

Figure 1 Canadian railroad revenues in 2015 ($ thousand) [4].

Canada's rail industry is dominated by two large freight railroads, Canadian National (CN) and Canadian Pacific (CP) which are defined as Class I[2]. The mainline freight operations of these two railroads are together responsible for 87% of the more than 2 billion litres of diesel consumed annually by the Canada's rail industry in Figure 2.

[2]: Class I in Canada is defined in Transportation Information Regulations under CTA http://laws-lois.justice.gc.ca/eng/regulations/SOR-96-334/page-3.html#h-6. See reference [25] for the U.S. definition.

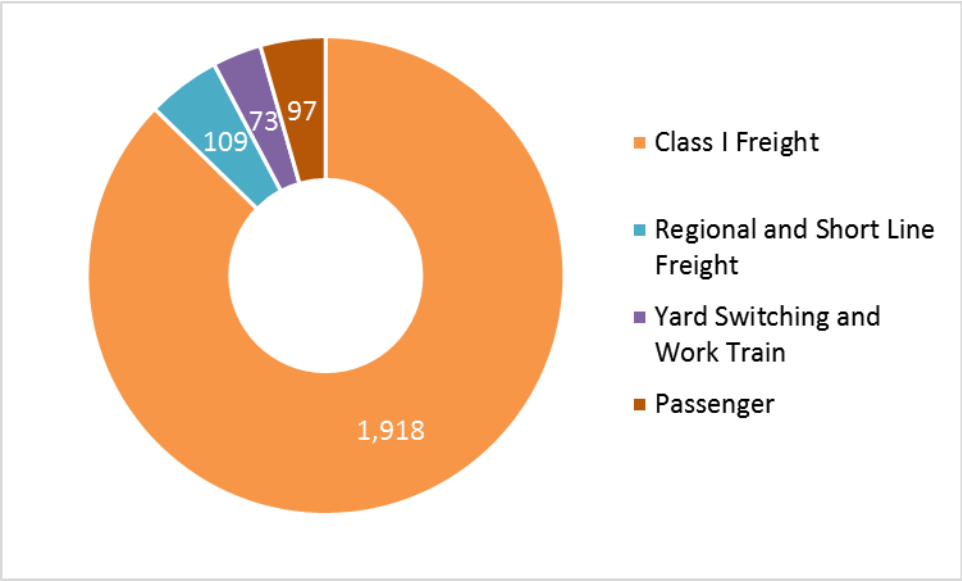

Figure 2 Diesel fuel consumption from Canadian railroads in 2014 (L thousands) [5].

Because the Class I freight railroads are responsible for the overwhelming majority of diesel fuel consumption, and therefore also fuel cost and emissions, this report will focus mainly on this segment of the Canadian rail industry.

CN and CP are ranked #4 and #6 amongst the North American Class I railroads in terms of revenue (see Figure 3).

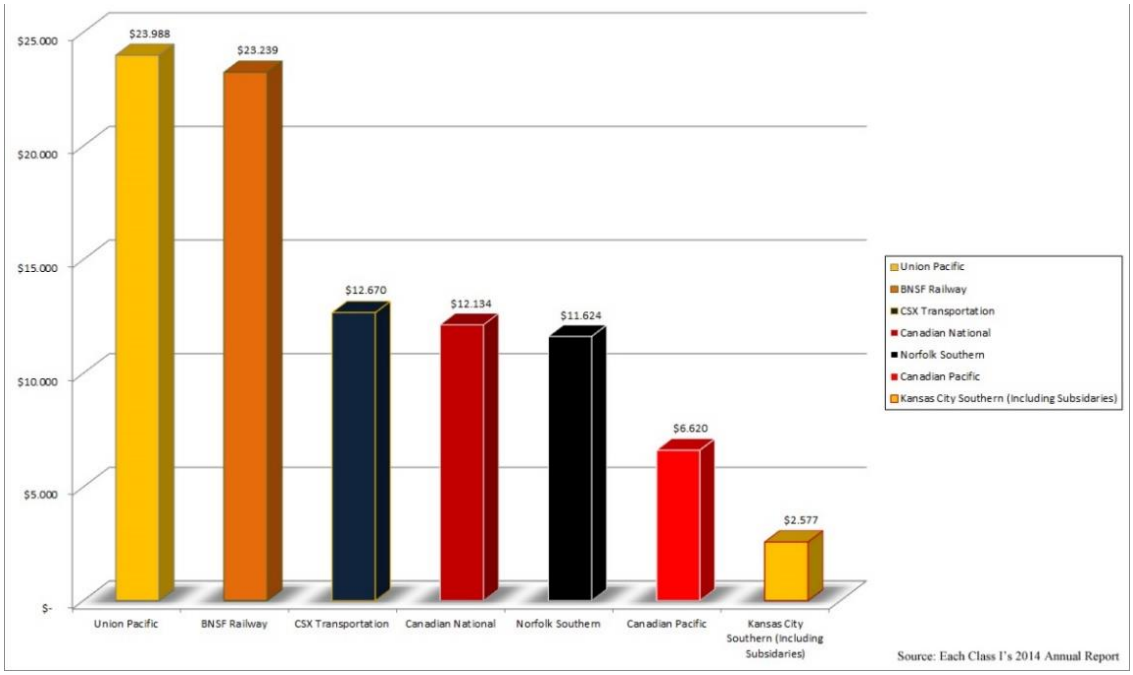

Figure 3 Class I railroad revenues in 2014 (USD billions) reproduced from [6].

The rail industry contribution to Canada's GHG inventory in 2014 was 6.6 M tonnes CO_{2e} or 4% of total transport emissions [7]. Mainline freight is responsible for the largest proportion of GHG emissions (92% or 6.1 million tonnes) [5].

The rail industry is responsible for a disproportionally larger share of criteria air contaminants (CACs), with NO_x emissions accounting for 9% of total Canadian transport emissions in 2008 [8]. By 2015 this had increased to 12% or 125 thousand tonnes [9]. This is due to the fact that other sectors of the transport sector have achieved greater reductions in NO_x emissions over the same time period and that carload volumes in the rail sector have increased.

Particulate Matter (PM) emissions from rail transportation in 2015 were 3,012 tonnes or 6% of total transport emissions in Canada [9].

1.2 Market and Competitiveness Issues

The rail freight industry business mix has seen a significant shift over the past 10 years. Figure 4 shows the dramatic increase in intermodal container traffic (primarily international) over the past 10 years and the declines in forest products, metals and paper products traffic. The industry has had to make investments in new products and services to react to this changing market demand. The three highest growth commodities (Intermodal, Manufactured & miscellaneous and Food products) all face competition from trucking.

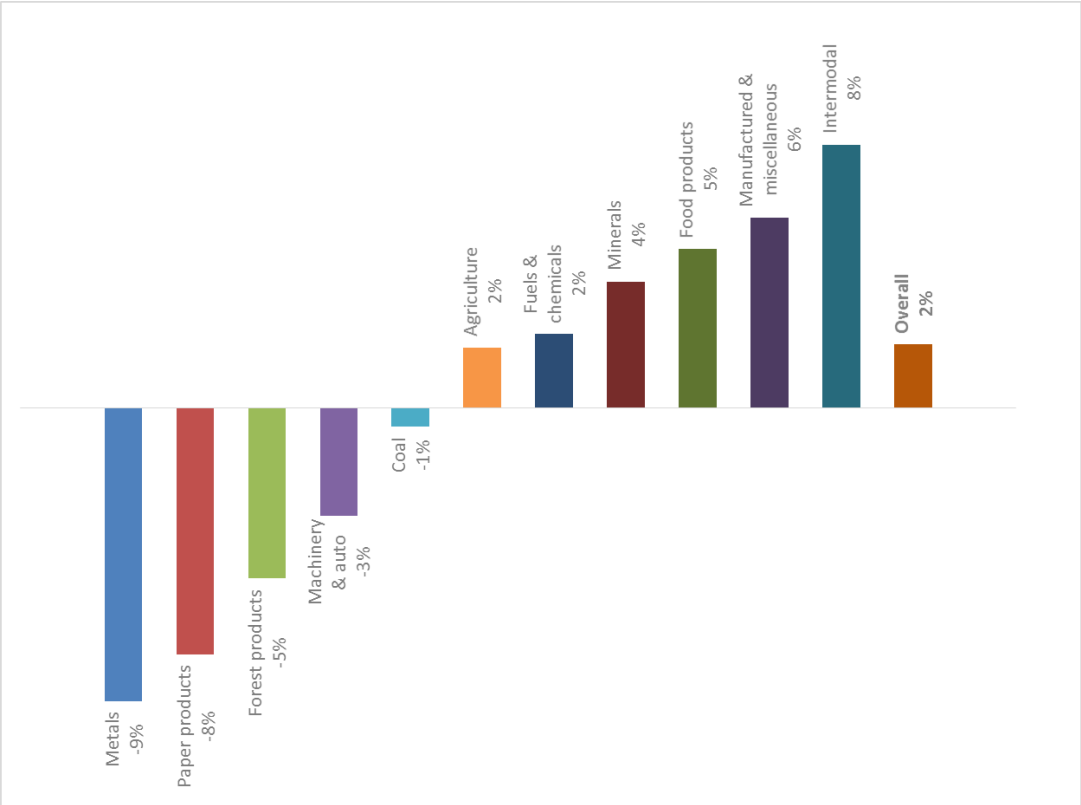

Figure 4 The changing face of Canadian railroad traffic: compounded annual growth rate 2006-2015 by commodity group [4].

Diesel fuel is a major portion of railroad operating costs. Figure 5 illustrates that, on average, fuel makes up 18% of railroad operating expenses.

