Study On Natural Gas Research and Development Priority Setting For Transportation in Canada

Contract #3000549922

FINAL REPORT

For: Natural Resources Canada

By: Canadian Natural Gas Vehicle Alliance
    350 Sparks Street, Suite 809
    Ottawa, ON, K1R 7S8

Date: February 27, 2015
Table of Contents

List of Figures ................................................................................................................................. 6
List of Tables ................................................................................................................................. 8
Acknowledgements ....................................................................................................................... 9
Acronyms ...................................................................................................................................... 10
Executive Summary ....................................................................................................................... 11
A – Natural Gas in Canada – Overview ....................................................................................... 13
   A.1 Introduction ............................................................................................................................ 13
   A.2 Stakeholders Consulted ........................................................................................................ 14
   A.3 Natural Gas Production in Canada ...................................................................................... 15
   A.4 Natural Gas Pipelines and Storage ..................................................................................... 16
   A.5 Natural Gas Price Outlook .................................................................................................. 17
   A.6 Demand for Natural Gas ...................................................................................................... 17
   A.7 Exports and Imports ............................................................................................................. 19
   A.8 Forecast Natural Gas Demand ........................................................................................... 19
   A.9 Impact of Transportation Demand on Utility Infrastructure ............................................. 21
   A.10 Infrastructure to Supply Natural Gas to Transportation Market ....................................... 22
   A.11 Natural Gas Refuelling Technologies .............................................................................. 24
B – Natural Gas-Powered Vehicles .............................................................................................. 27
   B.1 Introduction .......................................................................................................................... 27
   B.2 Stakeholders Consulted ........................................................................................................ 28
   B.3 Current Vehicle Population & Fuel Usage .......................................................................... 28
       Comparison with U.S. Market .................................................................................................. 30
       Natural Gas Consumption ..................................................................................................... 30
   B.4 Status of Infrastructure ....................................................................................................... 31
   B.5 Natural Gas Vehicle Manufacturers in Canada .................................................................. 33
   B.6 Current Incentives in Canada ............................................................................................. 34
       British Columbia Incentive Program .................................................................................... 34
       Quebec Incentive Program ................................................................................................... 35
C – Natural Gas Vehicle On-Board Fuel Storage ........................................................................ 36
   C.1 Introduction .......................................................................................................................... 36
   C.2 Stakeholders Consulted ........................................................................................................ 37
   C.3 Fuel Systems Overview ...................................................................................................... 38
       CNG Fuel Systems .................................................................................................................. 38
LNG Fuel Systems.................................................................................................................39
C.4 Fuel System Configurations..........................................................................................40
   Side Mount Rail Mount......................................................................................................40
   Behind the Cab..................................................................................................................41
   Roof Mount.......................................................................................................................42
   Front of Body.....................................................................................................................43
   Tailgate..............................................................................................................................43
   CNG Fuel Management Module......................................................................................44
   LNG Fill Interface............................................................................................................46
C.5 Impact on Safety and Usability......................................................................................48
C.6 Cylinder Valves..............................................................................................................57
C.7 First Responder Safety...................................................................................................58
C.8 Proposed Technologies to Improve Storage..................................................................60
   Adsorbed Natural Gas Technology...................................................................................60
   Metal Organic Frameworks...............................................................................................61
   Higher Fill Pressures.........................................................................................................62
   Research Initiatives to Improve Natural Gas Storage.......................................................62
C.9 Common Issues Related to Natural Gas Storage..........................................................64
C.10 Specific & Volumetric Energy, Cost and Refueling Rate...............................................66
C.11 Potential Additional Areas for R&D Effort...................................................................67
C.12 Differences Between Canadian & U.S. Requirements for Fuel Storage.........................67

D – Engine Development and Vehicle Integration..............................................................75
D.1 Introduction.....................................................................................................................75
D.2 Stakeholders Consulted..................................................................................................76
D.3 Overview of Current Natural Gas Engine and Vehicle Technologies............................76
   Spark Ignition Otto Cycle Engines....................................................................................76
   Compression Ignition Diesel Cycle Engines..................................................................77
D.4 Applications For MD and HD Engines and Vehicles.......................................................80
   On-Highway Medium Duty..............................................................................................80
   On-Highway Heavy Duty.................................................................................................81
   Off-Highway.....................................................................................................................83
   Mining..............................................................................................................................83
   Stationary.........................................................................................................................83
   Marine...............................................................................................................................84
   Rail.................................................................................................................................85
D.5 R&D Options to Enhance Engine Performance and Customer Acceptance....................86
   Vehicle Systems and Driver Aids....................................................................................86
   On-Board Diagnostics.................................................................................................86
   Dedicated Natural Gas Engine Design..........................................................................88
   Ion Current Sensing For Spark Ignition Combustion Analysis and Control..................89
   Micro Pilot Port Injected Gas Engine Systems..............................................................89
   Advanced Spark Ignition Engine Concepts....................................................................90
   Advanced Ignition Systems............................................................................................91
   Tailpipe Methane Conversion.......................................................................................93
   Methane Detection Systems.........................................................................................94
   Gas Seals.......................................................................................................................94
H.2 Overview of Issue Areas........................................................................................................153
Transaction Issues.........................................................................................................................153
Refuelling Process for Dual Fuel Vehicles.....................................................................................154
Off-Pipeline Stations......................................................................................................................154
Electrically Constrained Stations...................................................................................................155
Managing Moisture Content in Fuel..............................................................................................156
Managing Heat During the Refuelling Process to Improve Settled CNG Fill Pressure..............156
Strategies to Manage Boil-Off from LNG Stations.......................................................................157
High Capacity Nozzles for Off-Road Applications Including Marine, Rail, and Mining Trucks ... 157

I - State of Critical Technologies ...............................................................................................158

Engine Development and Vehicle Integration...............................................................................158
General Background.......................................................................................................................158
State of Maturity of the Technologies............................................................................................158
R&D Opportunities.........................................................................................................................163

Natural Gas Vehicle On-Board Fuel Storage..................................................................................164
General Background.......................................................................................................................164
State of Maturity of the Technologies............................................................................................165
R&D Opportunities.........................................................................................................................167

Safety, Codes and Standards..........................................................................................................168
Background......................................................................................................................................168
State of Maturity..............................................................................................................................168
R&D Opportunities.........................................................................................................................171

Canadian Natural Gas Vehicle Industry and Academic R&D Capacity........................................172

R&D Collaboration in a North American Context........................................................................174
R&D Opportunities.........................................................................................................................174

J – Recommended Priority Actions.............................................................................................176

J.1 Priorities for Engine Development and Vehicle Integration..................................................176
J.2 Priorities for Natural Gas Vehicle On-Board Fuel Storage.....................................................178
J.3 Priorities for Safety, Codes and Standards.............................................................................178
J.4 Priorities for R&D Collaboration in a North American Context............................................180
J.5 Overall R&D Priorities..............................................................................................................181

Appendices ....................................................................................................................................183

Appendix A - Spotlight - Aftermarket Conversions of Existing Vehicles..................................183
Appendix B - OBD Requirements Summary.................................................................................185

Bibliography....................................................................................................................................187

Endnotes..........................................................................................................................................188
List of Figures

Figure 1 – Natural Gas Resource Base - Canada ................................................................. 13
Figure 2 – Natural Gas Distribution Sector – Geographic Coverage Across Canada ............... 14
Figure 3 – Natural Gas Drilling Activity in Canada ............................................................... 15
Figure 4 – Natural Gas Production in Canada .................................................................... 15
Figure 5 – Natural Gas Distribution System Details ............................................................. 16
Figure 6 – Comparison of Energy Pricing in Canada ........................................................... 17
Figure 7 – Natural Gas Final Demand by Sector ................................................................. 18
Figure 8 – Natural Gas Demand by End Use ..................................................................... 18
Figure 9 – 2013 Natural Gas Sales by Province ................................................................. 19
Figure 10 – Forecast Natural Gas Demand to 2035 .............................................................. 20
Figure 11 – Projected Growth in Natural Gas Use ............................................................... 20
Figure 12 – Projected Growth in Natural Gas Use for Transportation ................................. 21
Figure 13 – CNG Fast Fill Station ...................................................................................... 24
Figure 14 – CNG Time Fill Station ...................................................................................... 25
Figure 15 – CNG FuelMule ................................................................................................. 25
Figure 16 – NGVs in Canada by Vehicle Type ..................................................................... 28
Figure 17 – New Medium & Heavy-Duty NGVs ................................................................. 29
Figure 18 - By-Province Distribution of New NGVs .............................................................. 29
Figure 19 – Natural Gas Demand for Transportation .......................................................... 30
Figure 20 – Public & Private Refuelling Stations ................................................................. 31
Figure 21 – Public CNG Stations by Province ................................................................... 31
Figure 22 – Breakdown of CNG & LNG Stations ................................................................. 32
Figure 23 – Eastern Corridor LNG Refuelling Stations ......................................................... 32
Figure 24 – Western Corridor LNG Refuelling Stations ....................................................... 33
Figure 25 – LNG Pressure & Density vs Temperature ......................................................... 39
Figure 26 – 45 DGE CNG Side Mount Rail Mount System with Integrated FMM ................ 40
Figure 27 - 70 DGE Per Side LNG Side Mount Fuel System .............................................. 41
Figure 28 - 60 DGE Behind the Cab System with Non-Integrated FMM ............................. 41
Figure 29 - 155/160 DGE Behind the Cab Fuel System with Integrated FMM .................... 42
Figure 30 – 144 DGE Roof Mount System on a Transit Bus .............................................. 42
Figure 31 – 75 DGE Front of Body CNG Fuel System on a Refuse Truck ......................... 43
Figure 32 – 90 DGE Tailgate CNG Fuel System ................................................................. 44
Figure 33 - FMM Faceplate Components ......................................................................... 44
Figure 34 - Internal Components of FMM ........................................................................ 45
Figure 35 – Behind the Cab Integrated FMM .......................................................... 46
Figure 36 - Typical LNG Fill Interface ................................................................................ 46
Figure 37 - LNG Fuel Flow Schematic .............................................................................. 47
Figure 38 - Galvanic Corrosion on CNG Cylinder Heads from Use of Steel Bracket on Aluminum 48
Figure 39 - Surface Damage to CNG Cylinder from Strap with Insufficient Rubber Padding .. 49
Figure 40 - Type 2 CNG Cylinder with Abrasion Damage from Being Dragged on Road ...... 49
Figure 41 - Type 2 CNG Cylinder with Abrasion Damage from Being Dragged on Road ...... 50
Figure 42 - Bonfire Test of a 155 DGE System Pressurized to 3,600 Psi ................................ 51
Figure 43 - Side Mount Rail Mount System Undergoing a Simulated 30 MPH Side Impact Test .. 51
Figure 44 – Heavy-Duty Truck with CNG Behind the Cab System After Severe Impact 52
Figure 45 - LNG Tank Prior to 30 Foot Drop Test ............................................................... 53
Figure 46 - Damage to LNG Tank from 10 Foot Drop Test .............................................. 53
Figure 47 - Damage to LNG Tank from 30 Foot Drop Test ......................................................... 53
Figure 48 - LNG Tank Undergoing a Bonfire Test ................................................................. 54
Figure 49 - Fuel Escaping the LNG Tank as a Result of a ~7.62mm Puncture ............................ 54
Figure 50 - Flame from ~7.62mm Hole Puncture Test Immediately After Ignition .................. 55
Figure 51 - Fire at its Largest Point as a Result of ~28.5mm Puncture Test ............................ 56
Figure 52 – Heavy-Duty Truck with a LNG Fuel System After a Fire ........................................ 57
Figure 53 - CNG & LNG Blue Diamonds Required on NGVs .................................................... 58
Figure 54 - Front Side of an Emergency Response Card for CNG Bus ..................................... 59
Figure 55 - Reverse Side of an Emergency Response Card for CNG Bus ............................... 59
Figure 56 - Small Scale Adsorbed Natural Gas Fuel Storage Tank ........................................ 60
Figure 57 - Production of a Metal-Organic Framework ............................................................ 62
Figure 58 - First Generation CNG Highway Tractor Study Vehicle ....................................... 64
Figure 59 - Fourth Generation CNG Tractor Aerodynamic Study Vehicle ............................... 65
Figure 60 - Rendering of Fifth Generation Aerodynamic CNG Highway Tractor .................... 65
Figure 61 - Factory Integrated Kenworth Natural Gas Truck .................................................... 82
Figure 62 - Delphi Ignition System with Ion Current Sensing ............................................... 89
Figure 63 - Example Of Plasma Ignition System ..................................................................... 92
Figure 64 - Comparison of Flame Front Formations - Spark Ignition & Plasma Ignition Systems 92
Figure 65 - Mahle Concept For Integrated Pre-chamber Ignition System ................................. 93
Figure 66 - SwRI - Dedicated EGR Concept with H2 Reforming .......................................... 97
Figure 67 - Engagement Model for LNG Technology Centre ................................................. 130
Figure 68 - Integrated North American Natural Gas Transmission System ............................ 135
Figure 69 - Natural Gas Potential Resource per the Potential Gas Committee ......................... 136
Figure 70 - U.S. Natural Gas Import and Export Volumes ...................................................... 136
Figure 71 - U.S. Natural Gas Use By Sector In 2013 in BCM ................................................. 137
Figure 72 - Projection of Industrial Gas Use Per DOE EIA AEO 2014 .................................. 138
Figure 73 - Projected Global LNG Capacity & Production by Region ................................. 138
Figure 74 - Projected 2025 U.S. Natural Gas Demand By Sector in BCM ............................ 139
Figure 75 – LNG & CNG Refuelling Stations as of July 2014 (Source: U.S. DOE) ............... 140
Figure 76 – Sample Large Scale LNG Refuelling Station (Source: Questar Fuelling) ............ 141
Figure 77 – Sample LNG & L-CNG Refuelling Station ......................................................... 141
Figure 78 – U.S. Federal Budget Authority for R&D and R&D Plant – Non-Defense Budget .... 142
Figure 79 – U.S. DOE Natural Gas Research Funding History ............................................. 143
Figure 80 – U.S. DOE Clean Cities Coalition Location ......................................................... 144
# List of Tables

Table 1 - Canada's Top Natural Gas Producers ................................................................. 16  
Table 2 – Types of NGVs in Canada & U.S........................................................................ 30  
Table 3 – Canadian Stations by Fuel Type......................................................................... 32  
Table 4 - North American Natural Gas Fuel Systems Providers ...................................... 36  
Table 5 – Weight Comparison - Comparable CNG, LNG & Diesel Engines and Fuel Systems ................................................................. 37  
Table 6 - Types of CNG Cylinders ....................................................................................... 39  
Table 7 - FMM Components & Their Functions ................................................................. 45  
Table 8 - LNG Components & Their Functions .................................................................. 47  
Table 9 - Auto Ignition Temperature & Flammability Range of Fuels .............................. 50  
Table 10 – Challenges & Limitations of ANG Fuel Storage Systems .............................. 61  
Table 11 – ARPA-E Funded Projects to Advance Natural Gas Storage Systems Technology ................................................................. 63  
Table 12 - Differences Between the CSA B109 & NFPA 52 for On-Board Fuel Storage Systems ... 74  
Table 13 – Summary of Current Natural Gas Engine Technology Approaches .............. 80  
Table 14 – Available Medium-Duty Engines, Path to Market & Fuel Type ................. 80  
Table 15 – Available Heavy-Duty Engines & Fuel Type ................................................. 81  
Table 16 - Summary of Technology R&D Priorities, Timing & Risk ................................ 99  
Table 17 - LNG Standards Needs & Other Gap Areas ................................................... 110  
Table 18 – New Canadian Training Courses ................................................................... 127  
Table 19 - Transportation-Related R&D Projects Led by GTI for 2012-13 ..................... 145  
Table 20 – Representative Leading NGV Technology R&D Issues and Needs ............ 150  
Table 21 – Cumulative 1970-2009 Patents by Energy Technology & Country ............. 152  
Table 22 – New Canadian Training Courses ................................................................... 173  
Table 23 - Summary of Conformity Requirements For Aftermarket Conversions ........ 183  
Table 24 - Outside Useful Life Engine Classifications .................................................... 183
Acknowledgements

Natural gas offers significant potential as a transportation fuel in North America. Both Canada and the United States (U.S.) are leading global natural gas producers. Leveraging our major continental resource advantage to derive economic, environmental, and competitiveness benefits in the transportation sector represents an important strategic opportunity.

Ensuring that the technologies for natural gas vehicles and stations continue to improve and advance is critical in order to sustain a competitive advantage and to deliver continued economic and environmental benefits to end users for both on- and off-road applications. The importance of ensuring ongoing competitiveness was cited as a key priority area in the December 2010, Natural Gas Use in the Canadian Transportation Sector – Deployment Roadmap.

As Project Lead, the Canadian Natural Gas Vehicle Alliance (CNGVA) was fortunate to work with a diverse team of knowledgeable industry experts, each of whom brought extensive experience and insight to this work. The CNGVA also benefitted from the involvement of Dr. Alex Lawson, Technical Advisor to both the CNGVA and to NGV Global, who acted as the subject matter expert and lead technical specialist for the project.

Thank you to the following organizations and individuals for their contributions:

  Agility Fuel Systems  - Alexander Melnyk, Todd Sloan
  Canadian Gas Association  – Bryan Gormley, Paul Cheliak, Adita Iyer
  Change Energy  - Ry Smith
  CSA Group  - Julie Cairns, Cliff Rondeau
  G. P. Williams Consulting  – Graham Williams
  GTI  - Rich Kooy, Tony Lindsay

For additional information regarding this study, please contact the CNGVA at info@cngva.org.

To learn more about natural gas vehicles, visit www.gowithnaturalgas.ca.

This report by the Canadian Natural Gas Vehicle Alliance was supported by the CanmetENERGY division of Natural Resources Canada with funding from the Program of Energy Research and Development. The funding organization makes no warranties or representations, express or implied, with respect to the use of any information contained in this report. Conclusions contained herein do not necessarily represent the views of the Government of Canada.
### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHJ</td>
<td>Authority having jurisdiction</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed natural gas</td>
</tr>
<tr>
<td>DGE</td>
<td>Diesel gallon equivalent</td>
</tr>
<tr>
<td>DLE</td>
<td>Diesel litre equivalent</td>
</tr>
<tr>
<td>DPF</td>
<td>Diesel particulate filter</td>
</tr>
<tr>
<td>ECA</td>
<td>Emission Control Area</td>
</tr>
<tr>
<td>ECM</td>
<td>Electronic control module</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust gas recirculation</td>
</tr>
<tr>
<td>EPA</td>
<td>U.S. Environmental Protection Agency</td>
</tr>
<tr>
<td>HD</td>
<td>Heavy-duty</td>
</tr>
<tr>
<td>IMO</td>
<td>International Maritime Organization</td>
</tr>
<tr>
<td>LNG</td>
<td>Liquefied natural gas</td>
</tr>
<tr>
<td>MD</td>
<td>Medium-duty</td>
</tr>
<tr>
<td>NGV</td>
<td>Natural gas vehicle</td>
</tr>
<tr>
<td>NOx</td>
<td>Oxides of nitrogen</td>
</tr>
<tr>
<td>NRCan</td>
<td>Natural Resources Canada</td>
</tr>
<tr>
<td>OBD</td>
<td>On-Board Diagnostics</td>
</tr>
<tr>
<td>OEM</td>
<td>Original equipment manufacturer</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate matter</td>
</tr>
<tr>
<td>PRD</td>
<td>Pressure relief device</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective catalytic reduction</td>
</tr>
<tr>
<td>SI</td>
<td>Spark-ignited</td>
</tr>
<tr>
<td>TSSA</td>
<td>Ontario Technical Standards &amp; Safety Authority</td>
</tr>
<tr>
<td>VRA</td>
<td>Vehicle refuelling appliance</td>
</tr>
</tbody>
</table>
Executive Summary

Natural gas offers significant potential as an affordable, lower emission transportation fuel. Ensuring that the technologies for natural gas vehicles and stations continue to improve and advance is critical so as to sustain a competitive advantage and to provide ongoing economic and environmental benefits to end users for both on- and off-road applications.

This study on R&D priority setting for natural gas as a transportation fuel in Canada provides broad contextual information with respect to natural gas infrastructure and downstream markets for natural gas in Section A. The current status of natural gas vehicle use in Canada including existing refuelling stations is detailed in Section B. Opportunity and issue areas associated with natural gas technology development R&D including potential collaboration opportunities between Canada and the U.S. are documented in Sections C through H:

- Section C – on-board fuel storage
- Section D – engine development and integration
- Section E – safety, codes and standards
- Section F – training and academic capacity
- Section G – North American context and collaboration
- Section H – refuelling infrastructure

Section I summarizes critical areas of R&D need. The final section, Section J, identifies the top ten recommended actions related to R&D for natural gas as a transportation fuel. The top ten recommendations across all areas of natural gas vehicle-related technology are as follows:

1. **Apply advanced SI engine concepts to natural gas engines.** Capitalize on advances in gasoline engine technology by applying these concepts to natural gas engines such as increased levels of boost pressure, higher EGR tolerance, and engine downsizing. Coupled with direct injection, it should be possible to significantly increase power and torque to levels approaching modern gasoline and diesel engines.

2. **Invest in research that addresses lowering the cost of compressed natural gas (CNG) fuel systems by taking a systemic approach to fuel system design.** This recommendation would also encompass the integration strategies for lower cost fuel storage technologies when available. This should include a “fresh eyes” investigative approach to the system as a whole including tanks, valves, and PRDs as one system. Opportunities should be explored to reduce complexity and decrease the number of components, including the possibility of eliminating some tank valves. Treating the tank, tank valve, and pressure relief device (PRD) as one system could lead to more efficient, safer, and less costly systems.

3. **Fund demonstrations of new technologies.** Government can play a key role in supporting the development, evaluation, and demonstration of new technologies in a pre-competitive environment to support the long term viability of natural gas systems. A range of areas of R&D needs identified in this study could be suitable for demonstration.

4. **Monitor results achieved related to the issues surrounding PRDs, tank valve failures, and vehicle safe refuelling** that are being addressed in the U.S. by Clean Vehicle Education Foundation (CVEF) Task Groups. There is a need to track these developments and apply the outcomes to revisions of Canadian standards as appropriate. Activities in
this area should be reviewed by the Roadmap Technical Advisory Group on a periodic basis.

5. **Fund the development of liquefied natural gas (LNG) vehicle component and station standards** work on a harmonized North American basis via CSA Group. This critical area requires financial resources to close existing gaps and to ensure that the codes, standards, and regulatory framework keep pace with market developments.

6. **Apply vehicle systems and driver aids that are used for diesel technologies to natural gas technologies.** The application of optimized diesel technologies to natural gas engines can improve performance and enhance the value proposition for natural gas. The application of waste heat recovery and start stop systems as well as intelligent driver aids and telematics are some of the options in this area.

7. **Apply smart vehicle-station communication systems so as to improve CNG fill quality.** Development of an on-board pressure management system involving smart fill receptacles, and possible smart stations would improve control over the amount of energy delivered to the vehicle’s tanks. This would result in improved CNG vehicle fills and enhanced CNG cylinder safety.

8. **Evaluate and identify R&D priorities of mutual interest between Canada and the U.S. related to Great Lakes and coastal marine LNG bunkering, rail locomotives, and mining applications related to Canadian oil sands and American coal.** Multi-modal pilot projects involving the use of LNG across marine, rail, and on-road trucking applications present an opportunity for R&D collaboration and benefits verification for both countries.

9. **Resource R&D work that supports the development of dispensed fuel quality standards** for CNG and LNG in order to identify contaminants and desired fuel composition.

10. **Leverage existing Canadian academic expertise and networks so that advanced natural gas vehicle and station technologies can be developed in partnership with industry.** To raise awareness and connect academic researchers with industry, it is recommended that NRCan include a focus on networking and information sharing with the academic community at an upcoming event, so as to initiative this important dialogue.

These top priorities are deemed to be the most likely to succeed in overcoming significant barriers to growth and sustainability of the industry. All items have been considered both in terms of cost effectiveness and lowest risk to achieving objectives.
A – Natural Gas in Canada – Overview

A.1 Introduction

The integrated North American natural gas market has undergone a dramatic supply side change in the past two decades. In the 1990s and early 2000s, natural gas production was flat to declining while consumption continued to trend upward in both Canada and the U.S. As a result, periods of high and volatile commodity prices were common.

This period of high prices and volatility began to come to a close around 2007 and later as producers began to economically produce large quantities of tight gas and shale gas by employing technological developments related to horizontal drilling and hydraulic fracturing. These new techniques unlocked significant new supplies of natural gas across North America. In Canada alone, the natural gas resource base has doubled since the year 2000 and is estimated at 1,300 trillion cubic feet, equal to 200 years of supply at current production levels.\(^1\)

Forecasts suggest that large quantities of low cost shale gas will be available to the market well into the future and, as a result, will have a moderating impact on the commodity price of natural gas. The National Energy Board (NEB) forecasts that Canadian natural gas prices will remain below $6 per million British thermal units (MMBtu) to 2035.\(^2\) For comparison, the average price for natural gas in Canada at AECO in Alberta, which is the primary pricing point in Canada, averaged just over $5/GJ between January 2001 and August 2014.