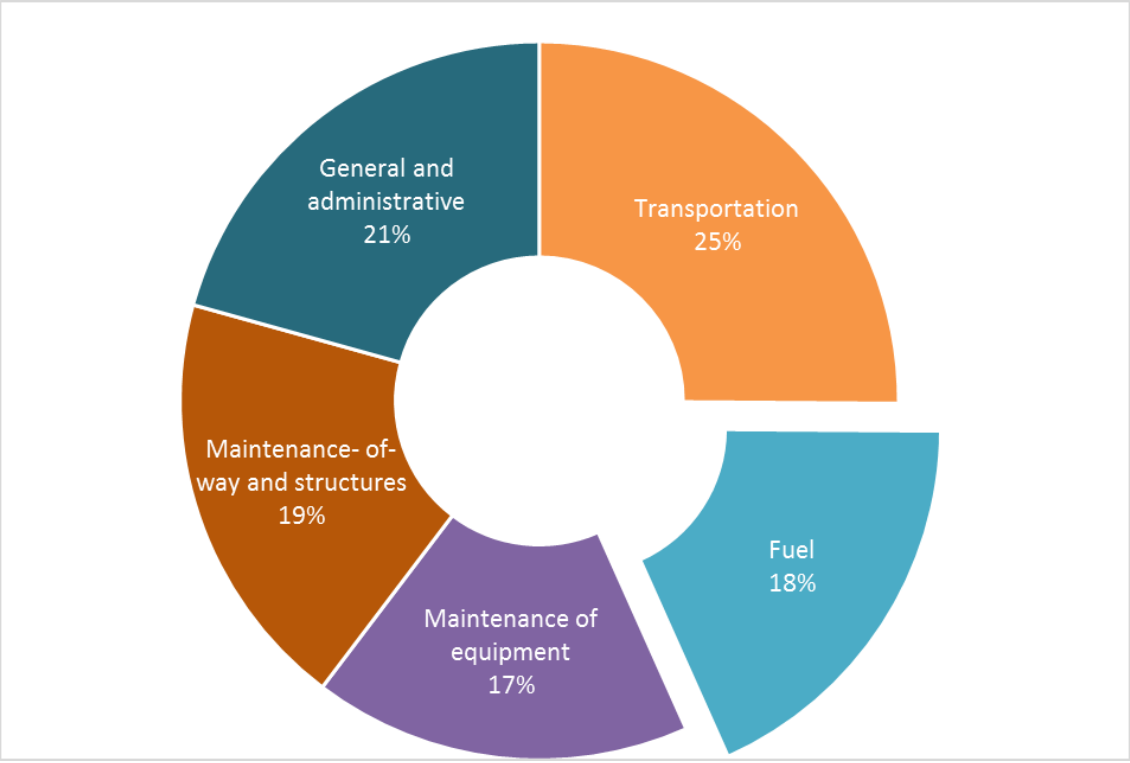

Figure 5 Canadian Railroad Operating Expense Breakdown[3] 2006-2015 Average [4].

Diesel fuel prices are volatile and subject to changes in global oil prices and exchange rate fluctuations. Consequently, fuel as a percentage of operating costs varies significantly from year to year increasing to greater than 20% in years where crude oil prices approached $100 and the Canadian dollar was weak. Fuel operating expense is closely correlated to the average price of crude oil. US Class I railroads see even larger variations in fuel operating expense percent with 2012 seeing the largest value in the past 10 years, with 28.6% of operating expenses spent on USD 11.5 B of fuel [10].

[3] Transportation costs are expenses incurred through the movement of rolling stock (locomotives, railcars, etc.) that are not reported under other operating expense categories.

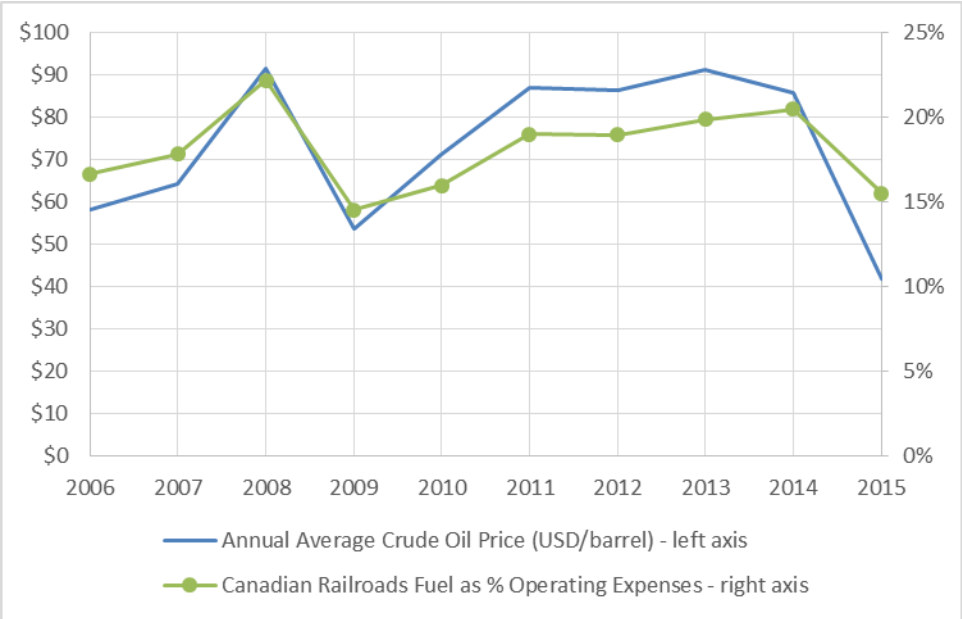

Figure 6 Variation in fuel as a percentage of operating expenses with oil price

Canadian railroads paid, on average, 82c/L of diesel over the period 2006-2016 [4]. This equates to $21.20 per Gigajoule (GJ). The high diesel prices in 2011 – 2014 was the principle driver of railroad interest in natural gas as a fuel. Recent price decreases in diesel fuel in 2015 and 2016 has diminished the economic case for using an alternative fuel, but the strong correlation of the diesel fuel price to oil prices allows us to project forward the expected price of diesel for Canadian railroads in 2016 and 2017. Figure 7 illustrates that the continued weak Canadian dollar combined with strengthening oil prices from their lows in 2016 will likely result in rail diesel prices once again approaching and exceeding the $1/L level, once again bringing fuel costs into sharp focus for Canadian railroads.

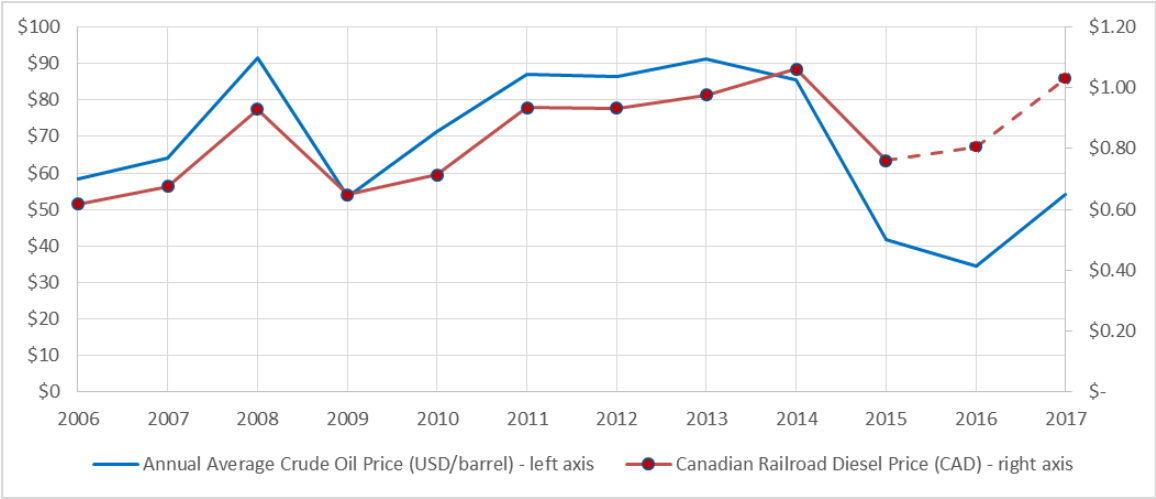

Figure 7 Canadian diesel fuel price: actual [4] and projected.

Figure 7 also illustrates the volatility in diesel price (44c/L between peak and trough over the 10 year period). Railroads concerned with this volatility will be interested in the potential for natural gas to provide a source of fuel with less price volatility. Since 2008, natural gas prices have remained relatively stable. Because the natural gas commodity cost is a smaller proportion of the overall LNG fuel price, LNG should be proportionately less volatile in price. See Section 2.1 for more detail on the relative prices of diesel and LNG.

IMPACT OF CARBON TAX

In March 2016, the Government of Canada proposed a pan-Canadian approach to pricing carbon pollution with a price on carbon starting at a minimum of $10 per tonne in 2018, rising by $10 per year to $50 per tonne in 2022.

In British Columbia, the current $30/tonne carbon tax is assessed according to the Ministry of Finance Bulletin MFT-CT 005 as follows:

Locomotive Fuel	7.67c/L
Natural Gas	1.4898 $/GJ
Natural Gas	5.76c/DLE[4]

In Alberta, a $20 per tonne tax came into effect 1 January 2017, rising to $30/tonne on 1 January, 2018. The published carbon levies for $30/tonne are as follows:

Diesel	8.03 c/L
Natural Gas	1.517 $/GJ
Natural Gas	5.81c/DLE

The likely carbon tax and the advantage offered by natural gas fuel for rail operators is calculated in the table below by extrapolating the average published values above.

Carbon tax [$/tonne]	$10	$20	$30	$40	$50
Diesel [c/L]	2.56	5.11	7.67	10.23	12.78
Natural Gas [c/DLE]	1.90	3.81	5.71	7.62	9.52
Difference [c/L]	0.65	1.30	1.96	2.61	3.26

Even at $50 per tonne, the potential saving of 3.26c/L would only equates to around $30,000 per locomotive per year (based on an average fuel burn of 963,000 L per year for a Class I freight locomotive) and is therefore unlikely to drive the decision to consider natural gas as an alternative fuel in isolation.

[4] Converted to diesel litre equivalent (DLE) using an energy intensity of 38.68 MJ/L

1.3 Regulatory Framework

TRANSPORT OF LNG BY RAIL

The transport of LNG by rail in Canada is permitted and is regulated by Transport Canada through the Transportation of Dangerous Goods (TDG) Act and the TDG Regulations. The TP14877 standard for railway tank cars is referenced in the TDG Regulations. It sets out tank car specifications for LNG transport. In addition to the DOT/TC113C120W tank car specification, there is also a TC113C140W standard. UN portable tanks, also called ISO containers, complying with the T75 instruction may also be used and CSA B625 is the standard for their design and use.

The equivalent transportation of dangerous goods legislation in the U.S. is the Federal Hazardous Materials Regulations (HMR) contained in Title 49 Code of Regulations (CFR) Parts 171-180. Currently 49 CFR 172.101 does not permit the transportation of LNG by rail either in a tank car or UN portable tank.

LNG FUEL TENDERS

With regard to the application of dangerous goods legislation to LNG tenders, the Federal Railroad Administration (FRA) published a clarification in a letter to BNSF dated 13 May 2013 [11]. It explains that 49 CFR § 171.8 contains an exemption for a fuel tank used only for supplying fuel to operate a transport vehicle or its auxiliary equipment. This exemption can be applied to LNG tenders. Canadian TDG regulations provide a similar exemption under SOR/2008-34 1.27 however its interpretation by Transport Canada for LNG fuel has not been publicly clarified. At present, Transport Canada issues equivalency certificates permitting the use of natural gas tenders on a case-by-case basis. This may be sufficient for pilot testing or small scale deployments of natural gas locomotives however it does not provide regulatory certainty to the rail industry if it were to pursue large scale adoption of natural gas as a fuel. An amendment to the TDG Regulations (or at least a clarification that the SOR/2008-34 exemption also applies to LNG tenders) would be required to allow the use of LNG fuel tenders for railway operations without the need for an equivalency certificate.

NATURAL GAS LOCOMOTIVES

Locomotives converted to be fuelled partially or fully on natural gas must meet the requirements set out within the *Railway Locomotive Inspection and Safety Rules*. The equivalent U.S. regulation is 49 U.S.C. Chapter 207, Locomotives - formerly known as the Locomotive Inspection Act (LIA).

Railroads wishing to operate natural gas fuelled equipment in the U.S. must conduct a comprehensive safety analysis and provide it to the FRA for approval. The procedure is clarified in the policy and guidance letter from 2013 [12]. It is not clear what additional requirements must be met to move from testing to full revenue service.

This report has not considered the regulatory framework for buildings (e.g. maintenance facilities) that vehicles carrying LNG or gaseous natural gas. Further research is required to understand the impact these regulations may have on the investment required by railroads.

PROPOSED LNG FUEL TENDER SPECIFICATIONS AND STANDARDS

Because several of the Class I railroads began to focus on natural gas as an alternative fuel in 2012, the AAR formed a Natural Gas Fuel Tender Technical Advisory Group (NGFT TAG) in October 2012. The TAG's mission is to develop AAR Fuel Tender Specifications and Standards to support the use of natural gas as an alternative locomotive fuel. Membership includes railroads and the AAR's Transportation Technology Centre Inc., along with the U.S. FRA, the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration. A number of component, railcar manufacturers and the locomotive OEMs participate as observer-participants. Representatives from Transport Canada are also included in the process. On 19 December 2016, the TAG published the following documents for comment in AAR Circulars C-12766 - C-12770[5]:

- Proposed new Specification M-1004, Fuel Tenders for Natural Gas and Other Alternate Fuels
- Proposed new Standard S-5025, Gaseous Natural Gas Supply Hose Unit for Natural Gas Fuel Tenders
- Proposed new Standard S-5026, Heat Exchange Fluid Hose Unit for Natural Gas Fuel Tenders
- Proposed new Standard S-5027, 21-Point Control Plug, Cable Assembly, and Receptacle (TC-21 Tender Control Cable)
- Proposed new Standard S-5028, Safety Appliances for Tank Car-Style Natural Gas Fuel Tenders

A comment period of 45 days was extended and following consideration of comments received by the TAG, the specification and standards will be implemented. The M-1004 specification and the related standards (S-5025 – S-5028) identify the tender's structural design requirements, operating performance, crashworthiness, fuel interfaces needed to supply natural gas to dual fuel locomotives, and fuelling interfaces needed to fuel the tender. In its initial format, the M-1004 specification has a chapter detailing the requirements for a tank-car style tender based on a DOT113C120W tank car. Tenders utilising a UN portable tank as the LNG storage tank can also be designed to the M-1004 standard according to the AAR representative responsible for the TAG. The NGFT TAG now plans to work on the additional chapters to the specification to cover CNG tenders.

Note that unless amended, the interconnect standards are only applicable for the current generation of dual fuel locomotive modification kits from GE and EMD and would not accommodate high-pressure gas or LNG to cross the tender-locomotive coupling potentially required for high-pressure direct injection fuel systems without further amendment to the specification.

[5] AAR Circulars are not public documents and are usually only available to AAR members, but because of the broader interest in Fuel Tenders, these circulars were made available to all interested parties.

1.4 Available Fuels and Specifics of their Use

The table below sets out the basic chemical properties of gaseous natural gas compared to diesel as a fuel for locomotive engines.

	Diesel	Natural Gas	Units
Specific Energy (LHV) [13]	42.91	45.86	MJ/kg
Energy Density [14]	38.68	0.0373	MJ/L
CO_2 Emissions Intensity [15]	74.1	56.1	tCO_2/TJ
Flash Point	74	-184	°C
Auto ignition Temperature	316	540	°C

It should be noted that the CO_2 emissions intensity suggests that on an equivalent efficiency combustion basis, tank-to-wheels emissions reductions of 24% are possible. A full lifecycle assessment of the GHG emissions is required to calculate the true GHG reduction potential that takes into account upstream well-to-tank emissions and the CO_2 equivalent of potential fugitive methane emissions (including exhaust methane slip). The auto ignition temperature of natural gas is higher than diesel which leads to the challenges of using it as a fuel in a conventional compression ignition engine. Though the specific energy looks attractive because more energy is contained per unit mass compared to diesel, the extremely low energy density of the fuel in its gaseous form quickly leads to the conclusion that it must either be compressed or liquefied for storage to make sense in a vehicle context.

In considering both LNG and CNG, the table below illustrates the relative properties compared to the reference diesel fuel.

	Diesel	LNG	CNG
Storage Pressure	1 bar	8 bar	250 bar
Storage Temperature	Ambient	-160°C	Ambient
Energy Density	35.8 MJ/L	22.2 MJ/L	9 MJ/L

In order to achieve the improved energy densities of CNG and LNG compared to gaseous natural gas, cryogenic temperatures (in the case of LNG) and high pressure (in the case of CNG) are required. The tanks, required to maintain the low temperature or high pressure respectively, add additional mass and volume to the fuel tank system compared to diesel, thereby reducing the effective energy density and specific energy available. The effect on energy density is exacerbated because of the cylindrical form factor required for the CNG and LNG tanks which makes them unable to make efficient use of rectangular spaces like the fuel tank on a mainline diesel locomotive.

Because of the superior energy density of LNG over CNG, most railroads have concluded that LNG is the best candidate for mainline freight operation. Because of the additional space required to achieve an equivalent energy quantity of fuel to the amount of diesel currently used, there is insufficient room on the locomotive to store sufficient LNG fuel to achieve the range required between refuelling of a line haul freight locomotive. An LNG tender is therefore required coupled to the locomotive (or

locomotives) that it provides fuel for. Those railroads also considering CNG as a storage means for shorter range operations (Norfolk Southern) have also concluded that a CNG tender arrangement is required. For yard switching, CNG storage on the locomotive may be possible.

The impact on the train operation (range, train length, additional tonnage) of the chosen fuel storage medium for natural gas fuel (LNG or CNG) depends on a number of factors:

a) Engine efficiency in natural gas mode
b) Diesel substitution %
c) Fuel tender capacity
d) Fuel tender configuration

Consideration will be given to these factors and their impact on railroad operation in Section 1.5 below.

1.5 Equipment and Approaches for Natural Gas

Canadian Locomotive Inventory Analysis

Of the 2,700 locomotives active in Canada in 2014, 239 were engaged in passenger operations, with the remaining freight locomotives deployed as follows [5]:

1,961 in Class I freight service

288 in Regional and Short Line freight service

212 in Yard Switching or Work Train service

Reference [5] provides a detailed inventory of locomotives in Canada from 2014 by manufacturer and model. Based on this data, the manufacturer market share distribution of the existing locomotive inventory can be calculated. Figure 8 shows that locomotives are relatively evenly distributed between the two main manufacturers, Caterpillar's Electro-Motive Diesel (EMD) and General Electric (GE). The majority of the older diesel locomotives (pre 1990 year of manufacture) were manufactured by EMD. Locomotives are long-lived assets and undergo remanufacture in preference to replacement.

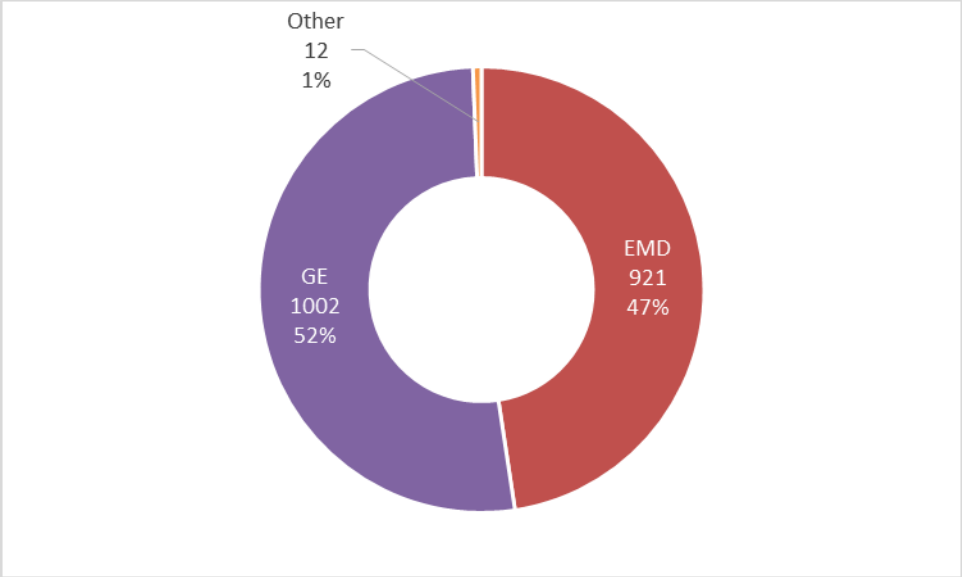

Figure 8 Mainline freight locomotive installed base engine manufacturer market share 2014

Combining the manufacturer model information with annual diesel fuel consumption figures for categories of locomotives provided in reference [5], a model of individual locomotive fuel consumption can be created. The model focuses on the 4 major varieties of engine used to power the Class I mainline freight locomotive fleet:

EMD 645: The previous generation of EMD's 2-stroke diesel engine with 645 cubic inches engine capacity per cylinder. It was used in EMD's popular GP-40 and SD-40 locomotive series manufactured up to the mid-1980s with a maximum of 3,800 hp in a V16 configuration

EMD 710: A more powerful 2-stroke diesel engine with 710 cubic inches capacity per cylinder. Used in EMD's SD-60, SD-70 series locomotives up to the present day. Recently superseded by EMD's new V12 4-stroke 1010 engine.