![Natural gas resource base - Canada](image)

**Figure 1 – Natural Gas Resource Base - Canada**

Complementing the stable price environment is the growing recognition of natural gas’ environmental benefits. On a carbon content basis, lifecycle natural gas emissions are up to 20% lower compared to diesel, the primary energy source for commercial trucks and buses. Further, natural gas produces few criteria air contaminants such as nitrous oxides, sulphur dioxides and other smog-producing pollutants.

On its price and environmental merits, the use of natural gas continues to advance with overall domestic demand in Canada increasing by close to 11 per cent since the 2009 recession, namely driven by power generation and oil sands markets.

The ongoing development of new U.S. supply capacity which can be delivered at affordable prices particularly from the Marcellus Shale play in the U.S. northeast, is putting pressure on traditional supplies of natural gas delivered from Western Canada to markets in Eastern Canada.
Increased demand for natural gas has led to growth in Canada’s natural gas distribution system which had expanded to just over 440,000 kilometres of pipeline by the end of 2013. The geographic areas served by Canada’s natural gas distribution companies are shown in Figure 2. The provinces of Newfoundland and Prince Edward Island do not have pipeline natural gas distribution infrastructure. In addition, outside of a small distribution network in Inuvik, none of the territories have pipeline natural gas distribution infrastructure.

The natural gas distribution sector invested more than CDN1.8 billion in new and upgraded infrastructure in 2013, and provides employment for just under 17,000 full-time-equivalent persons. The natural gas distribution sector GDP continues to increase, rising to just over $4.9 billion ($2007 base year). Natural gas continues to enjoy a wide price advantage over other energy commodities.

### A.2 Stakeholders Consulted

The following stakeholders were interviewed for their industry and expert perspective related to natural gas distribution and transportation demand:

- National Energy Board – Paul Mortensen
- FortisBC – Arvind Ramakrishnan
- ATCO Gas – Walter Dunnewold
- Enbridge Gas Distribution – Ritchie Murray, Robert Dysiewicz
- Union Gas – Pierce Jones
A.3 Natural Gas Production in Canada

As mentioned, the ability to cost effectively access shale gas and tight gas resources has driven the available natural gas resource base in Canada to over 200 years of supply at current demand levels. The location of much of the shale and tight gas in Canada is situated in British Columbia in the Horn River and the Montney. In addition to resources in British Columbia, there exist large shale gas bearing areas in Alberta, Quebec, and the Maritimes.

Despite the large resource base available in Canada, the ultra-low price environment between 2011-2013 which was driven by record production of natural gas in the United States, resulted in a drop in Canadian drilling for natural gas. The drop in drilling resulted in lower production from Canada with the most notable decline being in Alberta.

Alberta natural gas production continues to decline. Low prices have led to a “wait and “see” approach resulting in a drop of over 1,200 billion cubic feet in the province’s production compared to a few years ago. By comparison, production in British Columbia is surging. British Columbia continues to grow as a major natural gas producer in North America. Both the Montney and Horn River regions are proving to be world class plays. These two factors create significant slack in Canada’s supply potential that could be used to respond to increased demand for natural gas in the transportation and in other markets.

Figure 3 – Natural Gas Drilling Activity in Canada

Figure 4 – Natural Gas Production in Canada
The top natural gas producers in Canada supplied just under 70 percent of total daily production in 2012. A list of these producers is shown in Table 1 below.

<table>
<thead>
<tr>
<th>Natural Gas Producer</th>
<th>2012 Gas Production (million of cubic feet per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Encana Corp.</td>
<td>2,981</td>
</tr>
<tr>
<td>2 Talisman Energy Inc.</td>
<td>1,582</td>
</tr>
<tr>
<td>3 Canadian Natural Resources Ltd.</td>
<td>1,220</td>
</tr>
<tr>
<td>4 Cenovus Energy Inc.</td>
<td>594</td>
</tr>
<tr>
<td>5 Husky Energy Inc.</td>
<td>554</td>
</tr>
<tr>
<td>6 ARC Resources Ltd</td>
<td>343</td>
</tr>
<tr>
<td>7 Penn West Petroleum Ltd.</td>
<td>342</td>
</tr>
<tr>
<td>8 Suncor Energy Inc.</td>
<td>296</td>
</tr>
<tr>
<td>9 Tourmaline Oil Corp.</td>
<td>268</td>
</tr>
</tbody>
</table>

*Table 1 - Canada's Top Natural Gas Producers*

A.4 Natural Gas Pipelines and Storage

Canada’s natural gas pipeline and storage infrastructure is vast and robust. The network of pipelines in 2013 totalled 445,000 kilometres. More than half this total are distribution main lines that bring natural gas into neighbourhoods and along city streets. An additional 135,000 kilometres are service lines that carry gas directly to homes and businesses of the final customer. The remaining infrastructure consists of large transmission lines that move natural gas from production areas to local markets.

Natural gas storage capacity in Canada continues to expand with over 820 billion cubic feet of capacity available. Low prices and average demand has left storage facilities relatively full in recent years. Continued additional supply from new shale basins is supporting this trend. Storage provides the flexibility to respond to changes in demand and allows stockpiling of supply for peak winter demand periods. Canada has approximately 60 days of natural gas demand available in its storage reservoirs at the beginning of every heating season. This storage assists to moderate price for consumers.
A.5 Natural Gas Price Outlook  
Natural gas enjoys a wide price advantage over other energy commodities. The extensive North American natural gas supply base continues to put downward pressure on natural gas prices in Canada and in the U.S. In addition, the emergence of significant U.S. imports into the major Eastern Canadian market area has reduced demand for Canadian natural gas which has resulted in even lower domestic natural gas pricing.

In the most recent Short Term Energy Outlook, the US Energy Information Administration projects that Henry Hub, the major pricing point for natural gas in the U.S., will average $4.77/MMBtu in 2014 and $4.50/MMBtu in 2015.

![Graph showing energy commodity prices in Canada](image)

*Figure 6 – Comparison of Energy Pricing in Canada*

A similar story is told in Canada in the most recent NEB Energy Futures Outlook and Short-Term Natural Gas Deliverability report. These NEB studies have a reference case for natural gas prices going forward to 2015 of $4.35 rising slowly to $6.20 by 2035. Also, the NEB expects crude oil prices, as represented by the West Texas Intermediate benchmark price, to rise to $US 110/bbl by 2035 which would support long term movement to natural gas from diesel and gasoline which are priced off of crude oil.

A.6 Demand for Natural Gas  
Domestic demand for natural gas has increased by close to 11 per cent since the 2009 recession. This growth has been driven by double digit increases in demand from the industrial and power
generation sectors. In the residential, commercial, and industrial sectors, equipment efficiency gains have led to slightly declining residential natural gas use over the past decade.

In volume terms, the majority of natural gas sales go to the industrial sector, and this sector of demand has shown strong growth driven by oilsands production.

While transportation demand for natural gas is still very small, there is a modest level of current demand estimated at 2 billion cubic feet (Bcf)/year. This demand is for on-road vehicles and for small off-road vehicles such as ice resurfacers and forklifts. There is no current use of natural gas as a fuel for marine vessels, locomotives or heavy off-road vehicles in Canada.
Natural gas sales by province for 2013 are shown in Figure 9 below. Sales differ from distribution volumes as there can be transfers of natural gas to other utilities on a given local distribution system. Total sales in 2013 were 85,127 million m3 with sales in Alberta and Ontario accounting for 73% of the total.

![2013 Canadian Natural Gas Sales by Province](image)

**Figure 9 – 2013 Natural Gas Sales by Province**

A.7 Exports and Imports

With respect to imports of natural gas into Canada from the U.S., imports have been increasing which has, in turn, reduced demand for domestically-produced natural gas. At the same time, exports of Canadian natural gas to the U.S. continue to decline as local U.S. shale gas from producing areas like the Marcellus are being used to meet the natural gas need of the large U.S. northeastern market. Lower flows and higher pipeline transportation tolls from western Canada have exacerbated the cost advantage of imported US natural gas in the Eastern Canadian market. New pipelines are being proposed to bring new supplies of US produced natural gas to Canadian consumers. These changes in import and export patterns are reducing domestic market use of Canadian natural gas which has led to discussions around exports of liquefied natural gas for international markets and expanded use of natural gas in new markets in Canada.

A.8 Forecast Natural Gas Demand

On the next page, Figure 10 shows a year-by-year forecast for natural gas demand growth to 2035. Figure 11 compares the 2013 to 2035 increases in natural as demand across the residential, commercial, power generation, industrial, and transportation sectors.
The increases in natural gas demand between 2013 and 2035, as forecast by the NEB are as follows:

- Residential: +118.6 PJ (7.5% of total increase)
- Commercial: +98.4 PJ (6.3% of total increase)
- Industrial: +874.6 PJ (55.6% of total increase)
- Power generation: +379.3 PJ (24.1% of total increase)
- Transportation: +102.7 PJ (6.5% of total increase)

A year-by-year forecast for natural gas use for transportation is shown on the next page in Figure 12. By 2035, 105 PJ of natural gas use for transportation fuel is expected. This level of consumption equals the annual residential energy use from 1,000,000 Canadian homes.

While the increase in natural gas use to fuel natural gas vehicles (NGVs) is relatively small in comparison to the large increase in industrial and power generation, it is important to note that the growth in NGV fuel use roughly equals the growth in natural gas use in the residential sector.
A.9 Impact of Transportation Demand on Utility Infrastructure

In order to supply the needed CNG and LNG to serve the demand increase for the transportation sector, utilities and other market participants will be required to build new or upgrade existing infrastructure.

CNG

Given that CNG is primarily produced by compressing natural gas supplied by existing pipelines, there are two types of infrastructure investment needed – investment in station equipment including the compressor and investment in upgrading or “reinforcing” the service line to ensure there is adequate supply at the station for the projected fleet demand. For CNG refuelling stations, the gas pressure inlet requirements can, in theory, be as low as 10 psi, however, a higher pressure is preferred as this allows for less compression and lower associated power costs for compression. The existing utility distribution system can readily handle increased demand for CNG provided enough notice is given to allow for any required system upgrades.

Longer term, the use of CNG home refuellers is an opportunity that could provide the ability to refuel at home, limiting the need for an extensive network of public CNG refuelling stations. However, the current high installed cost of a CSA-certified home refueller means this opportunity remains undeveloped. For wide scale use of CNG home refuelling, the market requires an affordable (under $2,000 installed) CNG home refueller. The current installed cost exceeds $7,500, although work is underway in the U.S. to develop a more cost effective, higher performance home refueller. Once the technology improves and comes to market, the increased gas demand for home refuellers is not expected to affect the utility pipeline system. With a typical passenger vehicle requiring an estimated 2,000 m$^3$ of natural gas per year, this load is similar to the current demand for space and water heating for a home using natural gas.

Figure 12 – Projected Growth in Natural Gas Use for Transportation

![Natural Gas Use - for NGV Transportation](image-url)
LNG
For LNG, three types of infrastructure investments are needed – investments in LNG production facilities, investments in LNG refuelling stations to supply vehicles, and potential investments to upgrade existing infrastructure to supply a LNG production facility and/or to be able to offload LNG to bulk tanker trucks. The natural gas needed for liquefaction plants to serve transportation markets could be significant. For example, a large LNG liquefaction plant with a capacity of 100,000 gallons per day will require gas supply that is equivalent to the demand from a small industrial customer. For these large plants, some level of reinforcement of the natural gas distribution system could be required. For example, a 100,000 gallon per day LNG plant would need an 8 inch pipeline with pressures of over 500 psi to meet its natural gas supply needs. For smaller liquefaction plants of 10,000 gallons per day, a lower pressure line could be used, but some upgrading would likely still be required.

Where pipeline pressures are lower than what is required by the LNG plant, the installation of a pipeline compressor must be incorporated which adds cost to a project. Therefore, the optimal location for larger LNG plants are in areas where larger diameter pipelines exist and pressures are higher. These areas are usually located near existing industrial complexes or off higher pressure, larger diameter transmission pipelines.

In summary, given the extensive potential reinforcements required to supply a LNG production facility compared to CNG or LNG refuelling stations, longer lead times would be needed in order to accommodate utility planning and system upgrades. CNG and LNG refuelling stations will typically be located at or close to the fleet end user, so these small infrastructure investments will be more spread out - across the pipeline system for CNG stations and within a 300-400 km radius of LNG production points for LNG refuelling stations. Local impacts on pipeline capacity are not expected to be as significant for CNG stations as they will be for LNG plants which require more gas supply and higher pressures to operate.

A.10 Infrastructure to Supply Natural Gas to Transportation Market
In the past few years, there has been significant investment in new infrastructure in order to supply LNG and CNG to early fleet adopters transitioning from diesel to natural gas. These investments have been for new LNG production facilities as well as new CNG and LNG refuelling stations. These and future projects are driven by market demand. Ongoing discussions are commercial in nature, so it is not possible to provide a list of potential future installations until details are announced publicly by companies involved in various projects. Details for existing and known future investments are shown below:

**LNG production plants** - There are six existing LNG liquefaction plants in Canada including one in Quebec (Montreal), one in Ontario (Hagar near Sudbury), two in Alberta (Elmworth near Grande Prairie and Calgary), and two in BC (Vancouver Island and Delta). Major LNG plant expansions are planned in Delta and in Montreal. In addition, capital is being invested in Hagar to add bulk offloading capability. New LNG production facilities have been announced for Edmonton, Niagara Region, and Dawson Creek, although the Dawson Creek facility is not being built to serve the transportation market.

**LNG refuelling stations** - There are currently 12 LNG refuelling stations across Canada including both public and private stations. With respect to public LNG refuelling stations,
there are eight truckstop – or card lock-type stations that provide LNG. The initial build out of these stations follows two distinct corridors - one in the east and one in the west. The eastern corridor goes from Quebec City to Windsor, while the western corridor goes from Edmonton to Calgary and west to Vancouver. A common strategy is to start with a mobile LNG refuelling station and then to upgrade to a permanent station once there is sufficient demand from fleets.

Â **CNG refuelling stations** – In addition to the existing network of approximately 40 CNG refuelling stations that supply light-duty passenger vehicles, another 22 private CNG stations have been installed in the past few years for return-to-base fleet adopters in the refuse and transit sectors. Many of these stations are time fill stations for refuse trucks which are refuelled in an 8-10 hour timeframe. These stations typically have some fast fill capability as well. As of spring 2014, Canada has its first CNG refuelling station with high flow rates capable of refuelling CNG highway tractors on Vancouver Island in Langford, British Columbia.

Â **LNG import terminals** - There is one LNG import terminal operated in Saint John, New Brunswick. At present, this terminal is only set up to gasify imported LNG and to supply it into the existing transmission pipeline network for supply to the local Canadian Maritimes market and the northeastern U.S. market. While there have been very early stage discussions regarding the potential to use this source of LNG supply for East Coast marine vessels, there are no plans at this stage for supply to the transportation market.

Â **Bulk CNG and LNG projects** - There are now several industrial projects involving the use of bulk CNG. These projects include Heritage Gas supplying bulk CNG to industrial, off-pipe customers in Nova Scotia, Cavendish Farms use of CNG to meet factory energy demands on Prince Edward Island, Greenfield Ethanol’s use of CNG at their manufacturing plant in Ontario, and the CanGas Solutions-SaskEnergy project involving the supply of bulk CNG to replace diesel fuel used to power drilling rigs.

There are also a number of communities and mines in remote or northern areas of Canada that are using or planning to shift in part to LNG for power generation and/or residential and commercial heating. Currently, there are projects Inuvik in the Northwest Territories, and each of Watson Lake and Whitehorse in the Yukon that involve the planned use LNG to offset or replace diesel for part of or all of their energy needs. In addition to these community-based projects, there are several mining operations considering the potential to use LNG to reduce fuel costs.

While none of these bulk fuel projects currently include a transportation component, the availability of CNG or LNG and the related infrastructure may open up vehicle-specific opportunities at the local level.
A.11 Natural Gas Refuelling Technologies

This section of the report summarizes currently available technologies for CNG and LNG refuelling stations.

**CNG Refuelling**

CNG fast fill stations dispense natural gas at rates similar to gasoline or diesel refuelling. These stations cost in the range of $500,000 to $1,000,000\(^5\) depending on the technology involved, number of compressors, storage capacity, etc.

![Fast-Fill Station](image)

*Figure 13 – CNG Fast Fill Station*

As mentioned, Canada’s existing network of approximately 40 fast fill public stations has been designed for light-duty vehicle refuelling. An increasing trend in the U.S. market is the installation of high capacity, heavy truck CNG refuelling stations which are designed to ensure safe access and rapid refuelling at rates of up to 8-15 diesel gallon equivalent (DGE) per minute. At present, there is one heavy truck-capable CNG station in Canada on Vancouver Island that is used to fuel ten CNG Mack highway tractors owned by local fleet, ColdStar Solutions.

There are two variations on fast fill stations - cascade and buffer fast fill. Cascade fast fill stations dry, compress, and then store the natural gas for dispensing at a later time. Most private fleet stations and public CNG stations use a cascade application. Innovation in storage and refuelling technologies is a continuous process and will undoubtedly result in further improvements. Buffered fast fill stations are suited for high-fuel use vehicles such as shuttle buses, taxis, transit buses. These stations dry, compress, and directly dispense natural gas into vehicles. They have a smaller storage capacity, however, can dispense a large quantity of fuel in a short period of time as they use a high-capacity compressor.

Time-fill stations\(^6\) dispense fuel directly from the compressor into the vehicle. They are suitable for fleets that return to a central location for extended periods of time such as refuse trucks. These are the most affordable kinds of refuelling stations, however, they take the longest to fill the vehicles. Time fill stations can either be single unit where they serve just one vehicle overnight or they can be larger units that cost about $500,000 – $700,000 or more and can fuel 40 vehicles or more in an overnight 8-10 hour period.
Single vehicle re-fuelling appliances (VRAs) are typically used at homes, arenas or in factories for forklift and ice resurfacer refuelling. VRAs typically fill at the rate of 3 to 5 m³ per hour and are capable of refuelling a vehicle during an overnight period.

**CNG Refuelling Technology Under Development**

**Mobile Refuelling:** Mobile CNG refueling which consists of CNG storage tanks and dispensing equipment built into a delivery truck which can be parked at key operating locations helping to reduce early stage refuelling station costs. There are a range of technology solutions in the mobile refuelling market. For example, GTI in partnership with Ultimate CNG developed the FuelMule - a mobile - CNG fast-fill refuelling station that can fuel 35-50 medium to heavy-duty vehicles, fuelling two vehicles at a time.

**Scalability:** A host of large manufacturing companies are engineering increasingly smaller CNG compressor stations to meet new market needs. As stations decrease in size, the scale of the market opportunity increases as CNG becomes available for smaller fleets which use less fuel. Companies like GE, Eaton, Kairama, and others are working on smaller scale CNG systems.

**Home Refuelling:** Phill – the current CNG home refuelling appliance in North America is manufactured and sold by Italian company BRC. The installation cost for this time-fill home refuelling device in Canada is between $6,000-7,500. At this price point, the payback to consumers to switch to CNG is too long. The development of a cost effective CNG home refueller has been identified as a key technology development that is needed in order for natural gas vehicles to access the consumer market. While U.S. DOE had funded two projects to develop a cost effective home refueller with GE and Eaton, neither of this projects is moving.
forward as originally planned. The GE project has been wound down; the Eaton project has now been re-focused on the development of a more economic commercial-scale CNG refueller.

**LNG Technology Under Development**

**Small Scale Production & Refuelling:** Similar to CNG, smaller more cost effective modular LNG liquefaction units will help to expand market opportunities for LNG. While a smaller LNG production unit brings higher cost due to decreased economies of scale, their initial cost is lower which helps to minimize risk for investors. Further, by adding ‘trains’ or incremental smaller units as the market grows, the needed LNG supply can be better matched with fuel demand.

Nano and micro LNG technologies are also becoming more affordable. Companies such as GE, Dresser Rand, Galileo, Cryostar, Jereh International, and others sell small-scale LNG units that process as little as 6,000 gallons per day up to for Galileo to 50,000 gallons of LNG per day for GE’s LNG-in-a-box system.¹⁰

The Canadian Gas Association’s affiliate Energy Technology and Innovation Canada is studying multiple options for ultra small scale LNG production for off-pipe applications and looking at various aspects of LNG production and transport from a variety of technology manufacturers including Galileo, Dresser Rand, GTI, Wartsilla, Chart, Liquiline, SST Processing Solutions, and Jereh International.

**Transportation and Storage:** While LNG is an affordable fuel, increased bulk transport capacity would help make it even more affordable with reduced delivery costs. PROLOG Canada in partnership with Trimac and Cryogenic Vessel Alternatives has developed a 10-axle B-train for LNG delivery. PROLOG’s tank design would support higher LNG payload capacity and therefore improve economics of delivering LNG to mining sites and to remote northern communities.
B – Natural Gas-Powered Vehicles

B.1 Introduction

Natural gas-powered vehicles have been in use in Canada for close to 30 years. Until 2011, only CNG vehicles had been used in the Canadian market. Past market activity focused on on-road vehicles including transit buses and light-duty vehicles as well as off-road forklifts and ice resurfacer.

Early drivers of government interest in natural gas as an alternative fuel in North America centred on energy security and diversification of energy sources following the Oil Embargo of 1973-74 as well as on potential emissions reductions from the transportation sector. The Canadian government was a major supporter of early stage technology development activities related to natural gas as a transportation fuel including contributing to the creation of needed codes and standards, both domestically and at the international level. As a result of this past public-private collaboration, Canada now has many leading technology providers with the majority of equipment sales exported to markets outside of Canada. The list of companies includes:

1. Agility Fuel Systems – CNG and LNG fuel systems (Kelowna, BC)
2. Cummins Westport – natural gas engines (Vancouver, BC)
3. FTI International – CNG dispensers (Toronto, ON)
4. IMW Industries – CNG compressor stations (Chilliwack, BC)
5. Kraus Global – CNG dispensers (Winnipeg, MB)
6. Luxfer – CNG cylinders (Calgary, AB)
7. Viridis – CNG dispensers (Markham, ON)
8. Powertech Labs – CNG cylinder testing and certification (Langley, BC)
9. Westport – LNG tanks, engines & related technologies (Vancouver, BC)
10. Xebec Adsorption – natural gas dryers (Blainville, QC)

Several important technology development “firsts” were also achieved by Canadian companies with many of these achievements having been supported directly or indirectly by various levels of government:

- First natural gas transit bus in mid-1980s in Hamilton, ON
- First indoor transit bus refuelling in 1990s in London, ON
- First certified home refuelling appliance from FuelMaker in Toronto, ON
- First natural gas engine to match diesel engine efficiency from Westport in Vancouver, BC
- First engine to meet EPA 2010 emissions requirements from Cummins Westport with 8.9 litre ISL G natural gas engine

Early infrastructure development in Canada focused primarily on public refuelling stations for consumers and light-duty fleets, on private stations for transit, and on the use of VRAs for off-road vehicles. Investments in public CNG refuelling stations resulted in a network of more than 225 public CNG stations in six provinces at the peak of this phase of industry development more than a decade ago.
B.2 Stakeholders Consulted
The following organizations were contacted by the CNGVA or their reference materials were reviewed in the process of developing this section of the report:

- ATCO Gas
- Canadian Vehicle Manufacturing Association
- Compression Technology Corporation
- Enbridge Gas Distribution
- Ferus Natural Gas Fuels
- FortisBC
- Gaz Metro
- NGVAmerica
- SaskEnergy
- Union Gas

B.3 Current Vehicle Population & Fuel Usage
At present, there are an estimated 12,745 natural gas vehicles in use in Canada. The majority of these vehicles (94%) are light-duty vehicles which includes both on- and off-road vehicles such as forklifts and ice resurfacers. Medium-duty trucks and buses represent 4% of total NGVs in Canada, while heavy-duty trucks are 2% of the current vehicle population. The graph below provides a summary of the estimated number of each type of vehicle in Canada.

Approximately 80% of NGVs in Canada are on-road vehicles. The remaining 20% are off-road forklifts and ice resurfacers with 90% of these vehicles operating in the Ontario market. The reason for such a high percentage of off-road vehicles in a single province relates to: (a) the number of manufacturing facilities in Ontario with 130 facilities using natural gas forklifts; and (b) the fact that FuelMaker, a former Canadian company that manufactured vehicle and home refuelling appliances, was based in Ontario and offered equipment leasing options. Other companies including Ontario-based Compression Technology Corporation offer similar lease or equipment purchase options today. Forklifts are typically converted on an aftermarket basis. Ice resurfacers can be purchased as new factory-built vehicles.