GE FDL: Refers to GE's previous generation 16-cylinder 4-stroke engine used to power the popular Dash8 and Dash9 locomotive series up to around 2005/6.

GE EVO: Refers to the latest generation of GE 12-cylinder 4-stroke engine used to power the Evolution series ES44 locomotives up to the present day.

Using the average horsepower and a utilization factor that takes into account the fact that more modern reliable locomotives have higher utilizations that their older counterparts, the average fuel consumption for each locomotive subtype can be estimated. The model is shown in the table below:

	Number of Locomotives	Average hp Rating	Utilisation Factor	Fleet Annual Fuel Usage (L thousands)	Average Locomotive Fuel (L thousands/ year)	Locomotive Annual fuel Cost ($ thousands)
Class I Freight	**1,992**			**1,918**	**963**	**790**
Mainline	1,647			1,813	1,101	902
EMD 645	227	2562	80%	149	658	540
EMD 710	475	4238	90%	582	1225	1,005
GE FDL	597	4174	80%	640	1073	880
GE EVO	348	4380	90%	441	1267	1,039
Road Switcher	345	1900	50%	105	305	250
Regional and Short Line Freight	**288**			**109**	**380**	**311**
Switching and Work Train	**212**			**73**	**345**	**283**
Passenger	**230**			**97**	**422**	**346**

Number of Locomotives: Data from Locomotive Emissions Monitoring (LEM) Program 2014 Report [5]

Average hp rating: Calculated from fleet data in Appendix B-2 of the LEM Report

Utilisation factor: Model assumption

Fleet Annual Fuel Usage: Category data is from the LEM Report. Engine model grouping data is calculated a function of (Number of Locomotives x Average hp rating x Utilisation Factor)

Average Locomotive Fuel: The estimated average fuel used by an individual locomotive in this category calculated as Fleet Annual Fuel Usage/Number of Locomotives.

Locomotive Annual Fuel Cost: The estimated annual cost to the railroad to provide fuel for a locomotive in that category calculated as Average Locomotive Fuel x Fuel Price, where Fuel Price is the average over the period 2006 – 2016 of 82c/L

The results are summarized in the chart in Figure 9 below and show that high horsepower mainline freight locomotives have the highest annual fuel consumption. The 1,420 locomotives this subgroup are powered by only 3 engine types (EMD 710, GE FDL and GE EVO) in 5 locomotive models. These high fuel burn locomotives cost the railroads around $1 million per year on average to fuel.

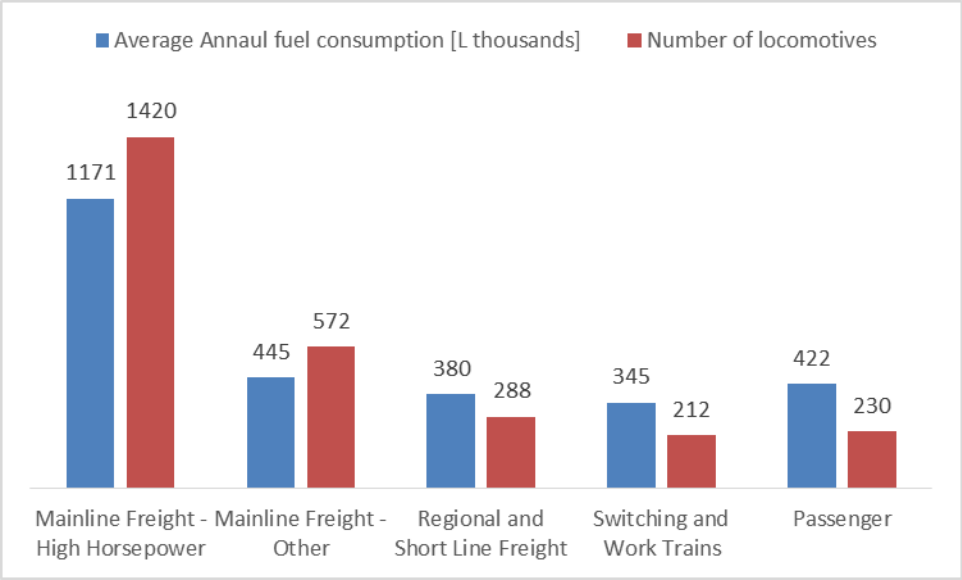

Figure 9 Calculated average annual locomotive fuel consumption and population

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Locomotive technology approaches

This section summarizes the locomotive engine technologies deployed or tested in North America.

Aftermarket Dual Fuel Conversion Kit

The most popular aftermarket dual fuel conversion kit trialed in North America is produced by Energy Conversions Incorporated (ECI). The ECI 645E-DF kit is available for the EMD 645 engine and includes modified pistons to reduce the compression ratio and a modified cylinder head to permit gas injection. Reported emissions results on the company web page indicate increased CO levels and NOx and PM levels in the range of EPA Tier 2 standards. Engine efficiency decreased because of the modified pistons and methane slip (defined as the percentage of natural gas injected passing un-combusted into the exhaust system) was significant (~8%). The ECI conversion is not sanctioned or supported by the OEM. The kit was most recently tested by CN in its 2013 pilot project as described below. Railroads are now more focused on the conversion kits released and supported by the OEMs.

Aftermarket Spark Ignited Conversion Kit

Energy Conversions Inc. also produces a spark ignition conversion kit to convert an EMD 645 engine into a dedicated gas engine. The ECI 645SIP kit includes modified pistons to reduce the compression ratio and a modified cylinder head to permit gas injection. The diesel injectors are replaced by a pre-chamber spark ignition system. The ECI conversion is not sanctioned or supported by the OEM. The kit is currently undergoing testing by Norfolk Southern. Spark ignited engines are not viewed as a viable solution for mainline freight locomotive operation due to their reduced power density compared to diesel.

GE NextFuel

GE has developed a dual fuel version of the 12 cylinder EVO engine. The GE NextFuel product includes individual gas injectors positioned in the air intake of each cylinder, replacing a portion of the diesel fuel with natural gas. The product is available as a conversion kit. When running in gas mode, the product currently achieves 50% diesel substitution on the AAR duty cycle at EPA Tier 3 emissions. PM is reported to be significantly lower in dual fuel mode that the Tier 3 emissions limit of 0.1 g/bhp.hr limit and approach Tier 4 standards. A diesel oxidation catalyst is used to control CO. The OEM does not report the increase in specific fuel consumption due to the dual fuel system. GE NextFuel locomotives have accumulated 136,000 miles of running with no loss of performance and comparable reliability to a diesel locomotive. An upgrade to the NextFuel product is under development that will achieve up to 80% substitution and reduced methane slip percentage. The NextFuel product is currently available on all Tier 2+/Tier 3 EVO powered locomotives. GE plans to move to develop a dual fuel conversion kit for the popular FDL engine used in the older Dash 8 and Dash 9 locomotives subject to customer demand. GE will also evaluate a Tier 4 gas solution subject to sufficient customer interest.

EMD Dynamic Gas Blending (DGB)

EMD has developed a dual fuel version of the popular 16-cylinder 2-stroke 710 engine. The EMD DGB product includes individual gas injectors positioned in a scavenge port of each of the cylinders, as shown in Figure 10, replacing a portion of the diesel fuel with natural gas. The kit is reported to be capable of 60-65% diesel fuel substitution at EPA Tier 3 emissions with confidential values of methane slip when running in gas mode. The OEM also does not report the increase in specific fuel consumption due to the dual fuel system. The EMD DGB kit is available for all 710-series 16-cylinder engines if they are upgraded to the latest electronic control standard. EMD has accumulated over 90,000 miles of field testing and reports no major reliability issues with the system.

Figure 10 EMD DGB system introduces gas through the scavenge port of the 2-stroke engine. [Image: EMD]

EMD Direct Injection Gas

EMD has developed a high-pressure direct injection gas version of the 16-cylinder 710 engine using technology licensed from Westport Innovations in a May 2012 deal. The engine relies on a diesel pilot injection for ignition (less than 5% of fuel). The engine is reported to achieve almost 0% (undetectable) levels of methane slip in the exhaust and to improve the fuel efficiency (and therefore specific fuel consumption). EMD reports CO_{2e} reductions in emissions of 25%. EMD is testing this technology in a durability test cell, as shown in Figure 11, and has also built a prototype locomotive with this technology installed. Plans for field testing are subject to customer interest and provision of a suitable LNG tender capable of supplying the high-pressure natural gas required.

Figure 11 EMD direct injection gas durability engine in test cell. [Photo: EMD]

Tender technology approaches

A tender refers to a rail vehicle coupled to one or more locomotives for the purposes of supplying fuel. The term originated during the steam era when tenders carried coal and water for the steam engine. UP and Burlington Northern ran diesel tenders in service during the 1980's and 1990's.

In an LNG tender, the natural gas fuel is stored as a cryogenic liquid at -162°C in a vacuum-insulated double-walled tank. The tender must be equipped with a means of warming the LNG to vaporize it ready for injection into the engine. Locomotives are therefore equipped with a secondary glycol filled coolant loop that transfers heat from the engine cooling system to the vaporizer on the tender by circulating the coolant to the tender by means of an electrically driven pump on the locomotive. In order to increase the pressure in the fuel sufficiently to achieve the desired flow rate and pressure to the locomotive engine, tenders are equipped with a pressure-build-up unit that vaporizes a small portion of the LNG to produce pressure in the tank, an electrically driven pump, or both. Tenders therefore also require electric power, controls linkages and pneumatics (air) for brakes and control valves.

Two strategies have emerged for LNG tender configuration:

LNG ISO tank tender

The ISO tank tender is based on a repurposed intermodal well car. The LNG is stored in a UN portable tank (often called an ISO tank because its dimensions conform to the International Standards Organization shipping container standards). 40' ISO tanks are the traditional means of storage which can provide approximately 40m^3 of LNG.

In the CN design built using Westport equipment, the tank and the gas conversion equipment is mounted in the recessed 48' well of the intermodal car and covered by protective shielding as can be seen in Figure 12 and Figure 20. BNSF also purchased

a number of LNG fuel tenders with this 48' well car design, though without the protective shielding in the CN design.