![Figure 16 – NGVs in Canada by Vehicle Type](image)

With respect to on-road vehicles, the majority are converted light-duty vehicles with an estimated 10% of these vehicles in use in natural gas local distribution company fleets. Historically, Canada’s natural gas utilities have been leaders in using natural gas vehicles and in educating their customers about natural gas a transportation fuel. The majority of utility fleet vehicles are light-duty service vans and pickup trucks. Medium-duty factory-built dump trucks are also used by several utilities. Enbridge Gas Distribution played a leadership role in
purchasing the first factory-built vocational truck in Canada when it added a Freightliner CNG dump truck to its Toronto area utility fleet several years ago. The natural gas utilities have not reduced the number of NGVs in their fleets; in fact, they have increased the use of these vehicles. Where there is less light-duty vehicle activity compared to in the past is with respect to taxis and contractor vehicles. With taxis, hybrids and propane have a large share than natural gas. For contractor and small business owner fleets, there is less market development emphasis in this area given the focus on factory-built and high fuel consumption vehicles.

The new area of on-road market development activity in Canada involves factory-built medium- and heavy-duty vehicles. Approximately 745 new trucks and buses have been purchased for use in the Canadian market in the past few years. These vehicles include CNG refuse trucks, CNG transit buses, and both CNG and LNG highway tractors. All vehicles have been purchased by fleets and the majority of vehicles are for use in private sector fleets.

The availability of incentives at the provincial level has played an important role with respect to early adoption with 77% of the new medium- and heavy-duty vehicle purchases having been eligible for incentives in either Québec or in British Columbia. Incentivization has been most prominent in the area of highway tractor purchases where 85% of the 294 new highway tractors have benefitted from incentives. By comparison, 39% of the 421 new CNG refuse trucks have involved incentives.

On a by-province basis, the two provinces that currently offer incentives are leading in terms of the adoption of new factory-built trucks and buses as shown in Figure 18 below.
While federal excise tax does not apply to natural gas for transportation and most provinces also exempt natural gas from provincial road or fuel tax, it is not clear whether this significant tax advantage is a driver of early adoption. This aggregate tax benefit ranges from $.13-.20 per diesel litre equivalent (DLE), depending on the province. This tax treatment contributes to the overall economic benefit for early adopters, but the challenge is that there is a lack of certainty associated with this benefit given that governments could choose to modify tax policy which would, in turn, affect payback for early fleet adopters. While the taxation of natural gas as a transportation fuel may create a revenue stream for governments at a future date, the revenue potential at present is minimal.

Comparison with U.S. Market

The Canadian market is at an earlier stage of development compared to the U.S. market with respect to adoption of factory-built medium- and heavy-duty vehicles. Vehicle population data from NGVAmerica for 2013 shows that 40% of NGVs in use are medium- or heavy-duty vehicles compared to only 6% in Canada. There are several factors which could account for the higher proportion of factory-built vehicles in the U.S. including the availability of fiscal incentives at the state level, the existence of air quality and emissions reductions programs in California and other states, and the weight differences for heavy trucks. With respect to weights for highway tractors, the Canadian market is particularly disadvantaged by the lack of an engine above 400 horsepower given that heavier trucks are the norm in Canada. and are used in the oil, gas, forestry, and mining sectors.

<table>
<thead>
<tr>
<th>Type</th>
<th>Canada</th>
<th>U.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light-duty</td>
<td>11,924</td>
<td>85,000</td>
</tr>
<tr>
<td>Medium-duty</td>
<td>527</td>
<td>24,000</td>
</tr>
<tr>
<td>Heavy-duty</td>
<td>294</td>
<td>33,000</td>
</tr>
<tr>
<td></td>
<td>12,745</td>
<td>142,000</td>
</tr>
</tbody>
</table>

*Table 2 – Types of NGVs in Canada & U.S.*

In addition, based on 2013 data, the pace of new natural gas vehicle adoption is at least 50% higher in the U.S. with 9,525 new medium- and heavy-duty factory built vehicles purchased in 2013 compared to 745 new factory-built trucks purchased in Canada in the past few years. Applying a simple 1/10\(^{th}\) factor, in order to keep pace with the U.S. market, NGV sales in Canada would need to be at a level of 950 vehicles per year.

While the pace of adoption has been modest in Canada, the relative impact on natural gas demand has been greater with a more than 100% increase in natural gas use for new vehicles. Total natural gas consumption for NGVs in Canada is now estimated at 2.1 Bcf which is equivalent to 61.2 million litres of diesel fuel. This level of demand roughly equals the energy needed to heat 30,600 homes per year.

**Figure 19 – Natural Gas Demand for Transportation**
With 57.9 billion litres of gasoline and diesel used in the transportation sector in 2012,\textsuperscript{11} natural gas’ share is less than 1%. By comparison, NGV fuel consumption in the U.S. is estimated at 400 million gasoline gallon equivalent to approximately 1.5 billion litres of fuel.

**B.4 Status of Infrastructure**

Canada has 94 natural gas vehicle refuelling stations. These stations are in six provinces. This station count does not include smaller VRA stations which are typically used for off-road vehicles.

The breakdown of stations based on public or private access is shown in Figure 20. Almost all publicly-accessible CNG refuelling stations dispense fuel at a settled pressure of 3,000 psi. These public stations are fast fill stations designed for light-duty vehicles, so fill time for a larger truck or bus would be considerably longer than what would be acceptable to most fleets for normal operations. The one exception to this is Canada’s first truck-scale CNG refuelling station in Langford on Vancouver Island. This station is owned by utility, FortisBC, and fleets can access the site once they have set up a fuel account with FortisBC.

![Figure 20 – Public & Private Refuelling Stations](image)

Many of the private CNG stations in Canada dispense CNG at 3,600 psi including the ten new CNG stations that have been built in the last few years for return-to-base refuse fleets. Canada’s CNG refuelling station code, CSA B109, has always allowed 3,600 psi refuelling at private stations and, with the March 2014 code update, public stations can also now dispense to a settled pressure of 3,600 psi.
The majority of natural gas refuelling stations in Canada are stations that dispense CNG as shown in Figure 22. All LNG stations are new stations that have been built in the past few years. Of the eight stations shown as public LNG refuelling stations in the table below, five are mobile refuellers which will be replaced with permanent infrastructure as fuel demand increases. For CNG stations, a gas dryer is typically used in order to ensure minimal moisture content in the fuel. Drying the natural gas before it is dispensed into a vehicle is particularly important in cold weather climates. There is no similar requirement or other form of processing at the station for LNG.

![Figure 22 – Breakdown of CNG & LNG Stations](image)

Canada does not have any L-CNG stations. These are stations that have a LNG storage vessel as well as both LNG and CNG dispensers. A vapourizer is needed at these types of stations to warm the LNG to the right temperature and pressure for dispensing as CNG.

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>CNG</th>
<th>LNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public stations (47)</td>
<td>47</td>
<td>39</td>
<td>8</td>
</tr>
<tr>
<td>Private stations (59)</td>
<td>59</td>
<td>55</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>106</td>
<td>94</td>
<td>12</td>
</tr>
</tbody>
</table>

*Table 3 – Canadian Stations by Fuel Type*

The public LNG refuelling stations are located along trucking routes in each of Eastern and Western Canada as shown in the two figures below. This is the early start of corridor infrastructure to serve the on-highway trucking market.

![Figure 23 – Eastern Corridor LNG Refuelling Stations](image)
In the U.S., there are an estimated 1,425 refuelling stations including more than 100 stations located along interstate highways to supply heavy trucks. In the past few years, there has been significant investment to build new stations, both for return-to-base fleets and for highway trucking. An estimated 275 new refuelling stations were built in the U.S. in 2013. Also notable in the U.S., is the trend toward regional networks of truck-capable CNG refuelling stations that can refuel a medium- or heavy-duty vehicles in times similar to diesel fuelling.

B.5 Natural Gas Vehicle Manufacturers in Canada

There are three companies in Canada that manufacture natural gas buses:

- **New Flyer** - Winnipeg, Manitoba (transit buses)
- **Nova Bus** - Saint-Eustache, Quebec (transit buses)
- **Motor Coach Industries** - Winnipeg, Manitoba (coach buses)

With respect to medium- and heavy-duty truck assembly, only two facilities remain in Canada and neither of these plants assemble natural gas trucks. Hino assembles medium-duty trucks in Woodstock, Ontario and Kenworth assembles medium-duty trucks in Ste. Therese, Quebec. Natural gas ice resurfacters are manufactured by the Resurface Corporation in Elmira, Ontario.

Canada has a number of vocational truck body manufacturers who currently install natural gas fuel systems on vehicles or who have the potential to do these installations on a multi-stage manufacturing basis following Transport Canada’s National Safety Mark requirements. These companies include:

- **Universal Handling Equipment** – Hamilton, Ontario (refuse truck bodies)
- **Labrie** – St-Nicolas, Quebec (refuse truck bodies)
- **Shu-Pak Equipment** – Cambridge, Ontario (refuse truck bodies)
- **Fanotech Environmental** – Bracebridge, Ontario (refuse truck bodies)
- **London Machinery** – London, Ontario (cement mixer bodies)

As mentioned in the introduction to this section, several Canadian manufacturers produce components for natural gas vehicles. Agility Fuel Systems is the largest manufacturer of CNG and
LNG fuel storage systems in North America. They supply modularized fuel storage systems to a range of vehicle manufacturers. With a research and manufacturing facility in Kelowna, British Columbia, Agility was formed from the merger of Canadian company Enviromech and American company, FAB Industries.

Cummins Westport is a joint venture of Canadian company Westport Innovations and American company Cummins. The two natural gas engines that this company offers are manufactured in the U.S. at a Cummins diesel engine facility in order to take advantage of manufacturing synergies and a high degree of parts commonality with Cummins’ diesel engines.

Westport Innovations manufacturers LNG tanks for vehicles as well as related technologies for LNG fuel systems. The company is based in Vancouver, British Columbia.

Calgary-based Luxfer manufacturers Type 3 carbon fibre-wrapped cylinders for vehicles as well as for bulk trailer applications. Luxfer is a global manufacturer of industrial gas cylinders who purchased Canadian company Dynetek Industries including manufacturing facilities in Alberta and Germany.

B.6 Current Incentives in Canada

As previously mentioned, two provinces currently offer financial incentives to encourage more rapid adoption of natural gas vehicles. In both instances, the incentive funding is driven primarily by a policy objective related to reducing greenhouse gas emissions from the transportation sector.

**British Columbia Incentive Program**

In 2010, the province introduced its Clean Energy Act with the goal of promoting energy self sufficiency, independent power production, and reductions in greenhouse gas emissions. Then in 2012, Section 18 of the Act was amended to encourage the adoption of natural gas as a transportation fuel in British Columbia. This amendment authorized public utilities to develop the natural gas for transportation market with up to $62 million in vehicle incentives and $42 million in station investments. This new program allowed for:

1. **Funding for natural gas vehicle maintenance facilities** with up to 100% of the engineering cost and 50% of the labour cost covered.

2. **Funding for a portion of the incremental cost for a natural gas vehicle** based on a declining percentage annually. The year 1 incentives covered 80% of the incremental cost for an eligible factory-built medium- or heavy-duty vehicle. Year 2 incentives covered 70%. The current year, Year 3, provides for incentive funding for 60% of the incremental cost.\(^\text{13}\)

The vehicle incentive funding also applies to marine vessels, mine haul trucks, and locomotives. Both purchased and leased vehicles qualify. Vehicles must be operated within British Columbia for at least 75 percent of the time and incentive funding is prorated based on the percentage of kilometres operated within the province.
Also in British Columbia, FortisBC is also the only regulated utility in Canada that has a tailored rate for light-duty natural gas vehicles. This rate allows for up to $2,500 toward the cost of a light-duty vehicle or a forklift. Both factory-built and aftermarket conversions are eligible for funding.

**Quebec Incentive Program**

Based on its 2013-2020 *Action Plan on Climate Change*, the province of Quebec has a $28.3 million program called “Ecocamionnage.” The objective of this program is to promote the use of equipment and technologies designed to improve energy efficiency while reducing greenhouse gas emissions from the goods movement sector. Funding for the program comes from Quebec’s Green Fund. Modelled on a similar program the province had previously had in place, the Ecocamionnage program came into force on February 25, 2014 and will end on March 31, 2017.\(^\text{14}\)

The program provides funding for: (a) acquiring new equipment including auxiliary power units, aerodynamic devices, and new natural gas trucks; (b) certifying new technologies; (c) demonstrating technologies; and (d) for enhanced logistics. The funding amount for a natural gas truck is 30% of the incremental cost to a maximum of $15,000. Applicants are eligible for up to $1 million in funding per calendar year.

Quebec also offers accelerated capital cost allowance (CCA) for 2010-compliant LNG highway tractors. This measure was announced in Budget 2010 and included: (a) an increase in the CCA rate from 40% to 60% for new 2010 compliant trucks; and (b) an additional tax benefit by allowing the truck owner to gross up the value of the new truck by 85% before applying the accelerated CCA rate. The budget excerpt for this measure is as follows:

“To further support the trucking industry with regard to the higher costs of the new-generation engines, secure the industry’s active participation in efforts to reduce GHGs and foster a “green shift” in its fleet of vehicles, the 40% capital cost allowance rate applicable to trucks or tractors designed for hauling freight will be raised to 60% where such assets are new at the time they are acquired.

In addition, to foster the development in Québec of technology enabling the use of LNG to power heavy goods road transportation vehicles, an additional deduction of 85% of the amount a taxpayer deducts in calculating his income for the year on account of capital cost allowance will be allowed for trucks and tractors that, in addition to satisfying the conditions stipulated for qualifying for the 60% capital cost allowance, are fuelled by LNG.” \(^\text{15}\)

In order to be eligible, the gross vehicle weight must exceed 11,788 kilograms and new vehicles must be acquired prior to January 1, 2016. This measure does not apply to CNG trucks.
C – Natural Gas Vehicle On-Board Fuel Storage

C.1 Introduction

While CNG and LNG are both viable transportation fuels that are proven to provide cost savings when compared to diesel and gasoline, technology improvements to on-board fuel storage and delivery systems are needed and are constantly being evaluated. Ongoing research and innovation must be maintained in order for natural gas to continue to compete with diesel and gasoline as a fuel source for vehicles in North America. CNG is the most commonly used form of natural gas for on-board vehicular fuel across all vehicle classes.

To date, research for natural gas storage systems has focused primarily on improving CNG fuel systems and is targeted toward: (a) lowering the storage pressure of the gas using adsorbent and adsorbent-like materials; and (b) developing conformable-style tanks. In the U.S., the Advanced Research Projects Agency-Energy (ARPA-E) provides funding for high-potential, high-impact energy technologies that are too early for private-sector investment. ARPA-E awarded projects for CNG storage are generally focused on the fuel tank and storage medium. In Canada, there are no research initiatives that are underway to improve natural gas storage for vehicles.

As the use of natural gas as a fuel for vehicles grows, the variety of natural gas fuel storage systems also grows. Both CNG and LNG fuel systems are available in a range of sizes and configurations. There are currently five primary configurations of CNG fuel storage systems for heavy-duty vehicles consisting of:

1. Side mount rail mount (SM)
2. Behind the cab (BTC)
3. Roof mount (RM)
4. Front of body (FB)
5. Tailgate

There are three types of LNG storage systems: (a) side mount rail mount (SM); (b) roof mount (RM); and (c) behind the cab (BTC). The side mount rail mount systems are the most commonly used LNG system configuration. As a general rule of thumb, LNG takes up two times more space than diesel and CNG takes up four times more space than diesel on a vehicle to get an equivalent amount of useable energy.

There are five North American suppliers involved with fuel system development, design, and installation. The list of suppliers is shown in Table 4.

<table>
<thead>
<tr>
<th>Provider</th>
<th>Side Mount</th>
<th>Behind the Cab</th>
<th>Front of Body</th>
<th>Roof Mount</th>
<th>Tailgate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agility Fuel Systems</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>dHybrid</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quantum</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trilogy</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Mainstay</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4 - North American Natural Gas Fuel Systems Providers
Some typical natural gas fuel storage system configurations are listed in Table 5 below with their corresponding weights. The weight of a diesel system with the equivalent fuel capacity is also listed as well as the total weight gain from using a natural gas fuel system over a diesel system. The weight gain is calculated by: (a) subtracting the weight of the diesel system from the weight of the natural gas system; and (b) adding 400 lbs for the diesel system because the weight of a natural gas engine is approximately 400 lbs less than a comparable diesel engine.

<table>
<thead>
<tr>
<th>System Configuration</th>
<th>Weight</th>
<th>Diesel System Equivalent Weight</th>
<th>Weight Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CNG FUEL SYSTEMS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 x 40 DGE Side Mount (SM) (80 DGE) CNG</td>
<td>1600 lbs</td>
<td>705 lbs</td>
<td>+ 495 lbs</td>
</tr>
<tr>
<td>100 DGE BTC CNG</td>
<td>2800 lbs</td>
<td>880 lbs</td>
<td>+ 1520 lbs</td>
</tr>
<tr>
<td>120 DGE BTC CNG</td>
<td>3360 lbs</td>
<td>1055 lbs</td>
<td>+ 1905 lbs</td>
</tr>
<tr>
<td>160 DGE BTC CNG</td>
<td>4480 lbs</td>
<td>1410 lbs</td>
<td>+ 2670 lbs</td>
</tr>
<tr>
<td>100 DGE BTC + 40 DGE SM (140 DGE) CNG</td>
<td>3600 lbs</td>
<td>1230 lbs</td>
<td>+ 1970 lbs</td>
</tr>
<tr>
<td>120 DGE BTC + 2 x 40 DGE SM (200 DGE) CNG</td>
<td>4960 lbs</td>
<td>1760 lbs</td>
<td>+ 2800 lbs</td>
</tr>
<tr>
<td><strong>LNG FUEL SYSTEMS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 x 40 DGE LNG Tank</td>
<td>630 lbs</td>
<td>350 lbs</td>
<td>+ 120 lbs</td>
</tr>
<tr>
<td>2 x 40 DGE LNG Tank (80 DGE)</td>
<td>1255 lbs</td>
<td>705 lbs</td>
<td>+ 150 lbs</td>
</tr>
<tr>
<td>3 x 40 DGE LNG Tank (120 DGE)</td>
<td>1885 lbs</td>
<td>1055 lbs</td>
<td>+ 430 lbs</td>
</tr>
<tr>
<td>1 x 80 DGE LNG Tank</td>
<td>1255 lbs</td>
<td>705 lbs</td>
<td>+ 150 lbs</td>
</tr>
<tr>
<td>2 x 80 DGE LNG Tank (160 DGE)</td>
<td>2515 lbs</td>
<td>1410 lbs</td>
<td>+ 705 lbs</td>
</tr>
<tr>
<td>3 x 80 DGE LNG Tank (240 DGE)</td>
<td>3770 lbs</td>
<td>2110 lbs</td>
<td>+ 1260 lbs</td>
</tr>
</tbody>
</table>

*Table 5 – Weight Comparison - Comparable CNG, LNG & Diesel Engines and Fuel Systems*

C.2 Stakeholders Consulted
The following stakeholders were consulted directly or information from these organizations was reviewed in the context of developing the on-board fuel systems for CNG and LNG vehicles section of the report:
C.3 Fuel Systems Overview

**CNG Fuel Systems**

CNG is the most commonly used on-board vehicular fuel across vehicle classes. CNG is typically stored at 3,600 psi (250 bar) and 70°F (27°C) which increases its density by approximately 200 times the density at atmospheric pressure and temperature. In order to safely store CNG, specially designed cylinders must be used. There are four different types of cylinders. They are classified by the materials used in their construction. Table 6 describes the four CNG cylinder classifications as well as typical use considerations.

<table>
<thead>
<tr>
<th>Cylinder Type</th>
<th>Description</th>
<th>Characteristics</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>All Metal</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>Heaviest</td>
<td>Used where upfront vehicle cost is the most important factor.</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>Least Costly</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Metal liner using a composite wrapped around the middle of the cylinder.</td>
<td>Lighter than Type I, but more expensive than Type I.</td>
<td>Could be used in light-duty vehicles where weight is a greater factor.</td>
</tr>
<tr>
<td>III</td>
<td>Metal liner with composite, but the cylinder is carbon fiber-wrapped including the ends of the cylinder.</td>
<td>Lighter than either Type I or II, but more expensive.</td>
<td>Medium- duty and heavy- duty applications that are looking for weight savings, but where cost is a major factor.</td>
</tr>
</tbody>
</table>
### LNG Fuel Systems

LNG is well-suited to higher horsepower and long-haul trucking applications as it is the most energy dense form of natural gas. Natural gas is cooled to -260°F (-162°C) to produce LNG which is approximately 600 times more dense than natural gas at atmospheric pressure and temperature.\(^\text{18}\) An LNG fuel tank is a cryogenic container that stores the natural gas fuel as a highly refrigerated liquid at a low pressure. The tank is a double walled, stainless steel tank, where the space between the inner and outer tank is vacuum sealed similar to a thermos.

A major advantage of LNG as compared to CNG is that LNG tanks occupy less space on the truck than CNG cylinders to achieve the same fuel capacity. The typical operating pressure for LNG is from 100 to 230 psi (6.9-15.9 bar), which correlates to a temperature range of -200°F to -170°F (-140°C to -112°C).\(^\text{19}\) As shown in Figure 25, as the temperature of LNG is decreased, the stored pressure also decreases and the density increases.\(^\text{20}\) Therefore, as the storage temperature of the LNG is decreased, more fuel can be stored.

#### Table 6 - Types of CNG Cylinders

| IV | Gas tight liner reinforced by a full composite wrap of the entire liner. | Lighter than Type III across the full range of products. Smaller diameters generally more expensive than Type III with larger diameters generally less expensive. | Cost and weight are similar to Type III on diameters <21”. Type IV are typically used for diameters >21” where cost and weight are a major factor |

![Figure 25 – LNG Pressure & Density vs Temperature](image_url)
C.4 Fuel System Configurations
Specific mounting considerations and maximum capacities for the different CNG and LNG fuel system configurations follow. It should be noted that, regardless of the type of CNG or LNG fuel system used, a fuel management module (FMM) is required. The FMM manages the on-board storage of fuel and the delivery of the fuel to the engine within a precise temperature and pressure range.

Side Mount Rail Mount
The side mount rail mount system is similar to diesel fuel tanks in appearance as it is mounted to the frame rail of the truck under the cab. The fuel capacity of a CNG side mount system ranges from 15-63 DGE per side and 28-80 DGE per side for an LNG side mount system. A DGE represents a quantity of fuel with the same amount of energy contained in a gallon of diesel.21 The term used in Canada is a diesel litre equivalent (DLE).

A vehicle’s fuel capacity can be increased by packaging the side mount system on the driver side of the vehicle with another side mount system on the other side of the vehicle and/or with a behind the cab system configuration. Using this approach for CNG given today’s offerings can provide capacity of up to 286 DGE. When bundling LNG systems in this manner, a capacity of up to 300 DGE can be achieved.

Depending on the configuration of side mounts and behind the cab systems, the side mount may have an integrated fuel management module (FMM) on at least one side.

Figure 26 shows a picture of a CNG side mount rail mount system with an integrated FMM at the back end of the system.22

Figure 26 – 45 DGE CNG Side Mount Rail Mount System with Integrated FMM
A side mount LNG system is shown in Figure 27. This is the most common LNG configuration.\textsuperscript{23}

\textbf{Figure 27 - 70 DGE Per Side LNG Side Mount Fuel System}

\textbf{Behind the Cab}

Behind the cab (BTC) systems are installed behind the cab of the truck and require at least 22 inches of frame rail space. The fuel capacity of CNG BTC systems range from 15 to 160 DGE and the fuel capacity of LNG BTC systems range from 40-190 DGE. The FMM of a BTC system is either located in a separate FMM box below the cylinder cabinet or is integrated in the cabinet as shown in Figure 28 and 29, respectively.

\textbf{Figure 28 - 60 DGE Behind the Cab System with Non-Integrated FMM}
Roof Mount
A roof mount system is mounted on the roof of the vehicle and is typically used on transit and refuse vehicles. Transit vehicles accommodate systems with fuel capacities typically ranging from 126-200 DGE, whereas refuse vehicles typically use 60-100 DGE systems. For roof mount systems, the FMM is mounted on the frame rail for ease of access. As seen in Figure 30 a roof mount system on a transit bus is very large. Not only does the size of the system increase the weight of the bus but, the addition of extra support and larger brakes also adds weight. To help support the roof mount system diagonal struts are positioned on the inside of the bus. The total added weight for a large roof mount system like the one shown below is typically upwards of 3,000 pounds.

Figure 29 - 155/160 DGE Behind the Cab Fuel System with Integrated FMM

Figure 30 – 144 DGE Roof Mount System on a Transit Bus
**Front of Body**
Front of body systems are used on refuse vehicles and are installed on the front of the body of the truck when there is no room on the chassis rail for a behind the cab system. The brackets of the front of body fuel system are typically welded onto the exterior surface of the body so that the fuel system sits above any components that take up room on the chassis rail.

Front of body fuel systems are currently only available as a CNG system and have a fuel rage of 60-75 DGE. The advantage of the front of body system is that it gives the vehicle a lower height which reduces the likelihood of any driving restrictions. Similar to the roof mount system, the FMM is mounted on the chassis for easier access. Figure 31 has a front of body system mounted above the components taking up the space on the chassis rail.