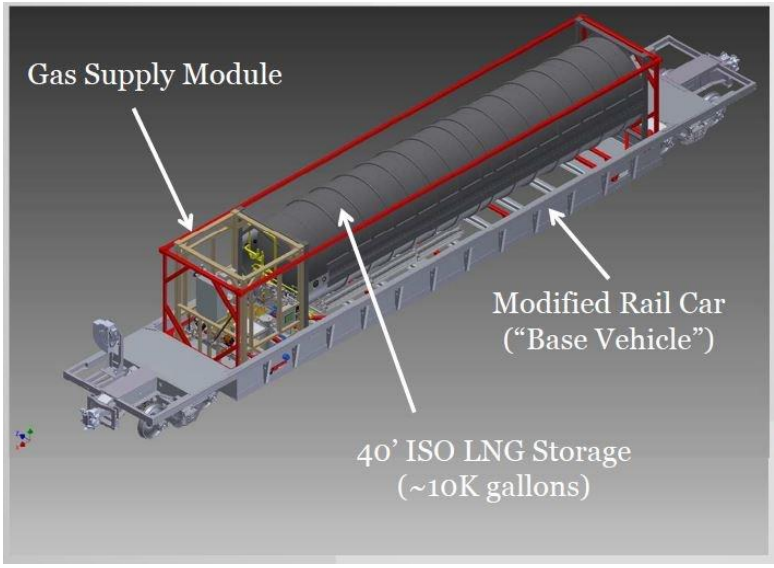

Figure 12 CN tender design using intermodal well car. [Image: Westport]

In the Chart design, pictured in Figure 13, ordered by Florida East Coast Railway (FECR), only the UN portable tank is mounted in the recessed 40' well and the gas conversion equipment is mounted on either end of the intermodal car reducing the car length by approximately 8'.

40m^3 of LNG stored in an ISO tank tender can provide approximately 6,000 diesel gallon equivalent (DGE) energy units. By comparison, a typical modern 4,400 hp mainline EMD or GE freight locomotive has a diesel fuel tank with 5,000 gallon capacity. A tender with this capacity supplying locomotives with natural gas at 60% diesel substitution will have approximately the same range as a locomotive equipped with a 5,000 gallon diesel tank.

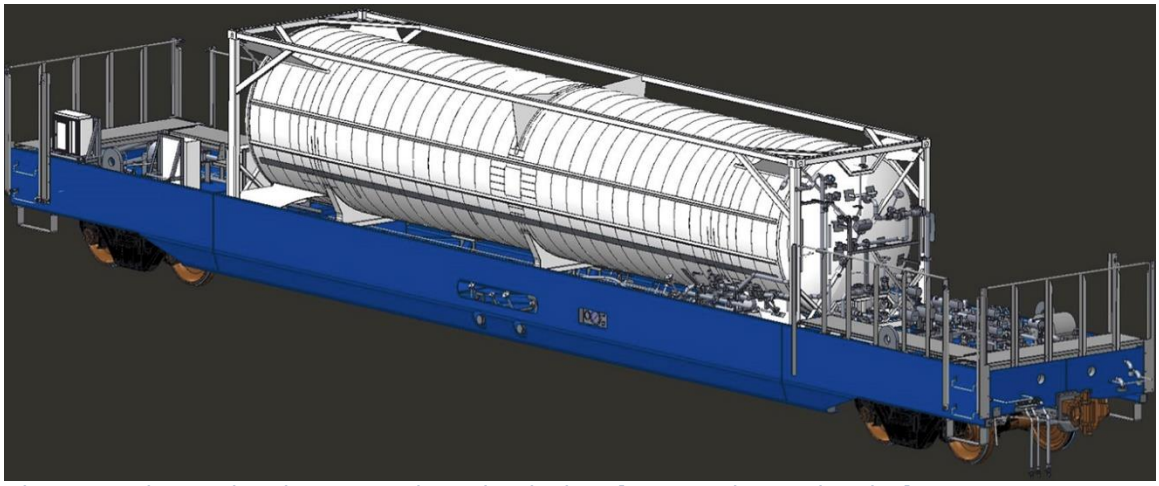

Figure 13 Chart Industries ISO tank tender design. [Image: Chart Industries]

LNG tank tenders

The first LNG tenders were based on a tank car design. The units for Burlington Northern during the Powder River Basin coal service trials (Figure 14) and UP tenders ordered for the advanced gas combustion program (Figure 15) were both of a tank configuration with a so called *through sill* or *under sill* forming the backbone of the tender, as opposed to the *stub sill* design utilized by popular DOT111 and DOT113 tank cars where the tank itself carries the longitudinal loads.

Figure 14 Burlington Northern tank tender. [Photo: Chart Industries]

Figure 15 UP tank tender. [Photo: Chart Industries]

Specialty cryogenic equipment manufacturer Chart Industries has a long history in manufacturing both LNG tenders and LNG tank cars, and has taken a leading role providing inputs to the AAR task force creating the standard for LNG fuel tenders. In addition, major railcar manufacturers have shown an interest in this market for LNG tenders. In particular, Trinity Industries has played a leading role, having acquired WesMor Cryogenics in January 2014. Other manufacturers involved in LNG tender discussions include INNOX CVA, Greenbrier and Hitachi High-Tech.

Tank tenders designed to the new AAR M-1004 specification would have a capacity of 29,325 gallons of LNG. When converted to diesel equivalent energy, this equates to approximately 17,500 DGE. Even if required to supply two locomotives with 100% gas, such a tank tender could achieve 75% greater range than a conventional diesel

locomotive equipped with a 5,000 gallon fuel tank[6]. A dual fuel locomotive using both diesel and LNG would be capable of 2.75 times that of a locomotive using diesel alone, opening the possibility of improved operational efficiency of trains (fewer stops for refuelling) and more concentrated capital investment in LNG refuelling infrastructure.

Price estimates for LNG tank tenders vary considerably depending on the configuration and quantity. No firm orders have been publicized for tenders designed to the new AAR M-1004 specification.

Current natural gas locomotive deployment projects

Several major North American railroads have embarked on projects to conduct pilot testing, and in some cases utilise natural gas in revenue service. The major projects are summarised below.

BNSF

Since 2013, BNSF has been testing dual fuel natural gas products from both EMD and GE. BNSF has refurbished and modernized tank tenders from the original Burlington Northern[7] natural gas locomotive trials in the 1990's to provide fuel. Figure 16 shows the tender coupled to two EMD SD70 locomotives converted using the DGB system described below. BNSF testing has provided important information for other AAR member railroads, locomotive OEMs and tender manufacturers through the AAR task force that has been formed around the NGFT TAG.

Figure 16 BNSF refurbished LNG tank tender with EMD SD70 DGB locomotives. [Image: Trains Magazine]

[6] 17,500 gallons / 2 = 8,750 gallons. 8,750 is 75% larger than 5,000.
[7] Burlington Northern is the predecessor company of BNSF

Florida East Coast Railway (FECR)

In 2014, as part of a large fleet renewal program, FECR purchased 24 GE ES44C4 “gas ready” Tier 3 diesel locomotives. ISO tank style tenders were purchased from Chart Industries. The LNG fuel tender and locomotive are show in Figure 17.

Figure 17 FECR ISO tank style LNG tender and GE NextFuel locomotive. [Image: FECR]

Approval from the FRA for revenue service operation was obtained in June 2016. GE reports that 12 locomotives have been converted with 4 more in the process of conversion as of the date of this report. All 24 locomotives are expected to be converted by the end of 2017. The locomotive conversions are being carried out at the FECR maintenance facility, however the engine conversion is being carried out at a GE facility.

As part of the project, FECR has built and commissioned a fixed LNG refuelling station for LNG tenders and is using this to refuel the tenders as shown in Figure 18.

Figure 18 FECR LNG tender refuelling station. [Photo: GE]

CN

In 2013, CN retrofitted two EMD SD40 locomotives with the ECI 645E-DF conversion kit. The locomotives operated with a tender provided by UP on a 300km run between Edmonton and Fort McMurray. Figure 19 shows the two locomotives in consist with the LNG fuel tender. The trial was subsequently decommissioned and the tender returned to UP.

Figure 19 CN Converted SD40s in consist with LNG fuel tender. [Image: HHP Insight]

In 2014, CN converted two EMD SD70 locomotives with the EMD DGB conversion kit. CN built four ISO tank tenders with equipment purchased from Westport (manufactured in partnership with INNOX CVA) and operated the locomotives briefly on the same track between Edmonton and Fort McMurray. The locomotives have subsequently been returned to diesel service and two of the tenders are still stored in Edmonton as shown in Figure 20

Figure 20 CN tenders purchased for EMD DGB trial currently stored in Edmonton. [Photo: Canadian Rail Observer]

Norfolk Southern

Norfolk Southern has converted an EMD GP38 locomotive using an ECI 645SIP kit. Fuel is provided by a converted locomotive underframe coupled to the gas locomotive with CNG tanks installed. Norfolk Southern has stated that they do not currently see a prospect for building additional units.

Indiana Harbor Belt

Indiana Harbour Belt railroad ran an extensive procurement competition from 2013 to 2016 to select vendors to convert 21 EMD SW1500 switchers to run on CNG. According to HHP Insight [16], R.J. Corman Railpower Locomotive has been selected to re-engine each locomotive with a pair of Caterpillar C18 engines converted to dual fuel operation using a relatively unknown kit provided by OptiFuel Systems. Very little public information is available about the OptiFuel system. The initial project scope was to use Cummins QSK19L engines with EcoDual kits. The locomotives will be equipped with onboard CNG cylinders for fuel storage. A previous plan to convert 10 GP-40 locomotives using Cummins QSK38L engines with EcoDual kits appears to have been abandoned.

Section 2: Drivers for Exploring Natural Gas and Potential Benefits

2.1 Economic Outlooks and Benefits

The economic opportunity of utilising natural gas as a fuel for rail is illustrated in Figure 21 below reproduced from the NEB Energy Outlook report. A sustained price gap of more than $10 per GJ between diesel and natural gas has been maintained since 2011.