![Figure 31 – 75 DGE Front of Body CNG Fuel System on a Refuse Truck](image)

**Tailgate**
The tailgate system is a fully integrated system that is mounted on the tailgate and acts as a regular tailgate. Similar to the front of body system the tailgate system allows for a lower vehicle height.
Figure 32 shows a CNG tailgate system which can range from 45-105 DGE depending on the number of cylinders it contains.24 The system can contain up to seven cylinders, with each cylinder having a fuel capacity of 15 DGE.

CNG Fuel Management Module
A highly sophisticated integrated FMM manages the onboard storage of fuel and the delivery of the fuel to the engine within a precise temperature and pressure range. The FMM typically houses filtration equipment, refueling and defueling receptacles, shut-off valves, temperature and pressure sensors, regulators, and various other components for safely and effectively delivering fuel to the engine. Figures 33 and 34 show the main components of an FMM and Table 7 lists their functions. An example of an FMM integrated into a behind the cab system can be seen in Figure 35.25
### Table 7 - FMM Components & Their Functions

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>¼” Turn Shut off Valve</td>
<td>Isolates components downstream including those enclosed inside the FMM to manually shut off the fuel supply to the engine and filter/regulator assembly components.</td>
</tr>
<tr>
<td>Fast Fill Receptacle</td>
<td>The fast fill receptacle is used to fill the fuel system quickly.</td>
</tr>
<tr>
<td>Slow Fill Receptacle</td>
<td>The slow fill receptacle is used to slowly fill the fuel system, typically, over-night.</td>
</tr>
<tr>
<td>Defuel Receptacle</td>
<td>The defuel receptacle is used to safely defuel the system for maintenance to avoid venting fuel to atmosphere.</td>
</tr>
<tr>
<td>High Pressure Gauge</td>
<td>Indicates the pressure of the CNG cylinders.</td>
</tr>
<tr>
<td>Low Pressure Gauge</td>
<td>Indicates the pressure of the fuel leaving the pressure regulator to the engine.</td>
</tr>
<tr>
<td>Pressure Regulator</td>
<td>Reduces the CNG pressure coming from the cylinders to a preset level (approx. 125 psi) which allows the engine fuel metering system to properly control the natural gas. Provides sufficient flow for all vehicle operation conditions and precise pressure sensing</td>
</tr>
</tbody>
</table>
LNG Fill Interface

While the components of a CNG FMM and an LNG fill interface have their differences, the overall function remains the same. The LNG fill interface is where the system is filled and fuel is conditioned to be sent to the engine. Figure 36 shows a typical fill interface of an LNG tank and Figure 37 shows the fuel flow schematic of an LNG system. Table 8 describes the components in Figure 37.
<table>
<thead>
<tr>
<th>Item #</th>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LNG Dispenser</td>
<td>With a locking fueling nozzle, provides fuel to the tank</td>
</tr>
<tr>
<td>2</td>
<td>Top Fill</td>
<td>Enables single hose fueling – spray of liquid collapses vapour for faster fills</td>
</tr>
<tr>
<td>3</td>
<td>Fuel Receptacle</td>
<td>A poppet valve on the receptacle is automatically opened by engagement of the fueling nozzle onto the receptacle. Receptacle has matching locking mechanism to the fueling nozzle to ensure a tight seal during fueling.</td>
</tr>
<tr>
<td>4</td>
<td>Fuel Gauge</td>
<td>Reads the fuel level and can be mounted in the cab or in a protected area by the fuel receptacle.</td>
</tr>
<tr>
<td>5</td>
<td>Vapour Space</td>
<td>Has a small hole near the top of the tank to absorb excess vapour pressure. Extends tank hold time when a vehicle is not in use for several days.</td>
</tr>
<tr>
<td>6</td>
<td>Economizer Regulator</td>
<td>Determines tanks operating pressure.</td>
</tr>
<tr>
<td>7</td>
<td>Heat Exchanger</td>
<td>Uses the coolant fluid from the engine to warm the LNG to a gaseous phase.</td>
</tr>
<tr>
<td>8</td>
<td>Over Pressure Regulation</td>
<td>Ensures that the vapourized fuel pressure does not exceed the pressure specified by the engine manufacturer.</td>
</tr>
</tbody>
</table>

*Figure 37 - LNG Fuel Flow Schematic*

*Table 8 - LNG Components & Their Functions*
C.5 Impact on Safety and Usability

While natural gas has many physical properties that make it a safer fuel than diesel or gasoline, there are some aspects of natural gas fuel systems that affect vehicle design and in-use considerations related to vehicle safety. For example, with some configurations such as roof mount systems, the height of the overall vehicle center of mass can increase, potentially increasing the vehicle’s roll-over risk. In such cases the chassis supplier will often upgrade the suspension and axle rating to mitigate the risk of a roll-over.

Another aspect that affects the safety is improper mounting methods that cause damage to the tank. Figure 38 shows a Type 2 CNG cylinder that was incorrectly mounted using a steel bracket that covered the aluminum heads of the cylinder. As a result of the improper installation, galvanic corrosion occurred causing damage to the cylinder.

Industry best practices suggest that CNG cylinders only be supported with rubber-padded straps that wrap around the centre of the cylinder. The only exception to this is for cylinders that are designed with an extruded boss on each end of the cylinder. These types of cylinders can be secured at the necks.

![Figure 38 - Galvanic Corrosion on CNG Cylinder Heads from Use of Steel Bracket on Aluminum](image)

A safety problem can also arise if there is insufficient rubber padding isolating the steel strap from the fiberglass tank. In these instances, vibrations from driving can cause the strap to scratch and damage the surface of the cylinder as seen in Figure 39.
Not only does the rubbing from vibration cause damage to the cylinder, but it could also cause the strap to break resulting in the cylinder coming loose from the bracket and dragging on the road resulting in the types of damages shown in Figures 40 and 41. Even though the damage looks significant, in both cases the cylinders were burst tested by the cylinder manufacturer and it was found that the damage had no effect on the minimal required-burst strength of the cylinders required by applicable regulations.
The high pressures associated with CNG fuel storage often lead to the misconception that CNG fuel systems are dangerous, however, a combination of the physical properties of CNG and robust fuel systems make CNG safer than diesel or gasoline. Since natural gas has a much higher ignition temperature than diesel and gasoline and only ignites within a very tight range, there is a much lower chance of an incident where the fuel ignites. Table 9 lists the auto ignition characteristics of natural gas, diesel, and gasoline. Natural gas fuel systems undergo safety tests to ensure they can withstand severe incidents.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Auto Ignition Temperature</th>
<th>Range of Flammability (% by volume of air)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>1100°F (593°C)</td>
<td>5-15</td>
</tr>
<tr>
<td>Diesel</td>
<td>350°F (177°C)</td>
<td>1.3-6.0</td>
</tr>
<tr>
<td>Gasoline</td>
<td>530°F (277°C)</td>
<td>1.4-7.6</td>
</tr>
</tbody>
</table>

Table 9 - Auto Ignition Temperature & Flammability Range of Fuels

Figures 42 and 43 show a bonfire test as well as a side mount system undergoing a 30 mile per hour (MPH) side impact test. In the bonfire test, a 155 DGE system pressurized to 3,600 psi was safely vented without a cylinder failure or ignition of the venting gas. After the side impact test the cylinder was burst tested and exceeded the original design intent.
Figure 42 - Bonfire Test of a 155 DGE System Pressurized to 3,600 Psi

Figure 43 - Side Mount Rail Mount System Undergoing a Simulated 30 MPH Side Impact Test
While tests can show the safety of natural gas fuel systems, only actual events can prove what has been tested. Below is a picture of a heavy-duty truck after a severe impact. It can be seen that while the cab of the truck is completely destroyed the behind the cab fuel systems and cylinders still remain. In addition all of the fuel in the cylinders was vented safely.

![Heavy-Duty Truck with CNG Behind the Cab System After Severe Impact](image)

**Figure 44 – Heavy-Duty Truck with CNG Behind the Cab System After Severe Impact**

Similar to CNG cylinders, LNG tanks undergo destructive testing to ensure the safety of the system. There are some unique safety issues related to LNG due to the cryogenic temperatures required to maintain natural gas in its liquefied form. These issues include an inability to add an odorant to the fuel, the potential for cryogenic burns, a need for intensive monitoring and control for bulk transfer and storage, the potential for weathering (slowly changing composition as a result of some components boiling off before others), the possibility of a rapid-phase transition resembling an explosion, reduced ductility and impact strength of wetted materials, and the extreme thermal cycling to which equipment and sealing devices can be exposed. Tests that have been completed to ensure the safety of LNG fuel tanks are a drop test at 10 and 30 feet, a bonfire test, as well as a puncture test with two different puncture sizes.

In order for the LNG tanks to pass the drop tests there could not be any loss of product for a period of one hour after the drops. For both tests the pressure and weight of the tanks were measured every ten minutes, and in both cases the pressure and weight remained constant throughout. Figure 45 shows the drop test set up for the 30 foot drop while Figures 46 and 47 show the damage to the tanks for the 10 foot and 30 foot test, respectively.
Figure 45 - LNG Tank Prior to 30 Foot Drop Test

Figure 46 - Damage to LNG Tank from 10 Foot Drop Test

Figure 47 - Damage to LNG Tank from 30 Foot Drop Test
The bonfire test performed on a tank is designed to ensure that an LNG fuel tanks safety devices function properly in the case of a fire. For an LNG tank to pass the bonfire test, it must be subject to an external temperature of 538 °C for 20 minutes without reaching relief pressure. Figure 48 shows an LNG tank undergoing a bonfire test in which the tank passed by not venting during the 20 minute duration.  

![Figure 48 - LNG Tank Undergoing a Bonfire Test](image)

Two puncture tests were performed on LNG tanks in an effort to learn how an LNG fuel system may react as a result of a puncture to the system. The two hole sizes that were achieved from the puncture tests were approximately 7.62mm from firing a 0.30 caliber bullet and about 28.5mm by means of a steel rod fired at high speed using a hydraulic ram. Figure 49 shows the initial jet that the fuel began escaping in and Figure 50 shows the flame from the burning of the vapour immediately following ignition. It was unclear whether the fuel was in a gaseous or liquid state before it ignited as it was surrounded by a white cloud of condensation. Once the fuel had been ignited the flame was clear for the first three feet and then orange for the remaining six feet.

![Figure 49 - Fuel Escaping the LNG Tank as a Result of a ~7.62mm Puncture](image)
After the tank was punctured by the steel tip, fuel began escaping the LNG tank as a large liquid jet which began to vaporize immediately and then catch fire. The large fire can be seen in Figure 51 which reached an approximate size of 30-40 feet tall and lasted for about 25 seconds but the radiant heat was significant enough to be felt by the observers approximately 60 feet away. After the large fire settled, a smaller fire remained for a period of time.
Even after an LNG fire is extinguished, the risk of cryogenic burns still exists related to direct contact with the fuel itself. In an accident, care must be taken when righting a vehicle to ensure the liquid fuel does not escape and injure any persons in the vicinity of the vehicle.

Tank design is critical to mitigate the potential hazards of a tank rupture and subsequent fire. The two puncture tests were designed to simulate worst case scenarios as the tank would be difficult to puncture in an accident due to its inherently strong construction. Similar to CNG, tests can show the safety of LNG tanks and aid in understanding how one may act in worst case scenarios, however only actual events can prove what has been tested. Figure 52 shows a heavy-duty truck that was in a fire as a result of an electrical short. It is clear that the fire destroyed everything in its path except for the LNG fuel system on the side of the frame rail.
C.6 Cylinder Valves

Currently every individual cylinder on a natural gas fuel system must be equipped with a valve capable of isolating the cylinder from the rest of the fuel system. In the United States, CNG practices were first patterned after the Transportation of Dangerous Goods regulations and, as a result, NFPA 52 required valves to be equipped on every cylinder in accordance with the Department of Transportation regulations.\(^{36}\)

Over the lifespan of NGV use, many serious incidents and most natural gas fuel system fatalities in North America have occurred because of cylinder valves. Some common issues with valves that have contributed to these incidents include:

1. Valves adding many uncontrolled leakage points.
2. Some newer manual valve designs having unsafe failure modes.
3. Valves adding concerns about leakage and impact damage.
4. Valves preventing expedited defueling after an accident or fire.

In addition to the issues with the valves, there are also safety concerns when dealing with fuel systems that have been in an accident for first responders. Recommended practice is that the Authority Having Jurisdiction (AHJ) be educated regarding common first responder practices for
natural gas vehicles. In addition, it is becoming more common that vehicles, especially transit buses, be equipped with a first responder tag as discussed in the following section. This area should be further explored.

While CNG vehicle safety test requirements are equivalent to or better than their gasoline and diesel counterparts, industry experts, government regulators and vehicle, fuel systems and cylinder manufacturers are all working together to further optimize the use and position of cylinder valves to enhance CNG vehicle safety.

C.7 First Responder Safety

Since natural gas is stored at either 3,600 psi in a CNG system or at a low temperature of -260°C in an LNG system, it cannot be treated the same as diesel or gasoline in an emergency situation. Once the vehicle has been identified as CNG or LNG by one or both of the two blue diamonds shown in Figure 43, there are different hazards that first responders need to be aware of.

![CNG & LNG Blue Diamonds Required on NGVs](image)

In the case of CNG systems, the pressure can be upwards of 4,250 psi and any compromise of the fuel supply piping should be avoided. If the vehicle is damaged, a leak in a CNG fuel system can easily be detected as it is odorized. A leak in an LNG fuel system will be more difficult to detect because the fuel is not odorized. Further, extra caution must be used when dealing with a LNG leak because of the extremely low temperature, which can cause first degree burns and frostbite if it comes in contact with skin. Inhalation of LNG vapours can also be harmful.

In the case of a fire in a CNG vehicle, similar extinguishing practices to a gasoline fire should be used. For LNG fires, attempting to extinguish the fire with water will cause the fuel to vapourize. Therefore, a dry powder or Purple-K-Powder should be used to extinguish the fire. In the case of an emergency on a natural gas vehicle an emergency response card may be present in the user manual. An example of an emergency response card can be seen in Figures 54 and 55.
**Figure 54 - Front Side of an Emergency Response Card for CNG Bus**

**Figure 55 - Reverse Side of an Emergency Response Card for CNG Bus**
C.8 Proposed Technologies to Improve Storage

While CNG and LNG are both viable transportation fuels that can provide cost savings when compared to diesel and gasoline, technology improvements to onboard fuel storage and delivery systems are constantly being evaluated. Research for natural gas storage systems is ongoing in areas including adsorbent technologies, higher pressure storage, and conformable tanks. Depending on which of these technologies proves to be commercially viable, existing standards will need to be modified and/or new standards will need to be developed to accommodate the use of different materials and different design approaches.

Adsorbed Natural Gas Technology

Adsorbed natural gas (ANG) is a technology for natural gas storage where the phenomena of adsorption is applied to maximize the capacity of a specific volume. Adsorption is a surface-based process where gas molecules adhere to a solid surface. In an ANG tank, the gas is adsorbed by a porous adsorbent such as activated carbon, for example, that is inside a thin-walled tank. The activated carbon contains a large number of pores which increases the surface area and allows the pores to fill with adsorbed molecules which are in equilibrium with the pressure and temperature of the gaseous phase. When the pressure of the gaseous phase is reduced as the gas is used in the engine, more molecules desorb from the pores to maintain the equilibrium gas phase pressure and temperature. Eventually when the pores are empty, the gas pressure reduces and the tank is empty.

Typical adsorbents are used in the form of spherical pellets, rods, or moldings. ANG technology is designed so that the gas is stored at relatively low pressures of 500-600 psi (34.5-41.4 bar). Figure 56 shows a cross-section of an ANG tank with a molded porous material as well as a full sized tank for a small vehicle [19].

![Figure 56 - Small Scale Adsorbed Natural Gas Fuel Storage Tank](image)

Although ANG technology can be used for bulk scale storage, the early work on ANG storage systems has been focused on developing safe, efficient and competitive fuel storage tanks for vehicles. The goal of ANG storage is to achieve the same capacity as CNG in less space, at a competitive cost. In order to achieve this outcome, the adsorption capacity of the carbon must
be maximized. In order for ANG systems to be a viable option for fuel storage tanks the challenges and limitations in Table 10 must be overcome.40

<table>
<thead>
<tr>
<th>Challenge/Limitation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat released during adsorption</td>
<td>Activation of the adsorbent material at high temperatures causes the pores of the adsorbent to open up, which decreases the total surface area inside the tank and in turn decreases the capacity.</td>
</tr>
<tr>
<td>Integration of tanks</td>
<td>Vehicle suppliers will not want to change their current designs so fuel systems will have to be designed to fit on existing designs without conflicting with design handling or regulations.</td>
</tr>
<tr>
<td>Fuelling and Delivery</td>
<td>A fueling nozzle specific for ANG may have to be designed as well as fast fuelling systems that conform to regulations. The ranges available from ANG must be comparable to CNG, LNG, gasoline, and diesel.</td>
</tr>
<tr>
<td>Gas Quality, Lifetime and Maintenance</td>
<td>The effect that the gas quality has on the adsorption efficiency as well as the life and maintenance frequency and cost must be acceptable. Dirty fuel is one of the major challenges for ANG as the fuel must be filtered during fueling as well as before it enters the engine.</td>
</tr>
</tbody>
</table>

Table 10 – Challenges & Limitations of ANG Fuel Storage Systems

Metal Organic Frameworks
BASF is currently working on a major project to produce a metal organic framework (MOF) for use inside natural gas fuel tanks as an enhanced adsorbent material. MOF materials are crystalline structures that have nanometer-sized pores that allow for the efficient storage of natural gas.41 MOFs currently have the highest known surface areas and storage ability for adsorbent type materials. For example, one gram of a MOF material has the equivalent surface area as a soccer field.42

The natural gas fuel storage capacity for heavy duty trucks could be increased through the use of MOFs. In addition, the use of MOFs could allow for decreased CNG storage pressures. Decreasing the storage pressure of CNG tanks could have significant cost savings for infrastructure as well as for on-vehicle fuel systems.

MOF materials are not currently commercially available, however, BASF plans to have MOF materials for vehicular applications available in 2015.43 MOF materials are produced by combining a metal salt with an organic linker to form a highly crystalline structure as seen in Figure 57. Currently BASF has a number of demonstration trucks equipped with tanks containing MOF adsorbent material. For these trials,
the MOF tanks are pressurized to the conventional CNG cylinder pressures of 3,600 psi (250 bar), and the adsorbent material in the tank therefore acts as a range extender.

![Figure 57 - Production of a Metal-Organic Framework](image)

**Higher Fill Pressures**
CNG is not inherently limited to a maximum storage pressure of 3,600 psi. There is technology available to increase the storage pressure to 5,000 psi (350 bar) which has some advantages. Increasing the storage pressure of natural gas to 5,000 psi gives approximately a 28% fuel capacity increase per cylinder. With an increased fuel capacity, trucks would not have to stop and refuel as often, allowing the driver to be on the road for longer periods of time during a shift.

To increase the pressure rating of CNG cylinders, the thickness of the walls must be increased by adding more composite wrapping. The additional wrapping increases the weight and cost of the cylinders which would have an offsetting negative effect on fuel economy and on return on investment. Additionally, with a higher pressure fuel system, the rest of the fuel system costs – tubing, fittings, filters etc. – would increase significantly. Higher pressure cylinders would increase the weight of the fuel system on the truck and also decrease the available payload space as the vehicle must remain within safety regulations. A further issue with increasing the storage pressure of natural gas to 5,000 psi is that much of the infrastructure is currently designed for either 3,000 psi (200 bar) or 3,600 psi (250 bar) and would require costly upgrades.

The disadvantages of 5,000 psi fuel storage currently outweigh the advantages. There is potential that, over time, technology improvements will either overcome these disadvantages or eliminate the need for increased pressure by reducing the pressure required to achieve an acceptable driving range.

**Research Initiatives to Improve Natural Gas Storage**
In the U.S., the Department of Energy’s Advanced Research Projects Agency-Energy (ARPA-E) provides funding for high-potential, high-impact energy technologies that are too early for private-sector investment. ARPA-E awardees are working towards developing new ways to generate, store, and use energy. ARPA-E has invested $21 million into eight research initiatives to advance the technology of CNG fuel storage systems. The research projects and their timing are listed in Table 11.46
<table>
<thead>
<tr>
<th><strong>Project</strong></th>
<th><strong>Description</strong></th>
<th><strong>ARPA-E Award, Project Term</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Low Pressure Material-Based Natural Gas Fuel System</strong></td>
<td>An onboard adsorbed natural gas tank system with a high-surface-area framework material will be developed, which will increase the energy density of CNG at low pressures.</td>
<td>$5,050,082</td>
</tr>
<tr>
<td><strong>2. Low Pressure Conformable Natural Gas Vehicle Tank</strong></td>
<td>Materials with the best characteristics for low pressure natural gas storage will be identified. These gas-storing materials are known as metal organic framework (MOF) adsorbents that hold natural gas the way a sponge holds liquids.</td>
<td>$1,499,999</td>
</tr>
<tr>
<td><strong>3. Adsorbent Materials for Natural Gas Storage</strong></td>
<td>A natural gas tank for light-duty vehicles that features a thin, tailored shell containing adsorbent pellets with nano-scale pores that function as valves to manage the pressure and facilitate more efficient storage.</td>
<td>$874,999</td>
</tr>
<tr>
<td><strong>4. Intestinal Natural Gas Storage</strong></td>
<td>Natural gas storage tanks made of small-radius, high-pressure tubes that allow for maximum conformability to vehicle shape. The space-filling tube design is modeled after the human intestines provides for maximum storage capacity.</td>
<td>$3,450,000</td>
</tr>
<tr>
<td><strong>5. Ultra-Light-Conformable Natural Gas Tank</strong></td>
<td>Low-cost, conformable natural gas tank for light-duty vehicles. The tanks are produced using friction stir welding, where metal is softened allowing the metal to retain its original properties. The tanks incorporate a high-strength internal strut technology that efficiently fits into a vehicle.</td>
<td>$600,000</td>
</tr>
<tr>
<td><strong>6. Conformable Core Gas Tank</strong></td>
<td>REL is exploring various materials that could be used, which allow for the internal structure of the tanks to be any shape as well as various methods of manufacturing the interconnected core structure and the tank skin.</td>
<td>$3,000,000</td>
</tr>
<tr>
<td><strong>7. Highly Adsorbent Materials for Natural Gas Storage</strong></td>
<td>Development of a highly adsorbent material for use in onboard natural gas storage tanks that could increase the volumetric energy density of methane, which makes up 95% of natural gas.</td>
<td>$3,000,000</td>
</tr>
<tr>
<td><strong>8. Modular Natural Gas Tank</strong></td>
<td>Modular natural gas storage units are being designed that can be assembled to form a wide range of shapes to fit a wide range of undercarriages.</td>
<td>$4,299,964</td>
</tr>
</tbody>
</table>

*Table 11 – ARPA-E Funded Projects to Advance Natural Gas Storage Systems Technology*
C.9 Common Issues Related to Natural Gas Storage

The largest disadvantage of CNG fuel storage systems is the size and weight of a system compared to a diesel system. The size of the systems can be a challenge when finding a location on the truck where the system will fit. In order for the vehicle to remain compliant with regulations, the chassis rail and axle may need to be upgraded due to the extra weight of natural gas systems compared to diesel. In addition to upgrading some components of the vehicle, there is also a payload tradeoff. The vehicle will not be able to carry as much of a load because the vehicle weight will take up a larger percentage of the overall combined weight of the vehicle. The aerodynamics of the truck can also be affected by the size of natural gas fuel systems.

Aerodynamics can have a significant impact on the fuel economy of heavy duty trucks, especially those used for long haul applications. Since natural gas fuel systems tend to be bulky, a considerable amount of drag is caused by these systems which reduces the fuel efficiency of the vehicle. In order for natural gas to be able to compete with diesel in terms of fuel economy, a joint effort between the truck and fuel systems manufacturing companies must be made to integrate the fuel system into the aerodynamics of the trucks.

Originally, natural gas fuel systems were built and put on vehicles with little thought about aerodynamics because the cost of the fuel is so much lower than gasoline or diesel. Because of the bulky nature of natural gas fuel systems, aerodynamic side skirts and side extenders had to be removed from the truck to make room for the behind the cab and side mount natural gas fuel systems.

In an effort to increase the fuel economy of natural gas vehicles an ongoing study performed by U.S.-based Saddle Creek Transportation is in place to measure the fuel economy of four generations of CNG highway tractors. Throughout the study, generations 1 through 4 had improved aerodynamics which led to increasing the fuel economy from 5.3 MPG to 6.3 MPG.

The first generation highway tractor only had a roof fairing for aerodynamics and there was a large gap between the cab and the trailer as seen in Figure 58.

![Figure 58 - First Generation CNG Highway Tractor Study Vehicle](image)
For generation 4 to achieve a fuel economy of 6.3 MPG, a fuel system that fit behind the side extenders was designed and the side skirts were utilized as seen in Figure 59.49 This 4th generation vehicle only has a behind the cab fuel system because the current side mount designs do not fit under the side skirts of the vehicle. Generation 5 will aim to have side mount natural gas fuel systems that will fit inside the side skirts to improve the overall fuel capacity of the vehicle. A 5th generation vehicle would look along the lines of the rendering in Figure 60.