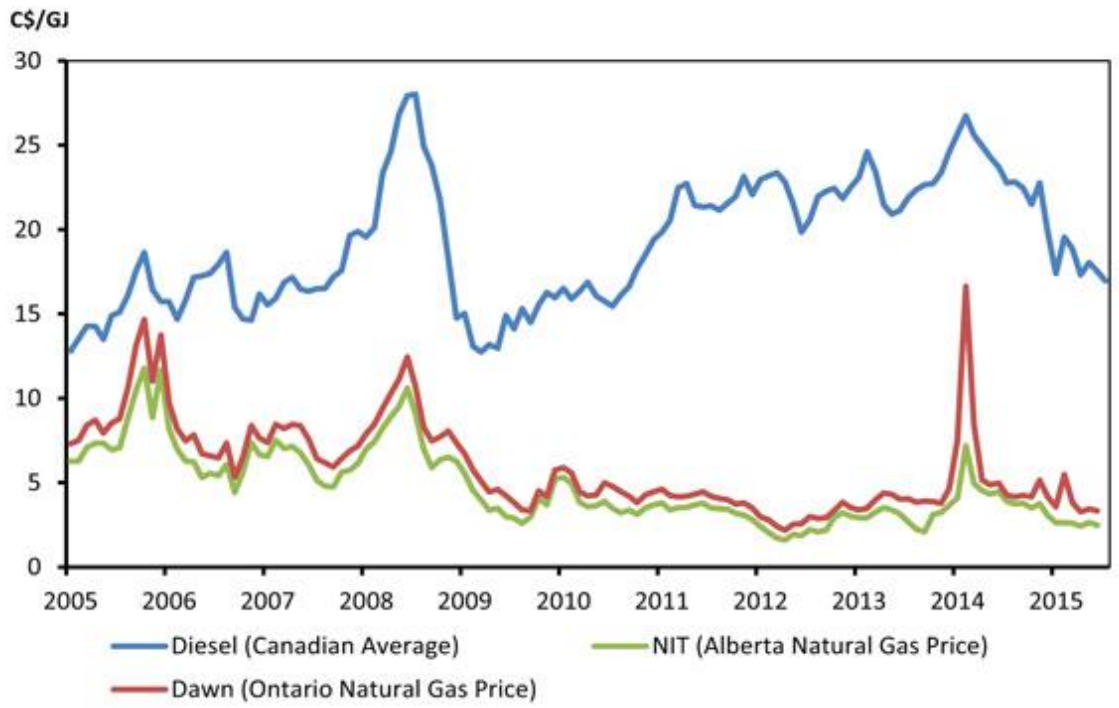

Figure 21 Wholesale diesel vs. natural gas prices [17].

However, to convert the natural gas into usable fuel it must be liquefied, the fuel tenders acquired and the locomotives converted to burn natural gas in favour of diesel. How much do these incremental costs eat into the price gap illustrated? To illustrate how these additional costs impact the economics, a model of total locomotive fuel price can be constructed including amortized capital and incremental operating expenses incurred. This is by no means a comprehensive analysis and is only intended to provide a directional framework for the opportunity assessment. Further work is required to complete a more detailed assessment.

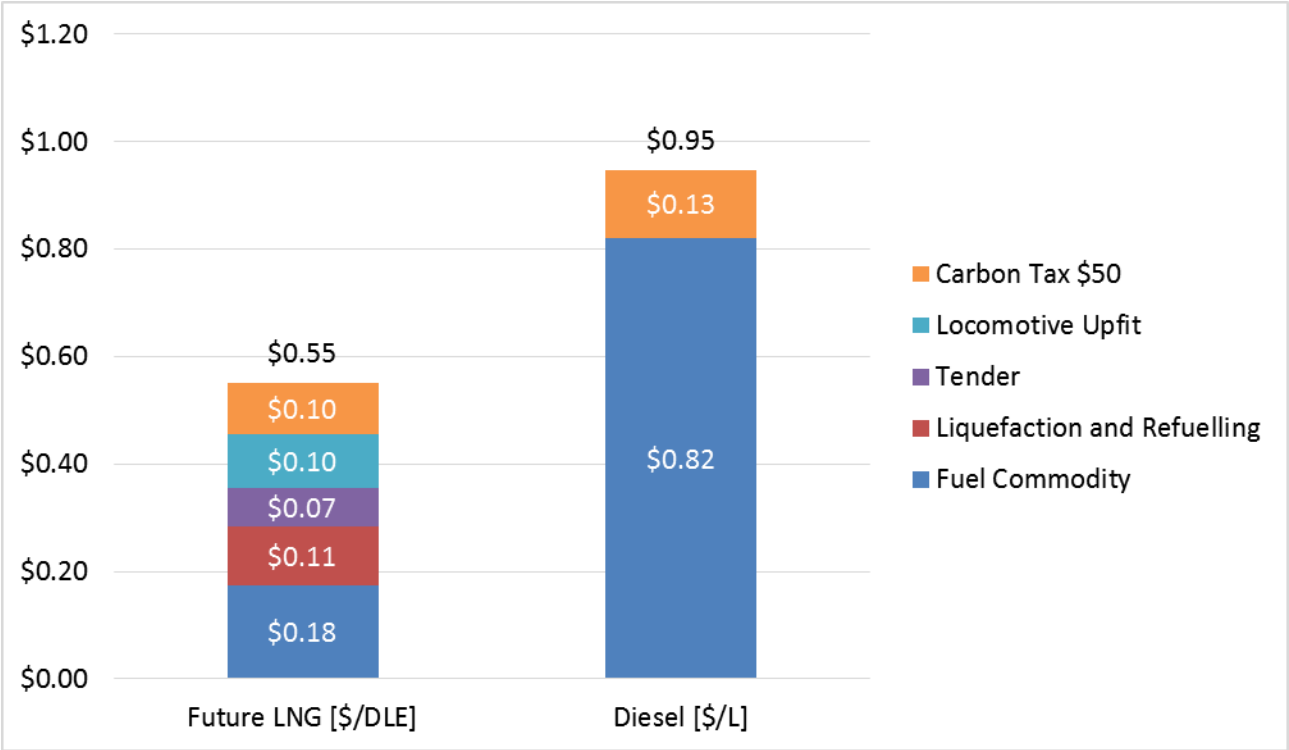

Figure 22 Comparison of LNG cost to diesel including carbon tax.

Figure 22 shows the comparison between the future price of LNG compared to diesel if the strategy outlined in the assumptions below were followed. It indicates a potential saving of 44% for this future LNG price compared to diesel. The assumptions used to derive these results are provided below and are based on industry estimates for a dedicated small to medium scale liquefaction facility constructed adjacent to the rail yard to eliminate any truck transfer of LNG. Transportation can add anywhere from 10c/DLE to 30c/DLE depending on the length of haul required by the road tanker truck. This is why it is essential to collocate the liquefaction facility with the rail refuelling facility. Current LNG prices including road tanker delivery are approximately $0.70/DLE which would only represent a very small saving compared to rail diesel. The assumptions used to calculate the Future LNG price are set out below:

Liquefaction and refuelling	
Capacity	400,000 L/day
Capital Cost	$80m
Utilisation	60%
Depreciation Period	20 years
Annual Capital Amortization Cost	$1.18 / GJ
Operating Cost	$1.65 / GJ

Locomotive

Conversion cost[8]	$600,000
Depreciation period	10 years
Annual maintenance cost	5% of initial cost
Diesel Substitution	75%

Tender

Tender cost	$800,000
Depreciation period	15 years
Annual maintenance cost	5% of initial cost
Locomotives per tender[9]	1.5

Fuel Prices

Diesel	$0.82/L 10 year Canadian rail diesel average
Exchange Rate	0.75 USD/$
Natural Gas	$4.53/GJ 10 year average of NEB reference projection
Carbon tax	$50/tonne

A sensitivity analysis to diesel price and diesel substitution percentage is presented in Section 2.2 below, however by continuing to use the reference case presented above it is possible to estimate the investment required and economic benefit in reduced transportation cost for Canada. The locomotive population model from Section 1.5 is used to simulate a scenario where the highest fuel burn mainline freight locomotives powered by engines with conversion kits are either in production or planned by OEMs are converted to run on natural gas. The locomotive population subset and its calculated fuel consumption is summarised in the table below.

Locomotive	Engine	2014 Population [Number of locomotives]	Estimated total annual fuel consumption [L millions]
EMD SD60/SD70	710	475	582
GE Dash8/Dash9	FDL	597	640
GE ES44	EVO	348	440
TOTAL		1,420	1,663

[8] Refers to the cost of the kit plus the cost of upfit to the locomotive.
[9] Many line haul freight locomotives operate in distributed power applications in the middle or at the rear of the train where they will require a dedicated tender. In addition, locomotive consists may be made up of 3 locomotives where the 3rd locomotive will require its own tender. A nominal value of 1.5 was used as a midpoint between shared tender 2.0 and dedicated tender 1.0.

Using the assumptions presented above, the investment values and economic benefits for this group of 1,420 locomotives is calculated below.

Investment:

Investment Item	Investment ($ thousands)	Locomotives Served	Cost per loco ($ thousands)	Total for fleet of 1,420 ($ millions)
Liquefaction and Refuelling	80,000	98	814	1,156
Locomotive Conversions	600	1	600	852
LNG Fuel Tenders	800	1.5	533	757
Total			**1,947**	**2,765**

Economic benefit:

Annual savings $500 million[10]

[10] Calculated based on 1,663 million litres of diesel burned annually by the target population of 1,420 locomotives, 75% diesel substitution and 40c/L price difference.

Environmental Benefit

Criteria Air Contaminants

The US EPA line haul locomotive emissions standards [18] together with EPA estimates for non-regulated emissions are presented in the table below.

US EPA Line Haul Locomotive Emissions Standards [g/bhp.hr]

Tier Level	Year	HC	CO	NO_X	PM
Non-regulated		0.5	1.5	13.5	0.34
Tier 0	2000	1.0	5.0	9.5	0.6
Tier 0+	2008	1.0	5.0	8	0.22
Tier 1	2002	0.55	2.2	7.4	0.45
Tier 1+	2008	0.55	2.2	7.4	0.22
Tier 2	2005	0.3	1.5	5.5	0.2
Tier 2+	2008	0.3	1.5	5.5	0.1
Tier 3	2011	0.3	1.5	5.5	0.1
Tier 4	2015	0.14	1.5	1.3	0.03

Based on OEM supplied data, HC, NO_x and CO for natural gas locomotives converted using the OEM dual fuel kits are able to achieve Tier 3 emissions standards but with PM at Tier 4 levels. An alternative CO standard is available under Part 1033.101 (i) of the regulations that allows manufacturers to meet an alternative CO standard of 10g/bhp.hr if a lower PM standard is met. For Tier 3 and Tier 4 locomotives, the lower PM standard is 0.01g/bhp.hr. This is a 67% reduction on Tier 4 PM levels and current emissions performance from dual fuel locomotives do not meet this standard which means than manufacturers cannot use the alternative standard and must use a diesel oxidation catalyst to control CO. Note also that in the locomotive emissions standards, HC is defined as non-methane hydrocarbons and the EPA has clarified that the other constituents of natural gas (e.g. ethane, pentane, butane) count as methane hydrocarbons and therefore do not count towards HC emissions. As a result, the presence of methane slip does not impact the capability of natural gas locomotives to meet the CAC emission standards.