![Figure 59 - Fourth Generation CNG Tractor Aerodynamic Study Vehicle](image)

The fuelling rate of natural gas fuel storage systems poses a technical challenge compared to diesel or gasoline because of the heat of compression while fueling. While time fill – a term used to define filling a vehicle over a long period such as overnight - is very effective from a
maximizing fuel storage perspective for return-to-base fleets that only require one fill per day, heating while fast filling causes the natural gas to be less dense. This results in less than full fills.

In general, the industry is seeing fast fill quality of fill in the 75% to 85% range, meaning a 100 DGE fuel system would only net 75 to 85 DGE of fuel in the tanks once the heat dissipates to ambient conditions. As is common, the tanks must be refilled or overfilled – typically to 4,000 or 4,200 psi - which allows higher final density levels in the cylinder. CNG cylinders are legally allowed to be filled to 1.25 times the service pressure which is 4,500 psi, however the industry standard stops at about 4,200 psi. R&D effort aimed at improving the effectiveness of fast filling is a priority, particularly for medium- and heavy-duty vehicles.

C.10 Specific & Volumetric Energy, Cost and Refueling Rate

Energy density, fuel economy, as well as the cost and fueling rates are important characteristics of fuels for transportation. Diesel has a specific energy of approximately 43 MJ/kg and a specific energy of about 35,900 MJ/m³. Specific energy is an intensive property and therefore cannot be changed, however, the volumetric energy is an extensive property and depending on the temperature and pressure the volumetric energy of a fuel changes. Thus, the benchmark for heavy duty trucks is a volumetric energy of about 35,900 MJ/m³.

Natural gas has a larger specific energy than diesel at approximately 46 MJ/kg however, the volumetric energy of NG is about 35 MJ/m³ at standard atmospheric pressure. In order for natural gas to begin to approach a similar volumetric energy to diesel it must be stored at high pressures in the form of CNG or at very low temperatures in the form of LNG. At the standard storage pressure for CNG (3,600 psi) the density of the gas is about 198 kg/m³. At 3,600 psi the volumetric energy of NG is about 9,033 MJ/m³. LNG is operated at about -260 °F and 100 psi which has a density of 394 kg/m³. At standard storage conditions, LNG has a volumetric energy of about 18,000 MJ/m³. At standard storage conditions for CNG and LNG, approximately four and two times the storage capacity is needed, respectively.

The goal for natural gas as a fuel for heavy duty trucks is to meet or exceed the current fuel economy and fueling rate while maintaining a significantly lower cost. As of 2011 the fuel economy of class 8 trucks that run on diesel was at 7.3 MPG while natural gas was at 5.8 MPG. The difference in fuel efficiency between a natural gas engine and a diesel engine is 12-15%. An added decrease to the fuel efficiency of natural gas vehicles is the added weight and lack of aerodynamic features. This causes the fuel economy of natural gas vehicles to be about 80% that of diesel.

With work on diesel vehicles underway with a goal of achieving 10 MPG, the fuel economy of natural gas vehicles will also need to increase in order to stay economically competitive even with a lower cost of fuel. The fueling rate for natural gas vehicles must also be competitive with fueling for diesel vehicles as, the longer a truck takes to fuel, the less time the driver will be on the road during a shift. Since the fueling rate depends on the type of fill receptacle as well as the fueling station fill rates tend to vary over a wide range. While the fueling rates for CNG are slightly below diesel at a range of about 8-15 DGE per minute, the fueling rate for LNG is comparable at a range of about 12-20 DGE per minute.
C.11 Potential Additional Areas for R&D Effort

Several areas have already been described as requiring more work in order to improve performance, enhance safety or lower the costs of natural gas fuel systems. These areas include enhanced CNG storage cylinders, improved vehicle aerodynamics, better adherence to known best practices for cylinder installation, and improving CNG fill rates.

In addition, the following two areas would benefit from analysis and research:

- Technical analysis to compare pull test results with finite element analysis (FEA) for various fuel system configurations to generate data for Transport Canada. The March 2014 update to the CSA B109 code technically allows for the use of FEA results in order to demonstrate compliance with impact loading requirements. However, Transport Canada has indicated that the use of FEA requires further study and review. As a result, Transport Canada has provided direction to fuel system providers and OEMs indicating that only pull test data will be accepted as the basis for compliance at the present time until more is known about the correlation between pull test results and FEA outcomes.

  It would be possible to undertake physical testing in order to better understand this issue. Resources would be needed to design and build test fixtures and instrument systems. Additional FEA would be required to simulate the actual test with follow up effort and analysis to correlate the data. Physical tests could include static load testing and a shaker test. The shaker test would require the use of a vehicle to instrument and to measure inputs to input to shaker device.

- System leakage analysis to better understand system-level issues which are not well-addressed in current codes and standards. Leakage rates on components are known and addressed in existing standards. There might be some additional testing that could be done to consolidate all of the known data related to components and their integration to form the vehicle fuel system. The best way to measure methane leakage rates is through a helium chamber that is vacuum sealed. Results are then measured in helium parts per million. This approach is typically used for component testing. No such device exists at a vehicle level, but the set up could be scaled to do this type of testing in a vehicle chamber.

C.12 Differences Between Canadian & U.S. Requirements for Fuel Storage

In order to manufacture natural gas vehicle fuel storage systems within Canada or the U.S., a set of standards must be followed. However the standards for each country are not the same. In Canada, CSA B109 is the code that is referenced in the Canadian Motor Vehicle Safety Standards which defines the legal requirements for OEM vehicles. For provinces that have adopted CSA B109 in their regulations, the code is binding for aftermarket vehicles. It should be noted that, at present, CSA B109 only addresses CNG vehicles, although LNG vehicle content is being added to this code.

Unlike Canada, there is no code in the U.S. that must be followed. However, there is a vehicular gaseous fuel systems code that is a recommended practice which is the NFPA 52. While NFPA 52
is only a recommended practice, state and local Authorities Having Jurisdiction may adopt it as part of their local legislation and therefore make it mandatory for their jurisdictions.

Although CSA B109 and NFPA 52 are very similar, there are some differences that could be harmonized to make travel by CNG vehicles between the two countries easier. Table 12 outlines these differences. As for LNG vehicles, as mentioned, Canada currently does not have a code that is comparable to what is in NFPA 52 is which addresses both CNG and LNG vehicles.

<table>
<thead>
<tr>
<th>Category</th>
<th>CSA B109</th>
<th>NFPA 52</th>
<th>Recommendation for Harmonization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scope</strong></td>
<td>B 109 applies to on-road vehicles and industrial trucks only. Includes the pressurized gas portion of an LNG system, but not entire LNG systems.</td>
<td>NFPA 52 applies to all types of vehicles (highway, marine, rail, off-road &amp; industrial trucks) includes LNG, CNG, &amp; L/CNG. Also includes fuel dispensing systems for the fuels listed above</td>
<td></td>
</tr>
<tr>
<td><strong>Cylinders</strong></td>
<td>Common fuelling pressures are 3,000 psi or 3,600 psi</td>
<td>3,600 psi is the standard fuelling pressure</td>
<td>3,600 PSI refueling was added to the 2014 update to CSA B108</td>
</tr>
<tr>
<td><strong>Cylinder and Assembly Mounting</strong></td>
<td>A fuel container or assembly shall be mounted so that the force necessary to separate the fuel containers and their mounting system from the vehicle is: i) Greater than 20x the weight of the full fuel container in the longitudinal direction (forward/backward) of the vehicle, and 8x the weight of the full fuel container in the transverse (side to side) direction for vehicles with a gross vehicle weight rating (GVWR) of less than 8847 kg (19500 lb) or; ii) Greater than 8x the weight of the full fuel container in the longitudinal and transverse directions for a vehicle with a GVWR of</td>
<td>Each fuel supply container rack shall be secured to the vehicle body, bed or frame to prevent damage from road hazards, slippage, loosening, or rotation using a method capable of withstanding a force in the six principal directions (up/down, left/right, forward/backward) of <strong>eight times</strong> the weight of a fully pressurized container.*</td>
<td>8g for HD truck was changed in CSA B109 in March 2014 and, as of July 2014, Transport Canada has confirmed the new 8g requirement applies provided compliance pull test data is submitted</td>
</tr>
</tbody>
</table>

---

*Note that for heavy duty vehicles both sets of standards use 8x the weight of the fuel container.*
A fuel container or assembly shall:

- Be mounted on the same vehicle as the engine and any equipment being fuelled by the fuel container.
- Include reinforcement of the vehicle structure as required to meet the loading requirements of Clause 5.4. The OEM recommendations shall be used, if available.
- Be mounted at two support points designed to minimize the effects of external loads on the fuel container.
- Be mounted such that its mounting bracket shall not interfere with, or join two sections of, otherwise isolated vehicle structures.

A fuel container or assembly installed above the operator or passenger compartment of a vehicle shall:

- Conform to drawings prepared by an engineer in accordance with this Code. The drawings shall be retained on file for a minimum period of ten years
- Be protected by a guardrail or similar device designed to absorb the impact of a collision with a unloaded vehicle is travelling at 8.05 km/h (5 mph) in either a forward or reverse direction
- Be protected from contact with overhead, street type, and electrical wiring
- Be installed such that the

Fuel supply containers on vehicles shall be permitted to be located within, below, or above the driver or passenger compartment, provided all connections to the container(s) are external to, or sealed and vented from, these compartments. Vehicle fuel supply containers shall be mounted in a location to minimize damage from collision. Containers shall be protected by covers from accidental contact with overhead electrical wiring. The fuel system, including container, shall be installed with as much road clearance as practical. This minimum clearance shall be measured from the road to the container, its housing, or its fittings, whichever is lowest, and shall not, with the vehicle loaded to its gross weight rating, allow any component to touch the road surface in the event of a flat tire or the removal of any tire. No portion of a fuel supply container or container appurtenance mounted on the undercarriage of the vehicle shall be located ahead of the
<table>
<thead>
<tr>
<th>Component Certification</th>
<th>Vent Lines</th>
<th>Harmonize NFPA 52 with CSA B109 since the requirements in CSA B109 are clearer.</th>
</tr>
</thead>
<tbody>
<tr>
<td>All fuel carrying components used in the installation shall meet the requirements of ANSI NGV 3.1/CSA 12.3 or the ISO 15500 series of Standards</td>
<td>Vent lines shall not lose gas-carrying capability when exposed to temp of 590 °C (1094 °F) for 12 minutes. Vent lines must be built in accordance with ANSI/CSA NGV 3.1.</td>
<td>If the vent line is a hose, it must be listed or approved.</td>
</tr>
<tr>
<td>The following Components shall be listed or approved: 1) Pressure relief devices, including pressure relief valves 2) Pressure gauges 3) Pressure regulators 4) Valves 5) Hose and hose connections 6) Vehicle fueling connections 7) Engine Fuel systems 8) Electrical equipment related to CNG systems</td>
<td>top of the fuel container, and its housing, fittings, or guardrail, do not exceed a height of 4.11m (13.5 ft), measured from the surface of the road with the vehicle unloaded. The brackets, bolts, and nuts that attach a fuel container to the outside of a vehicle shall have a corrosion-resistant coating or be corrosion resistant. If shields are used for protection, they shall be installed in a manner that prevents the design and location of both shields and flow barriers shall not interfere with the ability of the PRD to protect the fuel container.</td>
<td>front axle or behind the point of attachment of the rear bumper to the vehicle. Metal clamping bands and their supports shall not be in direct contact with a fuel supply container.</td>
</tr>
<tr>
<td>Fuel Receptacle</td>
<td>The mounting system for the fuelling receptacle shall not sustain any permanent deformation when a force of 294 N (66 lbf) is applied in any direction.</td>
<td>N/A</td>
</tr>
<tr>
<td>-----------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>-----</td>
</tr>
<tr>
<td>Fuel Gauge</td>
<td>Requirements for pressure gauge listed in NGV 3.1</td>
<td>Pressure gauge shall be capable of reading at least 1.2 times the system design pressure. Pressure gauges installed outside a driver or passenger compartment shall be equipped with a limiting orifice, a shatterproof lens, and a body relief and shall be mounted, shielded and installed in a protected location to prevent damage from vibration and unsecured objects.</td>
</tr>
<tr>
<td>Pressure Regulator</td>
<td>A regulator shall be protected from road damage, excessive heat, cargo spillage, and electrical equipment, and shall be oriented according to the manufacturer’s instructions.</td>
<td>A pressure regulator inlet and each chamber shall be designed for its service pressure with a pressure safety factor of at least 4. Means shall be provided to prevent regulator malfunctions due to refrigeration effects.</td>
</tr>
</tbody>
</table>
| Isolation from Exhaust | All fuel system components shall be installed a minimum of:  
  a) 50.8 mm (2in) from any | Fuel supply containers located less than 8in (200mm) from the exhaust system shall |
<table>
<thead>
<tr>
<th><strong>Piping and Tubing, Hose and Fittings</strong></th>
<th>Piping, tubing and fittings shall:</th>
<th>Pipe, tubing, fittings, gaskets and packing material shall be compatible with the fuel under the maximum service conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>a)</strong> Be capable of withstanding a test pressure of 4x the service pressure</td>
<td>c) Pipe, tubing, fittings, gaskets and packing material shall be compatible with the fuel under the maximum service conditions.</td>
<td></td>
</tr>
<tr>
<td><strong>b)</strong> Be capable of withstanding temps of -40 to 121°C (-40 to 250°F) within the engine compartment and -40 to 82°C (-40 to 180°F) in all other locations</td>
<td>d) Pipe, tubing, fittings, and other components shall be designed with a minimum safety factor of 3. Natural gas piping shall be fabricated and tested in accordance with ANSI/ASME B31.3.</td>
<td></td>
</tr>
<tr>
<td><strong>c)</strong> Be made from corrosion-resistant material or protected from exterior corrosion</td>
<td>e) Hose and metallic hose shall be constructed of or lined with materials that are resistant to corrosion and exposure to natural gas.</td>
<td></td>
</tr>
<tr>
<td><strong>d)</strong> Be made from a material resistant to the chemical action of NG</td>
<td>f) Hose, metallic hose, flexible metal hose, tubing and their connections shall be designed or selected for the most severe pressures and temperatures under normal operating conditions with a burst pressure of at</td>
<td></td>
</tr>
<tr>
<td><strong>e)</strong> Be sized to provide sufficient flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>f)</strong> Be clear and free from cutting burrs, threading burrs, scale, and defects</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>g)</strong> Have the ends of all piping reamed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tubing used for rigid high pressure fuel lines shall meet the requirements of ANSI NGV 3.1/CSA 12.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any installed hose shall</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>a)</strong> Meet the requirements of ANSI/IAS NGV3.1/CSA 12.52 and be installed with appropriate fire sleeving if required when installed within the engine compartment</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>b)</strong> Be of sufficient size to provide the required flow of fuel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>part of the exhaust systems for metallic fuel lines or metallic components</td>
<td>b) 200 mm (7.87in) from any part of the exhaust systems for fuel lines or components with non-metallic construction.</td>
<td>be shielded against direct heat</td>
</tr>
<tr>
<td>Acceptable Piping, Fitting, and Joint Components</td>
<td>The piping and fitting threads for joining components in that part of the fuel system subjected to fuel container pressure shall:</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>a)</td>
<td>Meet clause 24 (Fitting) of ANSI NGV 3.1/CSA NGV 3.1 or be designed for the purpose intended and have a Canadian Registration Number (CRN)</td>
<td></td>
</tr>
<tr>
<td>b)</td>
<td>Be one of the following:</td>
<td></td>
</tr>
<tr>
<td>i)</td>
<td>Pipe threads, general purpose (inch), in accordance with ASME B1.20.1</td>
<td></td>
</tr>
<tr>
<td>ii)</td>
<td>Hydraulic tube fittings having an O-ring boss in accordance with SAE J514</td>
<td></td>
</tr>
<tr>
<td>iii)</td>
<td>SAE straight thread O-ring boss capable of mating</td>
<td></td>
</tr>
<tr>
<td>g)</td>
<td>least 4x the service pressure. Prior to use, hose assemblies shall be tested by the OEM or its designated representative at a pressure at least twice the service pressure</td>
<td></td>
</tr>
<tr>
<td>h)</td>
<td>Hose and metallic hose shall be distinctly marked by the OEM or component manufacturer, either by the manufacturer’s permanently attached tag or by distinct markings indicating the manufacturer’s name or trademark, applicable service identifier and design pressure</td>
<td></td>
</tr>
</tbody>
</table>

- **Acceptable Piping, Fitting, and Joint Components**

  - **The piping and fitting threads for joining components in that part of the fuel system subjected to fuel container pressure shall:**
    - **a)** Meet clause 24 (Fitting) of ANSI NGV 3.1/CSA NGV 3.1 or be designed for the purpose intended and have a Canadian Registration Number (CRN)
    - **b)** Be one of the following:
      - **i)** Pipe threads, general purpose (inch), in accordance with ASME B1.20.1
      - **ii)** Hydraulic tube fittings having an O-ring boss in accordance with SAE J514
      - **iii)** SAE straight thread O-ring boss capable of mating

  - **The following components shall not be used for CNG service:**
    - **1)** Fittings, street els, and other piping components of cast irons other than those complying with ASTM A47, ASTM A395, and ASTM A536
    - **2)** Plastic pipe, tubing, and fittings for high-pressure service
    - **3)** Galvanized pipe and fittings
    - **4)** Aluminum pipe, tubing and fittings
with hydraulic hose fittings in accordance with SAE J516
iv) Straight thread O-ring boss with left-hand threads
v) A double ferrule grip-type tube fitting connection
vi) A female straight thread O-ring boss port in accordance with SAE J1926/3 or ISO 6149
vii) A male thread and seal designed to be installed in a port in accordance with SAE J1926/3 or ISO 6149
viii) An O-ring face seal connection in accordance with SAE J1453
ix) A male or female connection in accordance with ISO 1179

5) Pipe nipples for the initial connection to a container
6) Copper alloy with copper content exceeding 70%

<table>
<thead>
<tr>
<th>Vehicle Literature</th>
<th>The system installer is responsible for supplying a vehicle owner’s manual supplement(s) in each vehicle that contains at least the following information:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a) Instructions showing the user the safe and correct operation of the NGV fuel system</td>
</tr>
<tr>
<td></td>
<td>b) Instructions that when servicing the vehicle, components shall be replaced with components rated for the same service pressure as the original component</td>
</tr>
</tbody>
</table>

N/A

Manuals should be required for all vehicles across the board.

---

*Table 12 - Differences Between the CSA B109 & NFPA 52 for On-Board Fuel Storage Systems*
D – Engine Development and Vehicle Integration

D.1 Introduction

Increasing the application of natural gas across a wider range of engines (by size or by manufacturer) faces a number of challenges covering commercial, technical as well as regulatory aspects. While both OEMs and customers would agree that a broader range of engines and vehicles is required to enhance adoption, the OEMs are faced with balancing investment in their mainstream diesel engine businesses while looking for opportunities with natural gas that may be near term small volume businesses. With the development of a new engine offering costing in excess of $20 million, OEMs are looking to stronger market signals before making this level of investment.

On the other hand, fleets are challenged with the desire for low cost fuel balanced against whether there are engine offerings that first provide the right torque and power characteristics, and then a plethora of decisions around functionality including fuel efficiency, range, dedicated natural gas or bi-fuel operation, CNG or LNG etc. All of this under stringent consideration of the overall value proposition for converting or replacing their existing fleet.

With the recently introduced Heavy Duty Fuel Economy and Greenhouse Gas regulations, heavy duty on-road diesel engines will likely improve fuel economy by 5% to 7% by model year 2017. Many of the improvements coming for diesel focus on base engine architecture and will also benefit natural gas engines (parasitic loss and friction reductions, air handling improvements, etc.). Beyond this, fuel economy improvements for natural gas could come from increasingly optimising the combustion process, which will be specific to the technology choices available, and from careful integration of natural gas engines with new powertrain and vehicle systems.

While there appears to be great potential for natural gas as a transportation fuel with ever expanding markets and applications being considered and tested, the challenge of increasing the availability of product offerings remains great, with technology challenges as well as significant commercial risk resulting from the R&D investment needed to develop new engine families while the North American market continues to develop at a modest pace. While OEMs are very responsive to the opportunity to offer products with reduced operating costs, and this includes natural gas, the justification for investing many millions of dollars into new products in addition to their commitments for their primary diesel product ranges, can be marginal in a slowly growing market. If natural gas engines were able to make incremental or preferably step changes in performance and cost, to offer a more compelling proposition for the customer, then the business case for OEMs to diversify and more natural gas options would become stronger. However, many of the existing natural gas technologies have evolved from simply identifying how to introduce natural gas fuel to engine systems, with a much higher level of complexity and sophistication required to both comply with regulatory landscapes, meet customer expectations of quality and support, and produce ever higher performing natural gas engine systems.

Key to the expansion of natural gas engine availability is a clear technology path that simultaneously lowers the cost premium of engine and fuel storage systems and critically provides a long term horizon for continued improvements in performance, efficiency, emissions, usability, and reliability. Governments can play a key role in supporting the development, evaluation and demonstration of new technologies in a pre-competitive environment to support the long term viability of natural gas engine systems in transportation.
D.2 Stakeholders Consulted

The following stakeholders were interviewed for their industry and expert perspective related to natural gas engine development and vehicle integration:

- **Clean Air Power** – Kevin Campbell, Steve Whelan
- **Cummins Westport** – Dr. Tim Frazier
- **Westport Innovations** – Dr. Patric Ouellette
- **Linde Gases** - Ron Lee
- **Agility Fuel Systems** - Ron Eickelman
- **Kenworth Truck Company** - Andy Douglas

D.3 Overview of Current Natural Gas Engine and Vehicle Technologies

**Spark Ignition Otto Cycle Engines**

This engine technology is very familiar as the technology is utilized in passenger vehicles using gasoline. Natural gas is introduced into the intake air and drawn into the engine during the intake phase. The fuel and air mixture is then compressed at a ratio of around 12:1 and the mixture is ignited using a spark plug. This technology is used in natural gas engines of various sizes, from the engine used in the Honda Civic CNG up to Class 8 tractors using the Cummins Westport ISX12 G engine. There are some differences in the ways that the engines using this technology operate, however the fundamental combustion processes are similar.

In the majority of cases for natural gas engines of this type, the engines have been developed from an existing engine platform that was designed for a different fuel. For engines such as those based on gasoline engines, the changes required for natural gas use are often limited to a change of fuel system and engine management. Technologies such as those offered by World CNG, Impco, and Westport LD are based on this approach.

In the case of heavy duty engines such as the Cummins Westport ISL G and ISX12 G, the engines are adapted from diesel engines. The adaptation is more complicated and involves modifying a specific head cylinder to accept spark plugs, moving to four valves per head, and lowering the compression ratio. Externally, a throttle is added to modulate airflow. This is often accompanied by a reduced size turbocharger because of the lower air demands relative to diesel. Much like gasoline passenger vehicles, these latest generation engines use exhaust gas recirculation (EGR). The addition of EGR and stoichiometric air-fuel ratios means in-cylinder emissions can be kept low with ignition timings optimized for fuel efficiency. Aftertreatment systems on these engines are relatively conventional three-way catalyst (TWC) as opposed to the complex combination of diesel particulate filter (DPF) and selective catalytic reduction (SCR) systems employed with diesel. Neutralizing methane emissions is not part of the design strategy for these TWCs given current regulations.

Previous generation spark-ignited natural gas engines had used lean burn combustion strategies. Using fuel to air ratios on the lean side of stoichiometric, the fuel-air charge is diluted with air...
which in turn has the effect of reducing the thermal production of NOx emissions during combustion. The lean air-fuel ratio also improves the theoretical thermal efficiency of the engine. As NOx emissions regulations continued to tighten, lean burn engines faced increasing challenges to extend their low NOx operation. In the past few years, lean burn engines have been largely replaced by stoichiometric-EGR engines which can make use of TWCs for tailpipe NOx emissions controls. The use of lean burn engines using SCR for NOx is a technology that had been offered by Doosan Infracore for use in transit buses, but no longer appears to be available.

Compared to diesel engines, natural gas spark-ignited engines typically have a reduced thermal efficiency due to throttling and low compression ratios. Before the advent of SCR on diesel, it was estimated that these compromises resulted in approximately 7% to 10% lower fuel economy, but some fleets are suggesting that this gap has widened to >15% as diesel fuel economy improved post-2010.

Generally, spark ignition systems are scalable up and down engine sizes. At higher engine sizes, cylinder size can represent a challenge for ignition and flame propagation, but in many cases it is the loss of fuel efficiency for very heavy fuel use applications that is the limiting factor.

**Compression Ignition Diesel Cycle Engines**
This section covers engines that are considered diesel cycle. Diesel cycle engines use the heat created from the compression of air within the combustion chamber to start combustion. Compression ratios within a diesel engine are typically around 17:1. Diesel fuel is typically used within these engines as the auto ignition temperature is low enough to ignite in the conditions that can practically be created within an engine. Natural gas has a higher auto ignition temperature and will not ignite in the conditions created in a typical diesel engine. This means that current natural gas engines using compression ignition still maintain diesel fuel as an ignition source. There are two distinct methods of introducing the natural gas to the engine as described in further detail below.

**Diesel Pilot Ignition with Fumigated Natural Gas**
Engines such as these utilise the ability to offset diesel use in a diesel engine by introducing natural gas into the intake air of an engine. These fumigation-based systems retain the complete diesel fuel injection system and add a second gas fuel injection system to introduce low pressure natural gas to the intake air of the engine. The method by which the fuel is introduced varies between manufacturers - some introduce the natural gas under pressure to the intake air post turbo, some introduce the natural gas pre-turbo. Both types of systems are often referred to as “dual-fuel” since, given the retention of the diesel systems components, it is possible for the vehicle to be operated in normal diesel mode if natural gas fuel supplies are unavailable.

The flow of natural gas is metered by a control valve upstream controlled by a supplied electronic control module (ECM) that interfaces with, or works in tandem with, the standard engine ECM. The gas-centric ECM uses signals that are available on the open CAN harness such as engine speed, diesel fuel flow, exhaust temperatures, and other important engine operation parameters.

The engine inducts a charge mix of air, EGR, and natural gas into the cylinder. The retained diesel fuel injection system is used to provide a relatively small but load
dependent quantity of diesel which acts as the ignition source for the charge mix. Combustion is instigated by this diesel injection, which in turn ignites the main natural gas fuel charge.

As the diesel fuel system is retained, particulate filters are required to control particulate matter (PM) emissions. NOx control methods are similar to diesel, using either urea-SCR systems or the combination of very high levels of EGR and low temperature combustion.

Dual fuel technologies are most often applied in retrofit applications to existing diesel engines and are often described as being “non-invasive” as they require no internal hardware changes to the engine itself and the standard diesel fuel system is retained. This approach does allow the engine to operate on diesel only since the diesel systems are largely unaffected, but it cannot operate on natural gas only since the diesel is required as the ignition source. Given the current level of refuelling infrastructure, the potential to operate on diesel only is a potential market advantage, however the certification constraints on such applications may limit the applicability of this feature to a de-rated or “limp home” approach. In many cases, if a dual fuel engine is intended to offer 100% diesel back-up operation, then it falls into a different certification category from dedicated natural gas or pilot-ignited natural gas engines. Within this category, the potential to certify to lower emissions under natural gas operation can be negated if diesel operating emissions are higher.

A drawback of fumigated compression ignition is the limited substitution of natural gas due to pre-ignition or knock. Because the gas charge is premixed with air and EGR, the engine can be sensitive to combustion knock at high loads or mis-fire at lean air-fuel ratios. As a result, the fuel split between diesel and natural gas is varied considerably across the operating range of the engine. This limits how much natural gas can be introduced to an engine via fumigation. Typically the maximum substitution in engines of this type is between 50% to 70%, with the upper levels being obtained only with more sophisticated diesel fuel systems and greater interaction between the natural gas system electronics and the diesel engine controller. Dual fuel engine systems are also susceptible to higher methane emissions compared to other technology approaches due to the distribution of a relatively lean mix of gas and air across the combustion chamber, and as result of fuel pass through during valve overlap periods.

**Diesel Pilot Ignition with Direct Injected Natural Gas**

Rather than introducing the natural gas into the intake air before the combustion chamber, direct injection engines inject the natural gas directly into the combustion chamber. This method of injection requires special injectors that either can inject both diesel and natural gas, such as the Westport High Pressure Direct Injection (HPDI) or have enough space in the combustion chamber to have two injectors, such as in the Wartsila marine engines.

These types of natural gas engines operate on the diesel cycle with combustion characteristics very reminiscent of diesel engines. Both the diesel and the natural gas are injected directly into the combustion chamber. A small quantity of diesel is used as
the ignition source (between 5% and 10% of total fuel energy). Gas is injected at high pressure (>3,000 psi) in fuel sprays comparable to diesel, which are ignited by the existing diesel flame.

Operation on diesel alone is not enabled in this engine type (or it is severely restricted), nor is operation on natural gas alone an option in the absence of the diesel ignition source. DPFs are used for particulate emission control, and as with diesel engines, the choice for NOx control is either SCR catalysts or very high levels of EGR depending on regulated emissions standards.

The torque and power potential for direct injected compression ignition natural gas engines is, in principle, equal to diesel. Fuel efficiency is essentially equivalent to diesel with diesel displacement typically being between 90% and 95%.

The benefit of directly injecting natural gas compared to fumigation is that there is no premixed gas and air in the cylinder at the start of combustion. This means that knock is not an issue, so high levels of gas utilization can be achieved across the entire engine operating range. Additionally, the more sophisticated natural gas fuel systems can vary injection pressures and injection periods. This allows for the natural gas to be accurately metered into the flame front created by the diesel injection and can optimise the combustion across the engine operating range. The absence of premixed gas also results in lower tail pipe methane emissions.

Control strategies for compression ignition engines closely mirror those used for their diesel counterparts. That said, modifications are required related to hardware and software controls to account for the use of the two fuels which require more complex fuel metering, timing, and control algorithms. A significant degree of integration with the base engine controls is required for optimal engine operation and compliance with emissions regulations.

Diesel cycle natural gas systems are scalable to the largest engine sizes. However, their applicability becomes challenging as engine size is reduced, in part due to packaging constraints and cost, but also due to limitations on diesel pilot injection quantities. As engine sizes reduce, the level of diesel injection that can be maintained will struggle to be continuously reduced resulting in diesel consumption becoming a larger portion of the overall fuelling strategy.

A simple summary of engine technology approaches is provided below:

<table>
<thead>
<tr>
<th>Technology</th>
<th>Spark Ignited Otto Cycle</th>
<th>Diesel Pilot with Fumigated Natural Gas</th>
<th>Diesel Pilot with Direct Injected Natural Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nat Gas Type</td>
<td>CNG or LNG</td>
<td>CNG or LNG</td>
<td>LNG only</td>
</tr>
<tr>
<td>Fuel Efficiency</td>
<td>10-15% less than diesel</td>
<td>~5% less than diesel</td>
<td>Equivalent to diesel</td>
</tr>
</tbody>
</table>
D.4 Applications For MD and HD Engines and Vehicles

On-Highway Medium Duty
Medium Duty vehicles are considered to range from Class 3 to 6, or a Gross Vehicle Weight Range (GVWR) from 4536 kg to 11,793 kg (10,001 lbs to 26,000 lbs). At the bottom end of the range you have vehicles such as the Dodge Ram 3500 or Ford F-350 and at the top end of the range you have vehicles such as the International Durastar or Ford F-650. Applications within this weight class start at the low end with work trucks that might be used on construction sites or small delivery vans. At the upper end of the range applications would be large parcel vans, shuttle buses, beverage delivery vans and other urban delivery vehicles. School buses also fall within the classification of medium duty. Engines that power vehicles in this weight range are approximately 3.5L to 7L in capacity with a power rating up to about 350hp and 800ft-lbs torque.

<table>
<thead>
<tr>
<th>Engine Manufacturer</th>
<th>Size &amp; Model</th>
<th>Capacity (L)</th>
<th>Path to Market</th>
<th>Fuel Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Solutions Inc</td>
<td>6.0L</td>
<td>6.0</td>
<td>Repower</td>
<td>CNG</td>
</tr>
<tr>
<td>Power Solutions Inc</td>
<td>8.8L</td>
<td>8.8</td>
<td>Repower</td>
<td>CNG</td>
</tr>
<tr>
<td>Ford</td>
<td>Triton V10</td>
<td>6.8</td>
<td>OEM-approved upfit</td>
<td>CNG</td>
</tr>
<tr>
<td>General Motors</td>
<td>6.8L V8</td>
<td>6.8</td>
<td>OEM-approved upfit</td>
<td>CNG</td>
</tr>
</tbody>
</table>

Table 14 – Available Medium-Duty Engines, Path to Market & Fuel Type

Cummins Westport has stated plans to launch a new 6.7 litre engine, the ISB6.7 G, targeting the medium duty truck and school bus segment in 2015. This engine will be spark-ignited, using the same stoichiometric, EGR and TWC as their 8.9 litre ISL G and their ISX 12 G products.
On-Highway Heavy Duty

Heavy duty vehicles are considered to be in Classes 7 and 8. Class 7 covers vehicles from 11,794 kg to 14,969 kg (26,001 lbs to 33,000 lbs) and Class 8 covers anything over 14,969 kg (33,000 lbs).

A large majority of Class 7 vehicles are straight trucks such as the GMC 7500 and the Kenworth T370 and 470. These trucks can be configured in a number of ways to satisfy the needs of a given application such as trucks, large package trucks, cement mixers, refuse trucks, and some lighter duty tractor trailer applications. Class 7 also covers urban transit buses.

Most tractor trailer combinations fall within Class 8 and cover a broad range of applications. Regional haul applications would be considered applications where the vehicles return to their home base during the day and cover an area typically no larger than 600 miles in a return trip. This would cover applications such as drayage from ports, food delivery, cryogenic deliveries, and refuse transfer.

Long haul applications cover longer distances and potentially don’t return to base at night. Examples of this application are truck load (TL), oil and gas equipment, water hauling, fluid hauling, bulk haul and other long range delivery runs that are often on fixed routes.

Diesel engines for Class 7 and 8 vehicles start at a capacity of approximately 7L with 250hp for Class 7 vehicles and range up to 15L engines with over 500hp and 2000 ft-lbs torque for Class 8 vehicles. Currently there are only two natural gas engines available direct through the OEM channel in North America:

<table>
<thead>
<tr>
<th>Engine Manufacturer</th>
<th>Model Name</th>
<th>Capacity (L)</th>
<th>CNG or LNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cummins Westport</td>
<td>ISL G</td>
<td>8.9</td>
<td>Both</td>
</tr>
<tr>
<td>Cummins Westport</td>
<td>ISX12 G</td>
<td>11.9</td>
<td>Both</td>
</tr>
</tbody>
</table>

Table 15 – Available Heavy-Duty Engines & Fuel Type

Volvo and Westport Innovations had announced a collaboration to launch a 13 litre engine for heavy trucks using Westport’s HPDI technology. In October 2014, Volvo announced that it would not be moving forward with this planned D13 LNG engine which had been expected to have ratings up to 455 horsepower with 1550 – 1750 ft-lbs of torque.

At the higher horsepower engine ratings, the Volvo announcement and two other recent announcements have left a potential gap in the market, especially in the Canadian trucking market. The withdraw of the Westport 15L GX and the delay of the Cummins ISX15 G leaves a gap in available engines over 450 horsepower. Certain applications in Canada and the U.S. where trucks run higher weights such as B-trains hauling 63,500kg or operate over mountain roads require engines with over 450 bhp and 1750 ft-lbs torque. Although the market share for engines of this type is smaller from an overall industry viewpoint, the suitability of this application with typically higher fuel consumption, could see natural gas engines take a strong market position in this sector, if appropriately rated engines were to become available.
Westport announced the withdrawal of their 15L GX engine in the fall of 2013 stating that it was shifting strategies, and would focus on being a technology partner to OEMs rather than building its own natural gas engines.

Cummins announced in January 2014 that it was pausing the program to develop a 15L natural gas engine based on the spark-ignited technology used on the Cummins Westport ISL G and ISX1 2G products. This engine was originally scheduled to be in production in 2015. The Cummins statement cited that “...as a result of market timing uncertainty” the program was paused and the company would, “re-evaluate the market demand and readiness for the ISX15 G later in 2014”.

Power Solutions Inc (PSI) has proposed engines in the 11L to 15L range that do not currently have release dates, or announced OEM paths to market.

At this time, no dual fuel systems are offered direct from an engine or truck manufacturer in North America. The complexity of dealing with three fluids (gas, diesel and DEF) with only moderate diesel substitution might be a barrier. If diesel substitution could be increased (to strengthen the economic proposition) it could become more attractive, but solutions to methane emissions, packaging and OBD compliance also need to be demonstrated. OEM adoption of dual fuel technologies is critical to their wide scale viability since most fleets that purchase trucks in large numbers highly value warranty and service which many of the small dual-fuel manufacturers can’t offer.

It should be noted that, while broader engine availability remains a hurdle for the industry, a lot of work has been done by truck manufacturers, engine manufacturers, and fuel system providers to offer customers vehicles that are fully integrated. This is key to customer acceptance on a broad scale. This starts from the appearance of a truck with fuel tanks that fit the profile of the vehicle and are compatible with aerodynamic aids such as side skirts, through to offering the range of transmissions that are available in today’s diesel vehicles. Natural gas engines are also offered across more models than ever before with new truck models such as the Kenworth T680 shown below having natural gas engines included in first launch plans as opposed to being considered as possible later additions.

![Factory Integrated Kenworth Natural Gas Truck](image)

**Figure 61 - Factory Integrated Kenworth Natural Gas Truck**
Although out of scope for this paper, an overview of the landscape for aftermarket conversions or retrofits is provided in Appendices
Appendix A - Spotlight - Aftermarket Conversions of Existing Vehicles.

**Off-Highway**
Off-highway applications for natural gas engines have been gaining a lot of attention recently. Although the number of engines in applications such as these are lower than those for on-highway applications, the manner in which the vehicles are used may be more conducive to using natural gas as a fuel. Typical of many off-highway applications is that the volume of fuel used is much larger than for on-highway applications which supports a positive business case for natural gas use.

In many cases, given the size and cost of the parent diesel engine, the incremental cost to apply natural gas on-engine systems can be relatively small in comparison. This fact, despite the low production volumes and unpredictable order cycle, can lead to a stronger value proposition for the engine developer. In the marine and rail sectors, there are also increasingly stringent emissions regulations coming into force. In the case of marine applications, the number of vessels being designed with natural gas in mind is increasing.

**Mining**
There has been a strong interest in natural gas as a fuel from the mining industry. The large haul trucks that operate at the mines are heavy fuel users and the application is well-suited to natural gas. With trucks fuelling at one location and being domiciled in one area, the cost of refuelling equipment can quickly be paid back by the cost saving on fuel. Additionally, there is an opportunity to fuel the trucks or locomotives moving bulk materials to and from the mine with natural gas.

Natural gas engines have already been demonstrated in this market in North America. Dual-fuel conversions are leading the way with GFS Corp. having converted a number of engines for various mine operators. GFS has been a first mover in this market and offers a fully integrated LNG conversion solution for large mine haul trucks. The company's EVO-MT 7930 systems have been in use on CAT 793B model haul trucks for over a year at Alpha resources Belle Ayr mine in Gillette, Wyoming. CAT is also working on an OEM solution and has a prototype engine that will be in use at a mine in Arizona in late 2014.

Internationally, GFS has been very active, selling conversions for various engines to mine operators. In Australia, GFS stated in late 2013 that its EVO-MT 8300 System for the Komatsu 830 truck will be operating at a launch customer’s mine in the fourth quarter of 2014. Additional Komatsu trucks with either the EVO-MT 8300 and EVO-MT 9300 Systems installed will be operating at other locations shortly thereafter.

**Stationary**
Stationary engines are used for various applications and come in many engine sizes. Often these engines are used for temporary on-site power as part of a gen-set package, however these engines are also used to power machinery such as drilling rigs and completion pumps in the oil and gas industry. This application has been getting a lot of attention in recent years with
exploration and production (E&P) companies converting engines to run on natural gas in an effort to reduce the costs of drilling and completing a natural gas or oil well. In addition, pressure to reduce emissions from operations, especially in areas near urban areas that are in non-attainment, has led to many operators adopting this approach. One of the first to test out natural gas on their in-field equipment was Canadian based Encana. Chesapeake Energy, Noble Energy, and Apache were quick to follow.

Some operators have converted to 100% natural gas engines supplied by CAT, Cummins and Waukesha, whereas others have taken the route of adding a dual-fuel conversion to existing engines. CAT is now offering an OEM dual-fuel system and other notable suppliers are ComAP, APG, GTI Altronic and GFS. These engines are typically very large 2000 hp engines consuming large quantities of fuel daily. Natural gas can be supplied via portable LNG tanks, CNG tube trailers or by tapping into a nearby natural gas line.

**Marine**

Worldwide natural gas has been proven to be an effective fuel for marine vessels. In the Baltic Sea there are approximately 48 vessels using LNG as a primary fuel source today. A further 85 LNG ships are on order globally. The vessels range from small ferries, to large RORO ferries, container ships, and coast guard ships.

The engines used in commercial marine applications vary significantly in size. Small tug boats may employ multiple 6L diesel engines offering 300 bhp and 1000 ft-lbs torque. Large container ships may use multiple medium speed diesel and gas engines offering 8 MW. The smaller engines such as those offered by Cummins, closely resemble the engines offered for on-highway applications. For instance the Cummins QSM11 is physically similar to the on-highway ISM engine, however the QSM11 has been calibrated to meet EPA Tier 2 emissions and provide the engine response and torque curves required for marine applications.

Interest in natural gas for marine vessels has increased in North America due to two main factors, firstly the supply of low priced natural gas but secondly and more importantly the implementation of a Emissions Control Area (ECA) along the coastal waters. The ECA will come into effect in January 2015 and covers an area within 200 miles of the east and west coasts. The ECA requires a 90% reduction in sulphur for ships operating in that area. Natural gas engines are seen as one potential solution to the new ECA rules, especially for vessels that operate solely within ECA zones.

In North America, there is a lot of work underway aimed at bringing natural gas fuel to the marine sector. TOTE Marine was one of the first companies to announce their plans to convert two ships that operate between the Port of Tacoma, Washington, and Anchorage, Alaska. These ships operate solely within 200 miles of the coastline and move containers between the two ports as part of the Alaska Marine Highway. Another notable project is the Harvey Gulf project involving offshore supply vessels that operate in the Gulf of Mexico. These supply vessels shuttle supplies to the oil rigs. Ferry operators are also making moves to adopt LNG fuel in their fleets with BC Ferries and Quebec’s Societe de Traversiers in Canada as well as Washington State Ferries and Staten Island Ferries in the U.S. all working to incorporate LNG ferries into their operations.
Currently the focus has been on vessels that run on fixed routes of return to one port regularly to refuel. The cost of building refuelling infrastructure will dictate the growth of natural gas in the marine market much like it has in on-highway transportation, however the fuel volumes required for marine vessels can drive a strong business case, especially when compounded with the need to comply with new emission legislation.

The report, *Liquefied Natural Gas: A Marine Fuel for Canada’s West Coast*, was published in April 2014 based on a joint industry project in Canada. The report takes a holistic look at the market potential of LNG in marine applications. One of the findings in the report was that “The ready supply of high-powered LNG engines means that the availability of commercial engine technology is not a barrier to the use of LNG as a marine fuel.”

Given that LNG is a new fuel in the North American marine sector, there is a considerable amount of work that needs to be done to adapt current regulations and review processes in order to accommodate LNG-powered vessels and LNG bunkering. The work regarding this with the relevant authorities (primarily US Coast Guard and Transport Canada) is going on in parallel with organizations moving forward with their plans. Modifying the existing regulatory frameworks in both Canada and the US is very important and hopefully will not slow the implementation of projects in this market.

**Rail**

Rail locomotives are another application where the engines use large quantities of fuel and the rail industry is looking to reduce costs to stay competitive in the market they operate in. The Energy Information Administration (EIA) issued an article in April 2014 titled, “Liquefied natural gas shows potential as a freight locomotive fuel” which projected that LNG will play an increasing role in powering freight locomotives in the coming years.

According to the EIA, the seven major North American railroads consumed more than 3.6 billion gallons of diesel in 2012, which was 7% of all the diesel fuel consumed in the US, accounting for 23% of the total operating expenses for these companies. The potential cost savings using natural gas as a fuel are expected to more than offset any incremental cost for equipment.

Although in many cases locomotives stay within a certain region and typically run on fixed routes, there is often migration of locomotives from one line to another. For instance, CN may a swap locomotive to a BNSF line. This means that in addition to the engineering work being done to bring natural gas engines, fuel tender cars, and fuelling to the industry, there is also a great deal of work that needs to be done to manage the logistics of locomotive operation with LNG use.

Locomotive engines are predominantly supplied by two suppliers, GE and EMD. Both companies are running prototype natural gas engines at this time. Commercial offerings of both engines are expected in 2015. Demonstrations of converted diesel engines, such as available from Energy Conversions Inc., in locomotives have been completed by CN, most recently involving a locomotive in revenue service between Edmonton and Fort McMurray. It should be noted that Burlington Northern Railroad (BN) demonstrated a LNG- fuelled locomotive back in the early 1990’s with Air Products. 63
As with the marine industry, the hurdles that may hold back this application are the lack of rules and regulations regarding the use of natural gas as a fuel. There is a lot of development work ongoing on LNG tender cars to provide fuel to the locomotives. The regulations around tender cars are being developed in parallel with the equipment itself. More work needs to be done to identify other changes that are needed in the regulatory framework in order to accommodate LNG-powered locomotives.

### D.5 R&D Options to Enhance Engine Performance and Customer Acceptance

This section provides an overview of a number of areas of technical interest that would support the performance improvement, customer value, and regulatory compliance of natural gas engines.

**Vehicle Systems and Driver Aids**

Before considering specific combustion and engine system adaptations for natural gas engines, it is important to note that there are a number of technologies that have been studied extensively for diesel engines, but there are gaps in the knowledge base in terms of how to optimise these same technologies for use with natural gas engines. For example:

*Waste Heat Recovery* systems have shown potential to improve on-highway diesel fuel economy by as much 6% to 7%. For diesel cycle natural gas engines, with exhaust heat and flow characteristics similar to diesel the potential exists for similar gains. For SI engines, the potential could be even greater since they typically have higher temperature exhaust systems. However, the cost benefit trade-off may still not be as appealing as it is for diesel engines since the cost savings in terms of fuel use are reduced given the lower price of natural gas.

*Start-Stop Systems* for pick up and delivery are known to be an opportune area for fuel cost reduction, and could equally apply to natural gas, but again little detailed exploration and analysis has been conducted either technically or commercially. In addition, as the integration of start-stop systems could have a significant impact on the cycling and durability of solenoid tank valves, any research in this direction should also consider the effect on tank valves.

*Intelligent Driver Aids and Telematics*, technologies that increasingly reduce the impact of the driver in optimal operation of the vehicle as a whole, can have significant benefits related to fuel costs. It is well known that one of the largest sources of fuel economy loss or gain is driver behaviour. From automatic transmissions to predictive terrain and shift monitoring, the integration of these technologies could result in improved fuel economy for natural gas as well as for diesel vehicles.

**On-Board Diagnostics**

Another important consideration for natural gas vehicles are the requirements related to **On Board Diagnostics (OBD)**. OBD for medium- and heavy-duty engines (targeted at vehicles
model demonstrated OBD have although engines, 2018. implementation, and level) detection emissions. The development use integration the 2010, allowing phase >14,000 - 27 lbs - 50 - 13 - 1. - 2. - 3. - 13 threshold monitors - 37 functional monitors - 50 rationality monitors - 80 circuit continuity monitors. Although no detailed data is available, it is likely that OBD systems for natural gas engines would have a similar number of elements.

OBD presents a double challenge for dual fuel engine systems as compliance must be demonstrated under both diesel and natural gas operation. Any dual fuel systems based on model year 2014 or later diesel engines will have to protect the diesel OBD systems already in
place, whether the dual fuel system is for new engines or retrofits, although the requirement to demonstrate OBD compliance for the natural gas system will not be required until 2018.

OEMs engaged in the development of new natural gas engines for sale as original equipment will be faced with increased development expenses related to the development and calibration of new OBD algorithms, as well as costs associated with rigorous testing, validation, and certification. While the OBD systems may not result in any additional components on the engine vehicle system, it is likely that changes to wiring harnesses, connectors, software, and potentially electronic hardware may be necessary to fully implement the detection and monitoring algorithms required by OBD.

In its original analysis of costs of implementation, US EPA estimated that basic algorithm development would cost $4.76 million per manufacturer, with another $1.5 million customisation per engine family, not including the cost of certification and production implementation. Comments from active OEMs suggest that full OBD implementation on the first natural gas engine families could run as high as $7 million to $8 million.

A brief overview of OBD elements is provided in Appendix B – OBD Requirements Summary.

**Dedicated Natural Gas Engine Design**

Since many natural gas engines are built around diesel engine architectures, some compromise in natural gas operation is inherent. There are distinct differences in optimised design for natural gas compared to liquid fuels. Listed below are some R&D development areas that could yield great gains in various facets of operation for natural gas engines.

**Combustion Optimisation** – Combustion chambers and intake ports are designed to optimise fuel air mixing for diesel operation where diesel is injected at very high pressures (20,000 to 30,000 psi). These designs are not inherently optimal for natural gas combustion when the highest gas injection pressures are <4000 psi. Reconfiguring combustion and intake systems in order to tailor them specifically for natural gas operation may result in further improvements in combustion characteristics and fuel efficiency.

With the recently introduced Heavy Duty Fuel Economy and Greenhouse Gas regulations, diesel engines will likely improve fuel economy by 5% to 7% by model year 2017. Many of the improvements coming for diesel focus on base engine architecture and would translate directly to natural gas engines (parasitic loss reduction, friction, air handling). Beyond this, fuel economy improvements for natural gas engines could come from increasingly optimising the combustion process, which will be specific to the technology choices available, and careful integration of engines with new powertrain and vehicle systems.