The current emissions standard of the 1,420 target locomotives based on 2014 data is as follows [5]:

	Non-regulated	Tier 0	Tier 0+	Tier 2	Tier 2+	Tier 3	Total
EMD SD60/SD70 : 710	48	83	171	122	51		475
GE Dash8/Dash9 : FDL	23	65	185	28	295	1	597
GE ES44 : EVO				181	104	63	348
Total Locomotives	71	148	356	331	450	64	1,420

Using the difference between the current Tier standard and the natural gas engine emissions performance, an emissions improvement profile can be calculated for each locomotive group. The percentage reduction expected by converting from diesel to an OEM natural gas conversion kit with Tier 3 NO_x and Tier 4 PM emissions for each current emissions tier level is shown in the table below:

Current Tier	NO_x	PM
Non-regulated	59%	91%
Tier 0	42%	95%
Tier 0+	31%	86%
Tier 1	26%	93%
Tier 1+	26%	86%
Tier 2	0%	85%
Tier 2+	0%	70%
Tier 3	0%	70%

The current (2014) NO_x and PM emissions for each locomotive subgroup are calculated by distributing the total emissions to each type using the fuel burn calculations presented in Section 1.5. The percentage reductions shown in the table above are then applied. Using this method, it is calculated that converting Canada's mainline freight locomotives to natural gas would reduce NO_x emissions by 30% on average. Just converting the 1,420 locomotives in the target group would reduce NO_x emissions by 15,875 tonnes annually, or 13% of the total rail NO_x emissions set out in Section 1.3.

For particulate matter, the reductions are more dramatic with an average reduction of 88%. For the 1,420 locomotives in the target group, particulate matter emissions would be reduced by 1,269 tonnes which would create a reduction in total rail particulate matter of 42% from the total emissions set out in Section 1.3.

Greenhouse Gas Emissions

The first generation of dual fuel natural gas engine conversion systems under test by North American railroads do not currently produce a net CO_{2e} benefit when the impact of methane slip is assessed. Methane slip is particularly damaging to the GHG emissions because the global warming potential of methane is 25 times greater than that of CO_2 over a 100-year time horizon based on the IPCC's Fourth Assessment Report. With updates to the technology, particularly the next release of the NextFuel product from GE where methane slip is reduced and diesel substitution increased to greater than 75%, it is likely that the CO_{2e} emissions will be comparable to or better than the base diesel.

The EMD Direct Injection Gas Technology (see Page 16) is capable of achieving 25% CO_{2e} reductions on a tank-to-wheels basis because of the high substitution and extremely low methane slip. GE representatives have indicated that they are also considering high pressure direct injection when questioned during conference presentations. It should be noted that the tradeoff for these improved levels of GHG

reduction is that the engines are no longer dual fuel and are unable to produce 100% of the rated power in diesel mode.

It is clear from this discussion that additional R&D is required on advanced gas engine technology solutions if GHG reductions are to be achieved. The current testing by U.S. railroads, while not reducing GHG emissions, is providing important learnings regarding LNG tenders, refuelling, safety and operational experience. Once more advanced engine technologies become available, this initial experience with the first generation of technologies will help make the transition to more efficient lower-emissions technologies more rapid because railroads have achieved a level of comfort with LNG refuelling and gas safety.

2.2 Value Proposition

To understand the value proposition of the fuel cost savings potential presented in Section 2.1 above, a more detailed cash flow position needs to be considered. Initial investment items need to be separated from operating expenses. Initial investments include liquefaction facilities, locomotive conversion costs and LNG fuel tenders. Operating expenses include incremental maintenance costs for the natural gas kit and tender which are offset by the fuel savings[11]. Using the assumptions from Section 2.1 above, a directional high-level per-locomotive cash flow model can be created and the Internal Rate of Return (IRR) of the investment calculated. An IRR that is greater than the cost of capital represents a good investment, whereas an IRR below the cost of capital will not create value. Given the scope of this report, the analysis is not intended to be comprehensive but serves as directional indication for the key cost and benefit considerations. Based on this limited, high-level model, it is observed that the value proposition is most significantly influenced by:

a) The price of rail diesel
b) The diesel substitution percentage

The sensitivity analysis of the project IRR is shown in the table below

Internal Rate of Return % Sensitivity Analysis

Diesel Substitution %	Diesel Price [$/l]		
	0.60	0.80	1.00
50%	0%	12%	23%
75%	14%	31%	49%
100%	28%	52%	82%

The vulnerability of the business case to low oil prices is illustrated by the sensitivity analysis. When diesel prices are at 60c/L before the application of carbon tax[12], the project IRR is only clearly value creating when locomotive diesel substitution is >75%. The analysis also demonstrates that if locomotive OEMs can develop the technology sufficiently to guarantee high natural gas substitutions approaching 100%, then the project value proposition is no longer dependent on diesel price with IRR always greater than 20%.

[11] In the cash flow calculation amortized capital items are excluded from the price of LNG leaving only the natural gas commodity and operating cost of the liquefier.
[12] A carbon tax of $50/tonne is assumed for this analysis.

2.4 Cost Comparison Versus Alternative Emissions Controls

The US EPA Tier 4 standard for line-haul locomotive engines required for new locomotives manufactured in 2015 or later in g/bhp.hr is repeated here from Section 2.1.

Tier	HC	CO	NO_x	PM
Tier 4	0.14	1.5	1.3[13]	0.03

The Tier 4 NOx and PM limits represent more than 70% improvement over the Tier 3 standard. Note that the Tier 4 Off Road engine emissions standard for engines used for example in mine trucks only requires NO_x emissions of 3.5 g/bhp.hr (closer to the rail Tier 3 standard of 5.5g/bph.hr) and is generally able to be met without the need for exhaust gas recirculation or selective catalytic reduction (SCR) aftertreatment.

In response to the Tier 4 standards, both GE and EMD have released a Tier 4 certified linehaul freight locomotive product. The GE locomotive required the introduction of cooled exhaust gas recirculation (EGR) on the current V12 EVO engine. EMD introduced a completely new 4-stroke engine called the 1010 that replaced the 2-stroke 710 engine. The 1010 is a larger bore 4-stroke engine in V12 instead of V16 configuration and also requires EGR to meet the Tier 4 emission standards.

For passenger locomotives, engine options include the Caterpillar C175-20 in the EMD F125 or the Cummins QSK60 in the MotivePower MP54AC with additional SCR aftertreatment.

Could a natural gas locomotive meet Tier 4 emissions without the need for costly aftertreatment systems? Although no specific data is available, it has been postulated by industry observers that the incremental cost of Tier 4 modifications to the locomotive (EGR cooler, EGR valves, controls, sensors, etc.) may be similar to a natural gas conversion (gas injectors, controls, sensors, coolant pump, etc.) which would seem to create an attractive alternative proposition. However, while natural gas engines could likely achieve Tier 4 PM targets based on early OEM results, it is highly unlikely that natural gas engines will be able to achieve the extremely challenging Tier 4 NO_x targets without similar EGR systems to those used for diesel. The Tier 4 natural gas locomotives would therefore also need an EGR system[14].

[13] Manufacturers have the option to meet a combined NO_x + HC standard of 1.4 g/bhp-hr.
[14] If the locomotive is dual fuel and capable of normal operation in diesel mode then it will need to carry the full diesel aftertreatment/EGR system in addition to the natural gas conversion anyway.

2.3 Outlook for Future Price Differential

The National Energy Board of Canada publishes an annual report titled *Canada's Industry Future.* It's most recent update released in October 2016 contains revised projections for natural gas and oil commodity prices based on global supply and demand consensus. The oil price and the natural gas price are converted to an equivalent energy basis using the following assumptions:

1.0551	GJ/MMBTU
5.86152	GJ/Barrel of oil

The results are illustrated in Figure 23 and show that the gap between oil and natural gas is expected to be sustained for the forecast range of the report. The US Energy Information Administration publishes a similar report titled the *Annual Energy Outlook* and the latest projections from 2017 have been added to Figure 23. The EIA forecast shows a similar projection for a gap between oil and natural gas with the long term projected ratio between the two commodities on an energy equivalent basis.

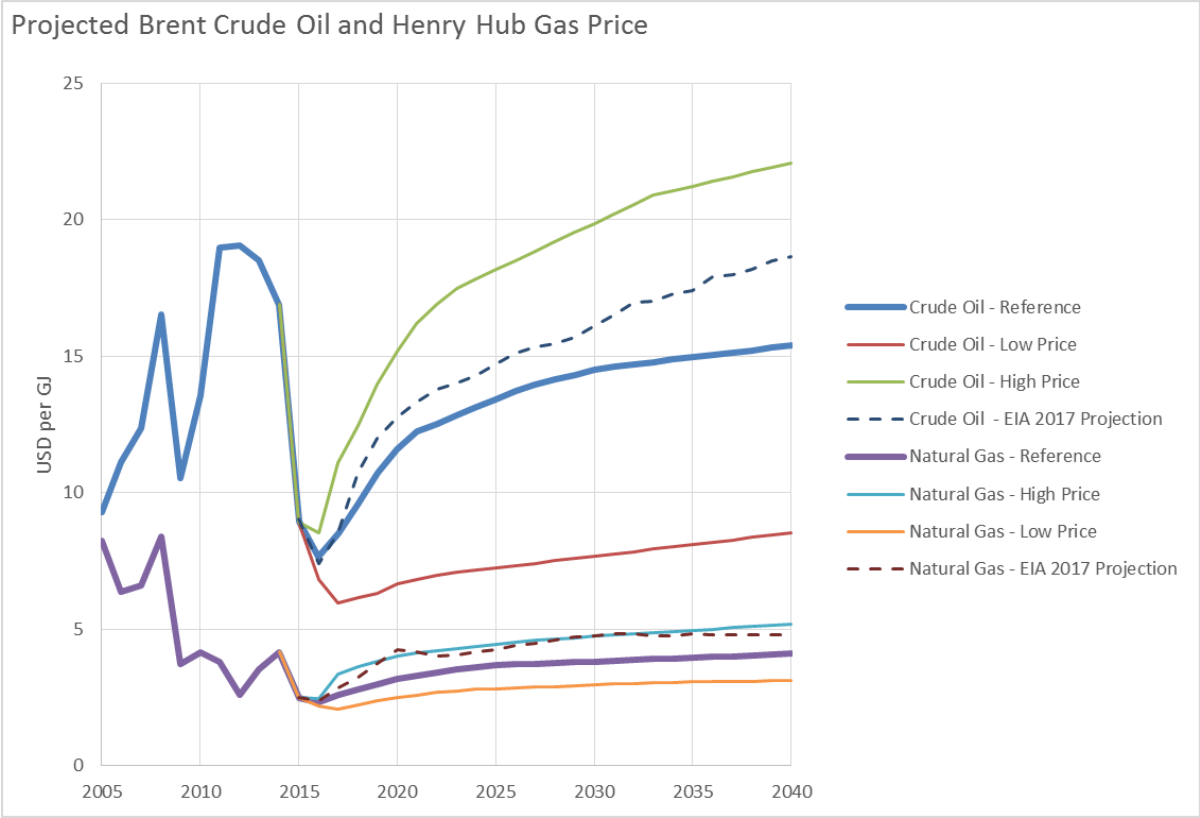

Figure 23 Sustained price gap between oil and natural gas [19] [20].