**Air Handling** – To avoid costly modifications to items such as turbochargers and EGR circuits, natural gas engines use standard configuration air handling components from the base engine. Tailoring these systems specifically for natural gas engines could result in improved engine performance and efficiency. R&D work focusing on natural gas-specific air handling strategies could be beneficial to understand the potential improvements available in this area.
Aftertreatment – As with the rest of the air handling system, aftertreatment systems are often not specific to the application of natural gas, particularly in bi- or dual-fuel engines. Again some specific customisation of aftertreatment designs could be beneficial to natural gas engines, so research work in this direction could provide some important learnings.

Ion Current Sensing For Spark Ignition Combustion Analysis and Control
Real time evaluation of combustion characteristics can present the opportunity for improved cycle to cycle control. Cycle by cycle and cylinder to cylinder variations in combustion represent a compromise as to how close to optimal an engine can be calibrated to perform. Being able to identify variations and adjust operation accordingly could allow engines to be operated with tighter tolerances resulting in improvements in efficiency, reduction in engine knock, and lower emissions. Although direct measurement of cylinder pressure is the ideal approach for combustion sensing, this requires additional penetration points to the cylinder head for sensors, and those sensors are themselves challenged by durability.

For spark ignition engines, the addition of ion sensing to the ignition system has been demonstrated to be a viable approach. Changes to ignition coil circuits allow the electrical current in an ionised gas (during combustion) to be measured. This current is indicative of flame temperature, pressure, and chemistry. With modifications to engine control unit circuitry, the ion sensing current can be processed in real time to determine such features as spark angle, knock, combustion phasing and rate of combustion. The following image is taken from a brochure for Delphi’s ignition system with ion sensing.66

![Delphi Ignition System with Ion Current Sensing](image)

*Figure 62 - Delphi Ignition System with Ion Current Sensing*

Through Iveco, Fiat has begun to integrate ion sensing into some of its natural gas engine lines in Europe (5.9 litre NEF and 7.8 litre cursor engines). To date, this technology has not been deployed on product in North America, but it represents an opportunity that merits research and further investigation.

Micro Pilot Port Injected Gas Engine Systems
Diesel cycle natural gas engines that fumigate the natural gas through port fuel injection have a trade-off of benefits and limitations. They are generally referred to as dual fuel systems since
they do not change or interfere with the underlying diesel fuelling and combustion strategies, so the vehicles can revert back to normal diesel operation in the event that natural gas fuel supply is unavailable. This redundancy is of significant operational benefit to customers. Because the natural gas is introduced at low pressure (<150 psi) into the intake systems, these engines also benefit from being compatible with current CNG and LNG fuel storage systems and, in the case of cold LNG, they do not require a high pressure pump or pressure booster system. However, they are constrained by the architecture of the diesel systems they are built on, with resulting lower utilisation of natural gas.

As diesel fuel injection systems continue to advance, especially with the capability to accurately inject ever smaller pilot quantities, the potential for improved micro-pilot combustion appears, with the potential to increase gas substitution from 50-70% currently to approximately 90%. Methane emissions may continue to be an issue due to the premixed gas-air charge, and some compromises may occur in terms of the degree of diesel redundancy. Ideally full diesel redundancy would remain an option, but the reality of injecting ever smaller quantities of diesel requires that the diesel fuel injection system be re-designed around these small injection quantities with likely compromise to maximum quantity capabilities. Additionally, the reduced diesel injection quantities pose a challenge for nozzle tip cooling, especially in systems that are designed primarily for diesel-centric operation. Overall, this presents a technical design challenge to optimise operation on natural gas while retaining full diesel operational capability.

**Advanced Spark Ignition Engine Concepts**

Advances in gasoline spark-ignited engines for light duty vehicles have shown the benefit of increased levels of boost pressure, higher EGR tolerance, and engine downsizing. Higher boost pressures and EGR tolerance enable the use of increased compression ratios and/or higher specific power outputs. In many cases, R&D has shown that downsizing with modest compression ratios is more effective than increasing the compression ratio. Many of these developments have arisen as a result of the adoption of direct injection gasoline strategies.

Spark-ignited natural gas engines, for light-, medium-, and heavy-duty applications, could benefit from adopting these technology concepts from gasoline engines.

Methane has an advantage over gasoline in that it has a higher octane rating (120-130 Research Octane Number) which, in principle, enables the use of higher compression ratios. Extending the EGR tolerance of natural gas engines through improved mixture formation and ignition could further increase the potential for higher compression ratios. The effect of higher boosting and EGR levels is to effectively increase the expansion ratio of the engine, with an ultimate improvement in overall efficiency.

A comprehensive consortium project conducted in Europe, the In-Gas Project (Integrated Gas Powertrain) examined the potential for applying direct injection, advanced combustion regimes, high EGR levels, boosting, and downsizing for -duty natural gas vehicle applications. Among its main findings were that the application of these technologies could significantly increase torque and power to modern diesel and gasoline equivalent levels, and that up to 16% reduction in CO2 emissions was possible relative to current technology level Light Duty CNG engines.
R&D to investigate the application of similar technology packages to engines for medium- and heavy-duty vehicles could lead to step change improvements in fuel efficiency, greenhouse gas emissions, and economic pay back for on-road natural gas vehicles.

Areas for specific research could include:
- Advanced ignition systems
- Direct injection fuel system
- Charge motion optimisation for direct injection combustion
- EGR and boosting strategies

**Advanced Ignition Systems**
Ignition of natural gas in spark ignition engines is one of the critical elements dictating performance. Typically natural gas requires higher ignition energies than gasoline engines, and that requirement increases as either power density or charge dilution are increased. Furthermore, the required increased energy levels have an impact on spark plug life, translating into an additional maintenance cost that is not present for diesel engines.

Improving ignition characteristics can help to improve the dilution tolerance (EGR, boosting) and mitigate misfire as well as improving the overall heat release characteristic of combustion resulting in higher efficiency and reduced emissions of unburnt end gases. A range of advanced ignition systems have been proposed, many of which may be applicable to natural gas engines although further development is required to improve performance, reliability, and cost.

For example, dual coil ignition (DCO) systems provide flexibility for more ignition pulse per combustion event or to prolong individual ignition events. South West Research has demonstrated DCO ignition with gasoline engines, to extend the EGR tolerance from 10% -15% to as much as 25%-40% with the net result of increased efficiency.

Plasma or corona discharge ignition systems have often been proposed, but have yet to penetrate into commercial applications in either gasoline or natural gas systems. The main claimed benefits are that ignition occurs at multiple locations, and over a greater arc length than with traditional spark ignition systems. Also, because the ignition is associated with electrical excitation of particles rather than heat, the thermal loading on ignition systems is less than with spark plugs, offering potentially longer life for components. The following images illustrate the concept of plasma ignition systems, taken from work by the University Of Southern California.
Figure 63 - Example Of Plasma Ignition System

Figure 63 above shows the generation of multiple plasma “streamers” through nano second duration high voltage pulses. These streamers generate multiple fuel ignition sites and associated flame fronts, illustrated in Figure 64, as compared to the single flame front from traditional single arc ignition systems.

Figure 64 - Comparison of Flame Front Formations - Spark Ignition & Plasma Ignition Systems

Another advanced ignition variant beginning to receive attention is that of turbulent jet, pre-chamber ignition, as illustrated by Mahle.\textsuperscript{70} Again the idea is to generate multiple high energy ignition sites that increase the combustion rate and enable high dilution levels. The high dilution can either be through increased use of EGR or by running ultra lean air-fuel ratios (\(\lambda>2\)) with the potential for low NOx and high efficiency.

In pre-chamber ignition systems, small quantities of fuel are ignited to produce turbulent jets of partially combusted gases, exiting into the main chamber through orifice arrangements. These
turbulent jets provide high energy ignition sources for the pre-mixed gas and air mix of the primary charge, with this charge having been delivered through separate fuel injectors.

In the Mahle system, being used here as an illustrative example, the main fuel mix is introduced into the combustion via a traditional port fuel injection system. In a customized ignition system, a direct injection system supplies a small quantity of ignition fuel which is in turn ignited by a traditional spark plug. This results in combustion of the ignition fuel in the pre-chamber (bottom left in Figure 65), which then, in turn, is directed through nozzle holes into the primary combustion chamber in the form of multiple jets.

Figure 65 - Mahle Concept For Integrated Pre-chamber Ignition System

Many of these advanced ignition systems are far from proven commercially viable, but they represent novel advances in performance potential that merit further R&D work in order to determine the potential impact they could have on improving natural gas engine performance.

Tailpipe Methane Conversion
Tailpipe methane emissions arise as a result of incomplete combustion of natural gas in the combustion chamber. The mechanics of combustion vary depending on the engine technology, but all natural gas engines fall short of 100% combustion efficiency, as do all diesel engines. Any methane emissions emitted from the tailpipe partially offset the lower carbon dioxide benefits of natural gas combustion and therefore reduce the overall greenhouse gas (GHG benefit) of natural gas as a transportation fuel.

Catalytic oxidation of methane is far more challenging than oxidation of heavier hydrocarbons, requiring higher catalyst temperatures and different catalyst formulations compared to non-methane gases. On some certification test cycles, and during in-use vehicle operation, exhaust temperatures can be below 350°C for large periods of time. Low temperature oxidation of methane would be beneficial as a source of reducing tailpipe emissions. It may also allow engine developers greater flexibility for combustion and calibration strategies that could then provide
further improvements in engine performance. If catalyst formulations with light off characteristics of approximately 250°C could be developed, without excessive precious metal content, such catalysts could find widespread use across highway, rail, and marine applications.

An alternative to full oxidation of the methane could be partial oxidation (reforming) resulting in conversion to hydrogen and carbon monoxide. Carbon monoxide is easier to convert through traditional oxidation catalysts, and the hydrogen produced is not a potent GHG, and could potentially be put to beneficial use within the engine system.

**Methane Detection Systems**
Methane detection is required by code for LNG natural gas vehicles. Current sensing systems are acceptable for detecting large leaks, but not sensitive enough for detecting ever smaller leaks which, while they may not present a safety risk, are still undesirable. Additionally, existing methane detection systems create a relatively high power draw on battery systems. Improved sensitivity, low power methane detection would be a valuable incremental improvement for all vehicle systems.

**Gas Seals**
Sealing gaseous fuel supply systems (plumbing, valve connections, etc.) is critical. This holds true for all natural gas fuel systems and is a particularly acute issue for high pressure fuel delivery systems including the entire plumbing system as well as fuel rails and injector fuel connections. R&D into low, cost high performing sealing technology would help improve the overall fuel system integrity and potentially reduce meaningful cost elements in the whole vehicle system.

**LNG Fuel Level Sensing**
Current LNG level gauges typical use a capacitive sensing method, with two plates mounted vertically inside the tank. LNG has a different dielectric constant than gaseous methane. The capacitance of the sensor changes as the level of LNG compared to the level of gaseous methane in contact with the sensor plates varies.

Some improvements to liquid fuel level sensing for LNG vehicle tanks would be beneficial, in part because of the need to improve the relatively poor accuracy of results from the current approach, but also because since they currently are housed inside the tank itself, any failure of the sensor can lead to a costly repair and re-vacuum of the fuel tank.

**Fuel Quality Sensing**
For all types of natural gas engine, fuel quality and composition is a key element in performance. With LNG, much of the unwanted contents of natural gas (heavier hydrocarbons, inerts) are removed during the liquefaction process and maybe captured for resale. “Weathering” of LNG fuel can be a problem, if methane is boiled off leaving a higher concentration of heavier hydrocarbons in the fuel tank, but efforts to reduce boil off and associated venting have reduced the risk of significant weathering effects.

Natural gas engine manufacturers typically suggest limits on specific elements found in fuel in order to ensure normal operation. Variations in methane number can lead to combustion knock
and the presence of heavier hydrocarbons (propane, ethane) can result in increased fuel energy being supplied to the engine, with subsequent concerns for engine durability.

Real time, on-board determination of fuel quality would allow for feed-forward (as well as feedback) control mechanisms to optimise the combustion process and mitigate harsh and potentially damaging operating regimes while simultaneously providing scope for dynamic optimisation of combustion.

**Fast Acting Wide Range Lambda Sensors**
Some natural gas engines, and particularly dual fuel diesel cycle engines, operate over a wide range of air fuel ratios and control of air fuel ratio can be a critical factor in combustion optimisation. Fast acting, wide range lambda sensors could improve the dynamics of air fuel ratio feedback allowing faster acting control systems, improved emissions, and enhanced OBD capability.

**Hydrogen as a Natural Gas Combustion Enhancer**
Hydrogen-natural gas fuel blends were tested and explored in the mid-2000’s on lean burn spark ignited engines. At that time, the main aim of using a hydrogen blend was to extend the lean limit of combustion in spark-ignited engines in order to reduce NOx. Since the advent of the 2010 NOx emissions levels, spark-ignited engines have generally adopted stoichiometric operation with EGR and three way catalysts to manage tailpipe emissions, so the benefit of lean air fuel operation with hydrogen blends has been diminished. However, the potential of hydrogen-natural gas blends for stoichiometric spark-ignited combustion and diesel cycle engines has not been fully explored.

Hydrogen has a high octane rating (>130), low ignition energy requirements (0.02MJ), high flame speeds and a short flame quenching distance when compared to methane. In spark ignited engines, under stoichiometric operation with EGR, the addition of hydrogen to the fuel charge mix may have benefits for:

- Improved knock resistance at high loads allowing more optimal spark timings or higher compression ratios
- Reductions in unburnt methane emissions through improved flame penetration to combustion chamber boundaries and crevice volumes
- Enhanced EGR tolerance due to improved ignition and reductions in unburnt methane

Many of these benefits could carry over to dual fuel engines, since the methane fuel mix is largely homogeneously spread across the combustion chamber prior to ignition. Dual fuel engines are susceptible to combustion knock at high loads forcing retarded ignition timings and a fuel efficiency penalty. At low loads, dual fuel engines often have to revert back to full diesel operation due to the excessively lean air-fuel ratios at those conditions, and the lean ignition characteristics of hydrogen may be beneficial in extending the lowest loads under which natural gas can be used.
In direct injection-type diesel cycle engines, the benefits on hydrogen addition have not been explored to any great lengths. Potentially, the higher flame speeds and lower ignition energies could support more complete combustion of direct injected natural gas fuel sprays with consequent improvements in unburnt methane emissions and some improvement in overall combustion efficiency.

There may be benefits to hydrogen-enhanced natural gas combustion, but it is unlikely that the industry would follow a path requiring fuel pre-blended at the pump due to the challenges of infrastructure and supply and the challenge for liquefied blended fuels. However, new technologies that may be able to produce hydrogen on board could be an interesting development. One specific avenue is the generation of SynGas (a mix of Hydrogen and CO) from natural gas using fuel reformers. SynGas is generated through the rich combustion of hydrocarbon fuels, including natural gas. Eaton\(^7\) has proposed the use of a fuel reformer (using diesel) as part of an advanced aftertreatment package. In the past, Arvin Meritor, along with MIT and others, explored the potential for SynGas via plasma generation for use in gasoline engines.\(^2\)

More recently, SwRI have proposed a novel alternative, initially for gasoline engines, that could be adapted for spark-ignited natural gas engines. Their so called “Dedicated EGR” engine (D-EGR)\(^3\) generates hydrogen and CO in one engine cylinder through rich combustion which is then passed to all cylinders through the EGR circuit.
In gasoline engines the presence of the hydrogen helps suppress knock, increases flame propagation rates, and improves combustion efficiency. In natural gas engines supplemental hydrogen could also help improve fuel efficiency and reduce methane emissions, but the benefits need to be studied carefully and considered in the context of both spark ignition and compression ignition engines.

D.6 Engine Development and Vehicle Integration R&D Priorities
Market expectations for the performance and quality of natural gas engine systems for on-road and off-road engines have increased as early stage evaluations have begun to bring natural gas to the forefront. The investments required to expand engine offerings in various applications are substantial, based on the thorough engineering and validation requirements, and increasingly stringent certification and regulatory expectations. While many engine and vehicle OEMs are introducing products into differing segments, there are a number of areas where research would provide insight into how to achieve incremental and step changes in system performance.
The natural gas engine space also receives relatively little attention in terms of detailed, independent, publicly disclosed research. Much academic research sheds light on the cost structure, economics, and performance aspects of diesel and gasoline systems (through examples such as the National Academies in the US) and, in many ways, the natural gas vehicle industry would benefit from similar attention. Such collaborative studies provide valuable long-term insights for technology companies, OEMs, end use customers, and policy makers.

In this section, a number of technology topics have been identified that could provide both incremental and potential step change improvements in natural gas engine and vehicle systems. This is not intended to be an exhaustive list, but reflects potential areas for near-term gain alongside other areas that represent higher risk and complexity. The following table summarises the R&D opportunities discussed and rates them for time line (near term, medium term or long term) and then with a risk factor (low, medium or high). In this case the risk factor represents the likelihood of achieving performance improvements via R&D activities.

The majority of these areas represent potential for improved efficiency, emissions and economics, with the acknowledgement that advances in gasoline, diesel and other alternative fuel technologies demand that natural gas engine solutions for all sectors must continue to show feasible long term trajectories, while simultaneously reducing cost premiums and improving customer acceptance and usability.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Timeline</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver Aids</td>
<td>Near Term</td>
<td>Low</td>
</tr>
<tr>
<td>Methane Detection</td>
<td>Near Term</td>
<td>Low</td>
</tr>
<tr>
<td>OBD</td>
<td>Near Term</td>
<td>Medium</td>
</tr>
<tr>
<td>Gas Sealing Technology</td>
<td>Near Term</td>
<td>Medium</td>
</tr>
<tr>
<td>Automatic Start/Stop</td>
<td>Medium Term</td>
<td>Low</td>
</tr>
<tr>
<td>LNG Tank Level Sensors</td>
<td>Medium Term</td>
<td>Medium</td>
</tr>
<tr>
<td>Fuel Quality Sensors</td>
<td>Medium Term</td>
<td>Medium</td>
</tr>
<tr>
<td>Ion Sensing Spark Ignition</td>
<td>Long Term</td>
<td>Medium</td>
</tr>
<tr>
<td>Waste Heat Recovery Systems</td>
<td>Long Term</td>
<td>Medium</td>
</tr>
<tr>
<td>Dedicated NG Engine design</td>
<td>Long Term</td>
<td>Medium</td>
</tr>
<tr>
<td>Micro Pilot Port Injection</td>
<td>Long Term</td>
<td>Medium</td>
</tr>
<tr>
<td>Fast Acting Wide Range Lambda Sensors</td>
<td>Long Term</td>
<td>Medium</td>
</tr>
<tr>
<td>Advanced Spark-Ignition Engine Technologies</td>
<td>Long Term</td>
<td>Medium</td>
</tr>
<tr>
<td>Technology</td>
<td>Timeline</td>
<td>Risk</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>----------</td>
<td>------</td>
</tr>
<tr>
<td>Advanced Ignition Technologies</td>
<td>Long Term</td>
<td>High</td>
</tr>
<tr>
<td>Hydrogen Combustion Enhancement</td>
<td>Long Term</td>
<td>High</td>
</tr>
</tbody>
</table>

*Table 16 - Summary of Technology R&D Priorities, Timing & Risk*
E – Safety, Codes & Standards

E.1 Introduction

The safety record of North America’s natural gas vehicle industry is based on more than three decades of technology development and market experience. During this time, an extensive system of codes and standards has been developed. With renewed interest in natural gas for transportation in Canada in recent three years, several significant work items have been undertaken including revitalizing CSA committees, up dating Canada’s CNG codes, CSA B108 and CSA B09, as well developing LNG refuelling content which has now been incorporated in CSA Z276, Canada’s LNG production, storage, and handling code. Recent results achieved in Canada also including harmonizing public station fill pressure at 3,600 psi and harmonizing the impact loading requirement for medium- and heavy-duty vehicles with the U.S. requirement.

Looking ahead and considering vehicle adoption trends in the U.S. market, the challenge now is to ensure that Canada’s system of codes and standards keeps pace with market development in a way that is safe, timely and, to the extent possible, harmonized with relevant U.S. and international activities. Key changes that are having a significant impact on safety, codes, and standards include:

1. The use of LNG as a vehicle fuel for this first time in Canada as of 2012.
2. The establishment of LNG refuelling stations – both mobile and permanent – in Canada.
3. The introduction of medium- and heavy-duty CNG and LNG commercial trucks.
4. The use of high fuel storage capacity CNG fuel systems on commercial trucks.
5. The transition to more of a commercial fleet focus for natural gas vehicles with the related interest in fleets being able to service their own vehicles in gas-safe facilities
6. Increasing focus on methane emissions at the codes and standards committee level.

While this list of changes is by no means exhaustive, it does provide an indication of the rate and extent of recent changes in the North American natural gas vehicle industry.

New activities are also generating new learnings which, in turn, need to be addressed through updated codes and standards. Issues related to CNG vehicles, LNG vehicles, and related refuelling infrastructure are documented in the following sections. While the various issues do not pose immediate safety hazards, they do represent areas that are recognized as needing improvement based on in-use observations and ongoing learnings from safety incidents.

A major challenge that the North American natural gas vehicle industry is facing is with respect to resourcing ongoing efforts to document and learn from safety incidents, and to ensure that there is a continuous process of related improvement with respect to codes and standards. U.S.-based CVEF is the organization that collects information on incidents and, in turn, channels observations and learnings to the appropriate code or standard committee via CSA Group. With U.S. DOE funding of CVEF scheduled to end as of mid-2015, this opens up a major gap area that will need to be addressed. All stakeholders involved in the natural gas for transportation industry in North America have an interest in ensuring that these important activities continue.
E.2 Stakeholders Consulted
CSA Group used a combined method of review of web search, documentation within CSA standards and learning services groups, as well as interviewing key stakeholders involved in the codes and standards development for the natural gas industry for this section of the report. Individuals contacted include:

- Gini Sage - GM Canada, CSA and NFPA 52 Committee member
- John Marshall - TSSA, Committee Member, Chair - Interprovincial Gas Advisory Council
- Craig Webster - CSA Group
- Livio Gambone - CSA Group
- Doug Horne - CVEF, CSA, NFPA 52, SAE and ISO Committee member
- John Dimmick - CVEF, CSA Committee member
- John Jordan - Agility Fuel Systems, CSA Committee member
- Norm Newhouse - Lincoln Composites

E.3 Current Issues Related to CNG Vehicles
Safety and issue areas requiring improvement related to CNG vehicle codes and standards include the potential use of components certified to European codes and standards that may not be suitable for use in North America, PRD issues, tank solenoid valve failures, methane fugitive emissions, the lack of a vehicle and subsystem-level recommended practice for fuel system design, installation, and verification for aftermarket converters, the lack of a facility code for Canada, a gap related to providing vehicle defueling guidance, and the challenge of integrating methane emissions in standards given the limited amount of information that is available. The following sections provide detailed information on each of these nine issue areas.

Issue #1 - Use of ECE R110 Components That Do Not Meet North American Requirements
ECE R110 2010 is the European design and installation code for natural gas vehicles. This document specifies performance and safety requirements for both discreet components and for vehicle systems comprised of those components. Both the components and the final systems require third party type approval from a notified body. The requirements set forth in this document were developed specifically to be harmonized with European regulations and legislation. This standard is managed by the United Nations Economic Commission for Europe (UN ECE) and, as a result, this document has become the default minimum requirements for NGVs in the European Union and in many other countries that adopt UN ECE regulations.

In North America, there is a different structure to the requirements and they are based on North American self-certification or third party certification regulations and codes. The national regulations in Canada are established by Transport Canada and in the U.S. by two parts of the Department of Transportation, the National Highway Traffic Safety Administration, and the Federal Motor Carrier Safety Administration. Environmental regulations are imposed by Environment Canada in Canada and by the EPA in the U.S.
The North American structure utilizes industry developed standards from standards development organizations such as CSA, the Compressed Gas Association, and SAE that are integrated and aligned with the national, provincial, and state regulations. The standards are voluntary in their enforcement, while the codes are mandatory and approved by the local Authority Having Jurisdiction. The standards are focused primarily on performance and safety requirements at the component level, while codes are focused on the safety of the integrated system. There are currently no performance-based requirements for integrated systems that are included in regulatory wording in North America.

One goal of the North American standards is to maintain harmonization, wherever possible, with the ISO 15500 series NGV component standards. The requirements included in the North American standards are more rigorous, demanding a higher minimum level of safety and performance when compared to ECE R110. As a result, there are requirements in the documents that are not in agreement making it difficult to harmonize UN ECE R110 with North American requirements.

It should be noted, however, that there is a European proposal to review and update ECE R110 including possibly harmonizing it with ISO 15500. Several issues including general safety, definitions, component specifications, tank/cylinder valves, etc. would be addressed as part of this review over the next three years. The purpose of this work would be to, “consolidate existing amendments to UN Regulation No. 110 in light of technical progress of other gaseous fuel regulations and standards and, where necessary, amend UN Regulation No. 110 to promote improved clarity and harmonization.”