2.4 Research Review

The baseline analysis of different natural gas combustion technologies undertaken by Southwest Research Institute during the 1990s is still an important touchstone for evaluating the benefits of natural gas combustion. The results are published in an SAE Journal publication from 1997 [21]. At this time, there was not such an acute focus on GHG emissions or the impact of methane as a GHG, so analysis of methane slip was not part of the focus at the time.

A comprehensive review of the current state of technology for fuelling locomotives with natural gas was undertaken by BNSF, UP and the AAR and published in a report published in December 2007 [1]. At the time, the primary motivation for considering natural gas was to reduce CACs rather than economics (i.e. the price differential between oil and natural gas was not as pronounced as it is today). The report concludes that efforts are better spent on diesel emissions reduction than natural gas R&D. However, UP and BNSF have now revisited that conclusion given the sustained gap between diesel and natural gas prices.

There is no published, peer-reviewed research detailing the emissions performance of the locomotive OEM dual fuel engines and we must rely on conference papers and direct communication from the manufacturers. Although the GREET model has been updated to include rail transport using natural gas [22], there is little research, if any, on the total lifecycle emissions profile of the various natural gas engine technologies combined with the potential fuel supply chain in Canada. Further research is required here.

In respect of LNG tender safety and crashworthiness, David Tyrell [23] from the Volpe National Transportation Systems Center in the U.S. has published the underlying research used to support the development of the AAR LNG fuel tender standard referenced in Section 1.3. Steven Kirkpatrick proposed an alternative method for the analysis [24]. The research includes crash simulations and dynamic finite element analysis of the LNG tender response. The research is aimed at creating a design standard that would assure the integrity of the inner LNG tank in the event of a derailment. The analysis does not cover the safety of personnel and equipment in the event of a rupture to the tank although tools developed for analysis of marine LNG transport and refuelling could be applied to this case.

2.5 Uncertainties, Barriers and Risks

Investment

Section 2.1 has illustrated the multi-billion dollar investment required to convert Canada's mainline freight locomotives to operate on natural gas. Financing for this investment from railroad sources or other alternatives will be needed. Any natural gas projects would need to compete with other industry investment priorities like infrastructure modernisation and rolling stock upgrades. Furthermore, because of interchange of equipment between North American railroads, infrastructure investment may need to be made simultaneously across the country.

Methane Emissions

It is clear from the GHG emissions discussion in Section 2.1 that methane emissions from exhaust methane slip can have a detrimental effect on the environmental benefits (GHG emissions) of using natural gas as a fuel. Without a clear path forward on how to address this issue, the GHG reduction potential of converting locomotives to run on natural gas remains uncertain. Investment to accelerate the pace of development of advanced engine technologies or other abatement technologies that reduce methane emissions is required.

LNG tender cost and complexity

The release of the AAR M-1004 tender specification will significantly reduce the uncertainty regarding LNG tender configurations, but it remains to be seen how costly it will be to meet these new requirements. Only once railroads have ordered a number of these tenders will this become evident. The additional costs incurred to meet the new requirements could harm the business case. Furthermore, additional complexity (e.g. high pressure pumps) required to fuel more advanced low-emissions gas engine technologies like high pressure direct injection will also need to be accounted for.

Regulatory Framework Harmonization

The ability for CN to obtain an Equivalency Certificate and operate a natural gas fuelled locomotive in revenue service with an LNG tender demonstrates that there are currently no regulatory barriers to the adoption of LNG as a fuel for rail locomotives in Canada – at least for a pilot scale project. Clarifications or even an amendment to the TDG Act may need to be considered for wider adoption in Canada. The main barrier to widespread adoption of natural gas by Class I railroads in Canada is the lack of harmonization between U.S. and Canadian regimes in respect of both the transport of LNG and the use of LNG tenders.

Value sharing between railroads and customers

The potential economic value referenced in Section 2.1 created through the use of natural gas as an alternative fuel to diesel can be used to increase railroad profits or decrease shipping costs for customers. If prices remain constant, all the benefit would accrue to the railroads and railroad shareholders. Since fuel represents approximately 20% of operating expenses for railroads as noted in Section 1.2, reducing fuel costs by 50% would reduce overall railroad operating costs by 10% which in theory could translate to a 10% discount in shipping rates - but leaving no return for the railroads to

recoup their investment in LNG equipment. Historically, railroads have passed through a significant portion of productivity savings to customers. Security in the knowledge for those making the significant investments in LNG infrastructure that sufficient economic advantage will accrue to them to generate an adequate return on investment is needed. Without it, progress is likely to be slow.

Operational Considerations

Railroad operational efficiency is predicated on asset utilisation. Although showing promising results from an economic standpoint, the extent to which natural gas fuel disrupts the efficient operation of the railroad will detract from the business case. Examples of operational disruption might include LNG fuelling procedures, inspections, interchange restrictions, additional safety procedures or special maintenance. LNG tenders will have an impact on train length. Natural gas also has potential positive operational simplification opportunities if the LNG tender can increase the range between refuelling. Uncertainty regarding these aspects will factor heavily into the decision to use natural gas.

Section 3: Recommendations

This report has highlighted the potential economic and environmental benefits of natural gas as a fuel for the rail industry. Currently there is very little activity in Canada (research, product development or testing). With a focused research, development deployment program, supported by government policies, Canada could take a leading role in advancing this opportunity that has the potential to reduce the cost and emissions of Canada's rail transportation system. Recommendations are therefore grouped in three categories:

3.1 Market Research and Economic/Emissions Modelling

3.1.1 A thorough assessment of the railroad network and the natural gas pipeline network is required in order to determine suitable locations for liquefaction plants to serve railroad fuel depot requirements. This will inform a more detailed view of the required liquefaction facility build out program and investment, taking into account potential synergies with other natural gas fuel usages.

3.1.2 Research potential investment financing models for the required infrastructure, e.g. utility investment, low-interest government backed loans, grants, tax credits or public private partnership.

3.1.3 Conduct customer and railroad behaviour research into how the benefits of decreased fuel costs will likely be shared based on historic case studies and microeconomic theory.

3.1.4 Comprehensive analysis of the value proposition and business case for natural gas locomotives is required to take into account risks and uncertainties. Customer behaviour modelling and value sharing from 3.1.3 must be included.

3.1.5 A complete lifecycle GHG emissions assessment is required for both rail diesel and natural gas.

3.2 Technology Development and Deployment

3.2.1 Testing of emissions from dual fuel locomotives (particularly methane emissions) and venting from LNG tenders. Abatement technologies can be considered where available.

3.2.2. Accelerated development of high-substitution high-efficiency low-methane slip gas engines for rail locomotives potentially through funding of a demonstration pilot project in Canada.

3.2.3 Further research into LNG tender technologies that support the locomotive engine technologies in 3.2.2

3.2.4 Stimulate research into LNG tender and refuelling technologies that minimize boil-off gas generation and eliminate methane venting.

3.2.5. Investigate LNG spill and derailment accident safety through computational modelling and risk assessment. Investigate and compare best practices from other sectors, e.g. marine.

3.3 Regulatory and Policy

3.3.1 Consider an emissions credit scheme for CACs that go beyond regulated tier limits (especially PM) either as a tradeable credit or monetary reward.

3.3.2 Focus Research, Development and Deployment funding models on technology advancement and increasing the pace of deployment, particularly for technologies that reduce GHG emissions.

3.3.3. Investigate feasibility of further harmonization of regulations applying to natural gas locomotives and tenders between the U.S. and Canada to facilitate easy interchange of equipment and increase choice for Canadian railroads.

3.3.4. Consider the impact of accelerated depreciation or other incentives for infrastructure investment in natural gas. Evaluate the benefit of direct government grants, subsidies or government backed loans.

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Units, Acronyms and Abbreviations

Units

MJ	Megajoule
GJ	Gigajoule
L	Litre
C	Celsius
M	Million
B	Billion
bar	Bar pressure
$	Canadian dollars
c	Canadian cents
USD	U.S. dollar

Acronyms and Abbreviations

AAR	Association of American Railroads
BNSF	BNSF Railway Company
CAC	Criteria Air Contaminants
CN	Canadian National Railway Company
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_{2e}	Carbon Dioxide Equivalent
CP	Canadian Pacific Railway
DLE	Diesel Litre Equivalent
ECI	Enegy Conversions Incorporated
EIA	U.S. Energy Information Administration
EMD	Electro-Motive Diesel
EPA	Environmental Protection Agency
FECR	Florida East Coast Railway
FRA	Federal Railroad Administration
GE	General Electric
GHG	Greenhouse Gas
LEM	Locomotive Emissions Monitoring
LNG	Liquefied Natural Gas
NEB	National Energy Board of Canada
NGFT TAG	Natural Gas Fuel Tender Technical Advisory Group
NOx	Nitrogen Oxides
NRCan	Natural Resources Canada
OEM	Original Equipment Manufacturer
PM	Particulate Matter
RAC	Railway Association of Canada

RCC	Regulatory Cooperation Council
SOx	Sulphur Oxides
TDG	Transport of Dangerous Goods
UP	Union Pacific Railroad
VOC	Volatile Organic Compound