In the meantime, some of the major differences between Europe and the North America are the service pressure rating of the components used for vehicles and stations. North America operates in a wider range of environmental extremes that demand more rigorous testing and validation of the component and the overall performance. In Europe the service pressure can only be approximately 2,900 psi (200 bar) at 15 degrees Celsius settled pressure while in North America, we offer two service pressures namely 3,000 psi (P30) and 3,600 psi (P36) at 21 degrees Celsius settled pressure. Historically, this is where Canada and the U.S differ; in Canada, the majority of stations operate with a P30 rating, but all new medium- and heavy-duty vehicles are designed to P36, which would result in a lack of a full fill is a P30 public station were to be used for refuelling. In the U.S. the majority of vehicles operate with a P36 rating, while there is still a mix of P30 and P36 public fueling stations.

Components designed to ECE R110 requirements do not meet the North American performance, pressure rating, and safety factor specifications and, as a result, there have been field incidents where these lower rated pressure components have performed poorly when subjected to P36 pressures. The most frequent issues have been observed with high pressure vehicle fuel system valves and fuel containers.

Currently in the NGV industry, most of the high volume valve manufacturers are based in Europe and Asia, in countries that recognize ECE R110. We are seeing an influx of these components into the U.S. and Canadian markets. Manufacturers are requesting approval from the AHJs to integrate these components into aftermarket conversions. Some AHJs have approved these components creating confusion in the market since they were not aware of the differences between ECE R110 and North American requirements. One of the principal differences leading
to misapplication of these components is that North American standards require that the components be marked with service pressure, while ECE R110 requires the components be marked with working pressure, which is 125% of service pressure for components upstream of the first stage of pressure regulation. This mismatch of marking has led to 200 bar (2,900 psi) components being misused on P36 (3,600 psi) systems. There is a very limited selection of components certified to meet the higher North American performance requirements; therefore, sourcing of components is difficult and sometimes impossible to do. As the North American NGV market continues to grow, it can be expected that new products designed and certified to meet the North American requirements become more available.

**Issue #2 – Premature Triggering of Pressure Relief Devices**

On the vehicle fuel system, there are critical components that are designed and installed in such a way to ensure that the fuel tank will never be subject to conditions that would result in catastrophic failures. These components are:

- **Pressure relief devices or pressure activated valves** are designed to fully open in the event the tanks are exposed to conditions beyond their normal design limits. North American codes require that all vehicles be fitted with at least one pressure relief device (PRD). This PRD must be certified to ANSI PRD1 and tested by a third party recognized laboratory. ANSI PRD1 is a component-level performance and safety standard that specifies the design qualification and batch performance of the component. This standard does not factor in other influences that result from integration of the PRD into the vehicle fuel system. CSA Group has observed instances in the field associated with incorrect performance of the PRD which appear to relate to other integration issues that are not addressed by the current PRD standard.

  There are two primary types of PRDs certified in ANSI PRD 1. Thermally activated PRDs designed for single use to relieve pressure in the container at a specified elevated temperature. The second type are pressure activated PRDs which are single use and designed to open and relieve the pressure at a specified set pressure.

- **Tank valves** which are installed near the opening of the tank. These electrically operated valves open when the vehicle key is turned to the on position. The valves close when the vehicle is not in operation, therefore isolating the fuel tank from the rest of the vehicle system to ensure that gas leaks do not occur when the vehicle is parked. There is typically one tank valve per tank, so multiple tank systems have multiple tank valves.

With respect to PRDs, there are three potential causes of unanticipated activation:

- **Improper Specification of Set Point** - PRDs have set points that are activated either by pressure, temperature or a combination of both. There have been instances in the field where the PRD has opened at a set point lower than expected resulting in the entire contents of the vehicle fuel tank being released into the area around the vehicle in a rapid fashion. In most cases, the root cause was due to incorrectly using burst discs that had been qualified for use on 3,000 psi containers on a 3,600 psi container. The releases occurred when the vehicle was being refuelled and an operator was present. Given that the vehicle would have been refuelled at a level appropriate for a 3,600 psi system, when the over-pressure occurred, this would have had the effect of exceeding the burst
disc set point. While this release did not result in a catastrophic failure, it still seriously concerned the operator nearby. In some instances, since a significant volume of gas was released, a formal safety incident was reported. In all cases, once the PRD triggered, the vehicle was unable to operate given that PRDs are designed as single use devices and cannot be re-set.

Cold Climate Issues – Even though the PRD is certified, testing of this individual component cannot reflect the final installation of a PRD into the vehicle system. In colder climate areas of North America, special care in positioning the PRDs needs to be taken to reduce the likelihood of moisture migrating into the valve. This moisture, if allowed to freeze and expand, can change the internal physical structure of the PRD therefore changing its trigger set point. Many field incidents of this nature have been reported in colder climates.

Over-Pressurization/Over-Densification - Another root cause associated with activation of PRDs is repeated over-pressurization/over-densification of the vehicle fuel system from the fuelling station. PRDs are designed to operate over multiple pressurization/depressurization cycles. Depending on the design of the PRD, if exposed to constant high pressure, the internals of the PRD deform slightly (“creep”). This change in dimension from its original manufactured condition changes the set-point of the PRD, resulting in two failure modes: premature release of the tank contents or catastrophic failure of the vehicle fuel tank because the PRD failed to function.

The industry has developed a temperature/ pressure compensation fuelling curve specifically for natural gas vehicles. This curve defines the maximum fill pressure that can be dispensed into a vehicle given the ambient temperature of the station. The shape of this curve follows the physical properties of CNG such that colder (more dense) CNG needs to be dispensed at a lower pressure. Since the vehicle’s fuel system is a closed system and the vehicle is autonomous, there is a high probability that the vehicle will move into a warmer environment. If the dispenser fuels at a pressure above that specified on the temperature compensation curve, once the vehicle container warms up, the CNG in the fuel container also warms up, resulting in an overall increase in pressure of the vehicle fuel system which could then exceed the specified settled pressure.

There are refuelling stations in North America that do not fill at or below the temperature compensation curve resulting in an over-densification condition. In some cases, this results in activation of the properly specified pressure activated PRD. Based on information from past incidents, in most cases this release occurs when the vehicle is being refuelled or when it is in use and an operator is present. While these releases did not result in catastrophic failures, they still would have seriously concerned all in the vicinity given the high pitched noise associated with the release of high pressure natural gas and the smell of odorant from the fuel. In some instances, since a significant volume of gas was released, a formal safety incident was needed. In all cases, once the PRD activated, the vehicle was unable to operate.

Issue #3 – Failure of Pressure Relief Devices to Activate When Anticipated
There are different issues that may lead to situations where PRDs fail to trigger. One issue area relates to the different thermal characteristics of the various types of fuel cylinders. Different
thermal properties associated with different cylinder materials may increase or decrease the time needed for the thermally activated PRD to reach its activation temperature. In North America, the most commonly used cylinder types are Types 1, 2, and 4. As Type 1 and Type 2 CNG cylinders use thick-walled metallic materials for pressure containment, the PRDs rapidly detect any temperature rise. By comparison, Type 4 CNG cylinders that are plastic lined, composite-wrapped designs with higher insulative capability could potentially delay the transmission of heat to the thermally activated PRD resulting in longer time to activation. If the resins in the Type 4 container degrade due to thermal exposure before the thermal PRD activates, the container may catastrophically fail.

In addition, if the fire is localized to a portion of the cylinder well away from the PRD, there is a potential for catastrophic fuel container failure before the PRD activates. For heavy duty vehicle and transit bus applications, there is a trend to provide fuel systems that utilize fewer large-sized fuel containers instead of multiple small fuel containers. With these designs, care in selection and position of the PRD or the array of PRDs is critical to ensure fuel system safety in the event of fire. Field incidents have been reported where the PRDs that were designed for smaller container systems were unable to adequately reduce the pressure in the CNG container before the container ruptured. In other cases, the thermally activated PRD did not activate because the fuel container was too large and the PRD was too far from the heat signal, and therefore did not activate. Also problematic is the practice of manifolding CNG tanks with a single PRD.

The standards need to be updated to reflect the critical differences between small and large fuel container installations. The PRD standard includes performance-based requirements which provide for evaluation of new technologies such as long trigger devices, which are designed to provide increased coverage of the container surface for thermal detection and activation of the PRD. Guelph, ON-based company Emcara Gas Development has a product involving thermally conductive trigger wires that spirally wrap around the full length of the fuel container, providing higher levels of protection against fire. Vehicle and subsystem level standards development work needs to begin in order to evaluate systems-level performance, including PRD packaging on the vehicle, PRD vent line routing, and various PRD technologies under a variety of fire scenarios.

As noted, the design and installation of the PRD on the fuel cylinder has a significant influence on the performance of the PRD. Counter measures, such as heat shields between the fuel system components and hot components such as the engine exhaust system, can greatly mitigate the risk of fuel system integrity failure. Care in selection and position of the onboard CNG fuel system relative to other vehicle systems is critical to prevent incorrect PRD performance. Currently there are no published guidelines or best practices available and the code coverage in both CSA B109 and NFPA 52 is limited in what these codes provide related to optimal PRD positioning, so this area requires further work.

**Issue #4 - Tank Valve Failures**
Another root cause for concern is failure of the container valve to open. This occurs with vehicle designs that have multiple fuel containers and multiple container valves. Either electronic or manual valves may be used.
In the first case, on a vehicle with electronic container valves, one of the solenoid valves of the container system fails to operate. Container valves are installed near or in the opening of the container. These electrically-operated valves open when the vehicle key is turned to the on position. The valves close when the vehicle is not in operation, isolating the fuel container from the rest of the vehicle system to ensure that gas leaks when the vehicle is parked do not occur. There is typically one tank valve per tank, so multiple container systems have multiple container valves. Because the solenoid valve is a one-way check valve that is designed to fail closed, the container with the inoperative valve remains at full pressure and is not allowed to defuel during normal vehicle operation. If the vehicle continues to operate with undetected failure, additional fuelling could lead to overpressurization of the fuel container. This was considered to be a contributing factor in the rupture of one container on a transit bus in Seoul, Korea and another in Brescia, Italy.

In the second case, on a vehicle with manual container valves, the internal components of one of the container valves fails to open when the valve is set to the open position. This condition leads to isolation of the container which results in inability to fuel or defuel that container. In a single container configuration, the vehicle would not be able to operate on CNG, and in a multiple container configuration, the range of the vehicle would be reduced.

**Issue #5 - General Installation Issues**
The CSA B109 and NFPA 52 codes were originally written to address the needs of aftermarket converters. Since that time, the industry has evolved and the majority of the systems are now being installed by OEMs or final stage integrators. As noted previously, the industry is lacking a published best practices document that could provide information on system design, component selection, system integration, manufacturing, and subsystem validation of the vehicle fuel system that could be utilized by OEMs, second stage manufacturers, and aftermarket conversion shops. Both the CSA B109 and NFPA 52 codes are unclear in some of these areas and do not provide sufficient information. The industry fall back has been to demand clearer instructions from the component manufacturers, however the component manufactures do not understand the systems their products are being placed into, so only general instructions are available. As a result of industry expressed need, CSA Group has initiated activity to develop a system integration document. The initial document will focus on “on-road vehicle” applications. Subsequent editions may address additional applications such as off-road and rail.

Besides the lack of an industry best practice or design and installation guideline, another reason why inconsistent application of components within the fuel system occurs is due to an inconsistent enforcement of the current codes. For example, unlike in Canada where jurisdiction for aftermarket conversions is clear and is at the provincial level, only a few states in the U.S. have recognized AHJs covering approval of the design and installation of aftermarket CNG fuel systems or conversion kits. If these converted vehicles cross into Canada, that poses a problem as they will not necessarily be in compliance with local regulations for aftermarket conversions.

In the U.S., automotive OEMs are regulated by the Department of Transportation (DOT) and by the National Highway Traffic Safety Administration (NHTSA) to FMVSS 303 and FMVSS 304 requirements. Similarly, in Canada, Transport Canada has the CMVSS requirements for new
factory-built vehicles that can travel interprovincially or be sold across provincial borders. For aftermarket conversions in Canada, the CSA B109 code is recognized by many provinces.

It should be noted, though, that the CSA B109 is a design and installation code and is written to describe minimum state of the art. This code is not a current best practices document. The NGV industry and AHJs in both Canada and the U.S. would benefit from having a published best practice document providing guidance on general installation issues.

**Issue #6 – Vehicle Maintenance Facility Code Gap**

Canada has a technical guideline for facilities in which CNG and LNG vehicles are maintained, loaded, and stored, but it does not have a code detailing Canadian-specific requirements related to indoor maintenance, storage, loading, and refuelling of NGVs. The CSA B108 code regulates the design and installation of CNG refuelling stations and was updated in March 2014. The scope of CSA B108 is limited to outdoor refuelling stations for either public or private fleets. However, the code does address indoor fuelling in an unenforceable Annex. Similarly, the CSA Z276, Annex D, outlines the requirements for outdoor LNG refuelling stations.

In the United States, NFPA 30A is the code for motor fuel dispensing facilities and repair garages. In addition, NFPA 52 addresses some requirements that allow for indoor applications for NGVs, however, industry believes some of these requirements are too conservative and new research is currently underway to support modification of the current requirements in the U.S.

There is currently no specific set of code requirements for indoor facilities used for NGV maintenance and repair, storage and parking, loading, and refuelling. As a result, CSA Group is seeing inconsistent application of requirements across different provincial jurisdictions. CSA Group has proposed to the Canadian natural gas vehicle industry the development of a unique code that specifically addresses requirements for approving facilities utilized for NGV storage, parking, maintenance, repair, and operation and for indoor refuelling.

**Issue #7 - Safe Vehicle Defueling**

There are two situations in which NGVs need to be defueled: (a) when performing vehicle service and maintenance tasks that involve the vehicle’s fuel system; and (b) if a CNG vehicle’s fuel cylinders are filled to a level above the temperature compensation curve and the vehicle is being brought inside during winter when the indoor temperature exceeds the ambient outdoor temperature. There currently is no standard or code language included in the Canadian or U.S. regulatory structure outlining the need for defueling prior to moving the vehicle indoors for either of these situations, although a request has been advanced to CSA to develop a temperature compensation standard for CNG dispensers. At present, this work is not resourced.

With respect to (a), in the U.S., the NFPA codes have developed the concept of large and small maintenance facilities to reflect the level of maintenance tasks performed. Large maintenance facilities are defined as ones where work on the vehicle fuel system can be performed along with other vehicle system maintenance and repair tasks. Facilities such as car dealership garages and transit bus garages are typically considered “large” maintenance facilities where the full range of vehicle maintenance tasks are performed. In large maintenance facilities, measures to safely defuel vehicles must be present and be operational with proper training provided. Small maintenance facilities are ones where general maintenance is conducted on the vehicle and the
fuel system remains intact (i.e., facilities used for oil changes, tire changes, car washes, etc.). In small maintenance facilities, vehicles would only be brought indoors for light service tasks, so defueling capabilities are not required because the fuel systems always remain intact and the vehicle remains indoors for only a limited time.

With respect to (b), if the vehicle fuel containers were filled to levels above the temperature compensation curve, the vehicle needs to have the onboard fuel level reduced by either driving or through prescribed maintenance prior to being brought indoors for storage or for maintenance tasks. This needs to occur to ensure that the fuel containers are not compromised. The potential presence of failed or disabled cylinder valves can make timely and safe defueling extremely difficult.

**Issue #8 – Leakage and Allowable Permeation Rates**

The current component level standards all specify allowable leakage rates. Historically, these defined external leakage rates and internal leakage rates have been driven by safety requirements. The allowable leakage rate for the vehicle and the CNG fuel subsystem are defined by the code documents, both NFPA 52 and CSA B109. The ANSI/CSA NGV2 and BS1 Part 2 standards both specify the allowable permeation rate of pressurized Type 4 fuel containers. This permeation rate is based on the surface area of the cylinder. Allowable permeation is also defined for other components such as flexible fuel lines.

These internal and external leak rates for components were originally established in the early 1990s when the technology that is now considered state of the art had not even been developed. Now that new technologies, such as new sealing design and technology, are regularly used in vehicle fuel system designs, a comprehensive review of leak rates for all components needs to be conducted. For example, the ANSI PRD1 requirement specifies a maximum PRD leakage rate of 0.7 Ncc/hour, while other components in ANSI NGV 3.1 have allowable external and internal leakage rates of 20 Ncc/hour. Also, as mentioned, the permeation rate on Type 4 fuel containers is determined on the basis of the surface area of the fuel container. The Type 4 containers commonly used in heavy-duty and transit applications will typically have an allowable permeation rate that is several orders of magnitude more than the allowable leakage rates for other components due to their large size.

Since the 1990s we have learned through experience, as well as from measurement and mathematical modelling, that the current conservative leak rate estimates may be far too low for some complex, large CNG vehicle fuel systems, which means that the overall actual leak rates on a total vehicle system basis are higher than is desirable. In addition, with the evolution and implementation of greenhouse gas-based vehicle regulations, new thinking needs to be integrated into new requirements for discreet components and for the proposed system-level best practices guideline to incorporate not only the safety requirements when setting allowable leakage and permeation requirements, but also the fugitive methane emission requirements for the vehicles. Emission requirements will be discussed further in Issue Area #9.

By comparison, the new standards for hydrogen vehicle technology consider leakage from a total system perspective resulting in different leak rate requirements for different components within the fuel system. It should be noted, however, that hydrogen vehicles are not subject to greenhouse gas-based vehicle regulations. In the U.S., during a June 2014 Clean Vehicle
Education Foundation (CVEF) workshop, a task force was established specifically to review this gap area for natural gas vehicles including the inconsistency associated with discreet leak rates for the different CNG components used in the vehicle fuel system and the fuel system as a whole. Beyond the newly-established task force, there is no current allocation of financial resources to address this fuel system leakage issue for the North American natural gas vehicle industry.

**Issue #9 – Quantifying Methane Emissions**

As the size of the overall NGV population continues to grow the environmental impact caused by methane releases from vehicles or from stations is now becoming an area of increasing interest for agencies such as Environment Canada and the U.S. EPA. A major challenge, though, is accessing data that can be used to support the development of emissions-based standards requirements from a holistic point of view. Ongoing work such as the 2011 well-to-wheel emissions study released by Argonne National Laboratory is helpful and provides more recent data. Nonetheless, more data is needed to support the development of methane-specific standards requirements.

In the interim, new emission requirements are going to be added to the scope of component and subsystem standards. The committees developing these standards are beginning to work on defining the requirements and testing protocols to satisfy these new needs.

CSA Group estimates that the first standards that will include intentional and unintentional natural gas releases will be published in the next 24 months. The first wave of component standards that include emission requirements will be directed towards LNG technology. Recently a work item for CNG fugitive methane emissions was submitted to CSA for consideration in existing component standards and in future vehicle and subsystem best practices guideline. These new environmental aspects of standards for CNG and LNG will span both vehicle and fuelling station components and subsystems. The industry has indicated that once formal regulatory language has been adopted, the standards will be revised accordingly.

**E.4 Current Issues Related to LNG Vehicles**

Currently, there are no North American standards for either LNG vehicle or station components. During September 2014, CSA Group held an industry workshop to identify needs related to LNG use as a transportation fuel including standards that are needed and their relative priority for development. As a result of input received from stakeholders at this workshop, CSA Group initiated work to develop standards for the LNG fuelling nozzle and receptacle (LNG1) and the onboard vehicle tank (LNG 2). These documents are being developed as harmonized U.S./Canadian standards and will have performance-based requirements including requirements for overall performance, safety, and emissions. Natural Resources Canada is providing funding support for this work.

Resource constraints continue to pose a barrier with respect to the development of additional LNG standards. CSA Group is working to identify funding sources to expand the number of active standards development projects to match the priorities established at the September 2014 workshop. The standards that still need to be resourced along with other gap areas are as shown in Table 12 on the following page.
Standards Needed

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LNG 4.1 Standard for LNG dispensing systems</td>
</tr>
<tr>
<td>2</td>
<td>LNG 3.1 Fuel system components for LNG vehicles</td>
</tr>
<tr>
<td>3</td>
<td>LNG 4.9 LNG fuelling station</td>
</tr>
<tr>
<td>4</td>
<td>LPRD1 PRDs for LNG fuel containers</td>
</tr>
<tr>
<td>5</td>
<td>LNG 4.4 Breakaway devices for LNG dispensing</td>
</tr>
<tr>
<td>6</td>
<td>LNG 4.3 Temperature compensation devices for LNG dispensing systems</td>
</tr>
</tbody>
</table>

Other Gap Areas

1. Combination “LNG/Diesel” dispensers
2. Standard for an integrated emergency shutdown device (ESD) between the vehicle and the station needs to be considered
3. Standard for integrated Emergency Shut Down (ESD) between the bulk LNG delivery truck or trailer and the station

Table 17 - LNG Standards Needs & Other Gap Areas

In Canada, a new Part 2 of the CSA B109 design and installation code is under development. Part 2 will be the first edition of a best practices document for LNG fuel systems in Canada. B109-Part 2 for LNG fuel systems is scheduled for publication March 2015.

Internationally, ISO TC22/SC25 has developed and published the ISO 12614 series of LNG component requirements for vehicles. These requirements follow the same structure as the ISO 15500 requirements for CNG vehicle components. The ISO 12614 does not include specific requirements for the nozzle, receptacle, and vehicle fuel containers. In North America, the ISO12614 standard has not been adopted as a nationally recognized requirement, although this ISO standard is now under review given its recent completion. In Canada, CSA Group manages the mirror committee and no work item to formally adopt this ISO standard has been proposed. In the U.S., SAE manages the U.S. Technical Advisory Group (U.S. TAG) to TC22/SC25, and similarly no formal work item has yet been proposed to adopt these requirements. National deviations will be identified once the adoption process has started.

In Canada, the CSA Z276, Annex D, outlines the requirements for permanent outdoor LNG refuelling stations. This document does not encompass mobile LNG refuelling stations which are increasingly of interest to industry given that they allow for a quick start-up with the ability to transition to a permanent station as fuel demand increases. As a result of this gap, the Canadian natural gas vehicle industry recently funded the development of a technical guideline for mobile LNG refuelling. This content has been provided to CSA for committee review as the CSA Z276 Committee has identified mobile LNG refuelling as an approved work item and will be revising the code to include this as of the 2017 code edition.

In an LNG refuelling station, there are critical components that carry unique requirements for performance and safety that are not specifically addressed in the current Annex D. Components such as a standard refuelling nozzle and interface, and a standard fuel dispenser which includes operation and multi-grade fuel dispensing capabilities, need to have their minimum performance and safety requirements defined. In the United States, NPFA 52 superficially provides some prescriptive requirements for LNG stations, but these require revision.
In the U.S., the Compressed Gas Association has formed an NGV advisory group. The advisory group has identified several standard development opportunities. This organization has undertaken the development of an LNG mobile refuelling station requirement as their first project. CSA Group is monitoring this activity.

E.5 Strategic Gap Areas Requiring Further Work

Ongoing in-use experience as well as safety incidents provide information that assists with improving natural gas vehicle and station codes and standards. As a result of a growing number of issues being identified, CVEF organized a Critical Issues Workshop in June 2014 in the U.S. with industry stakeholders in attendance in order to discuss several areas requiring further work. The issues reviewed at the workshop are encompassed in the following list.

The following list of strategic gap areas is not in a set order of priority or with any indication as to cost and likelihood of success, although more urgent items are listed earlier in the list.

1. Update CNG Dispenser Standard & Add Temperature Compensated Fuelling Protocol
The majority of CNG standards were published in the late 1990s and require updating to reflect lessons learned and changes in technology. The CNG dispenser standard, NGV 4.1, is long overdue for an update given that it was last published in 1999. Within the scope of a dispenser standard update, it is also recommended that a temperature compensated fuelling protocol be developed and published to reduce the risk associated with the over-pressurization/over-densification issues described earlier in this section.

2. Lack of Standards for LNG Vehicles & Stations
As noted in the previous section, there are no standards in North America for any of the LNG components used in vehicles and stations. Work is now underway to develop two of the standards needed – LNG1 for fuelling nozzle and receptacle (LNG1) and LNG2 for the onboard vehicle tank. These documents are being developed as harmonized U.S./Canadian standards and will have performance-based requirements including requirements for overall performance, safety, and emissions. Additional resources are needed in order to form active standards committees to develop all of the other standards that are required and that are listed in the table on page 95.

3. System to Communicate Critical Information to Committees
A better, more formal system is needed to communicate information that arises from the review of safety incidents as this information is critical for code and standards developers to be aware of and to learn from. Currently, when an incident occurs in the natural gas vehicle industry, available details are forwarded by CVEF to CSA Group who directs the information to the appropriate technical subcommittee for review and discussion of codes and standards revisions that may be necessary based on the lessons learned. Quite often, there is a lag in acquiring information due to legal issues and ongoing litigation. In addition, it is not entirely clear as to whether information on Canadian incidents is, in fact, distributed via the current system. Any incident information provided to CVEF is provided on a voluntary basis only. With CVEF being an American organization with no direct linkage to the natural gas vehicle industry in Canada, it is not clear whether Canadian information has historically been provided. A
more formal system for gathering and relaying incident information would benefit the NGV industry and enhance overall safety. As part of considering how to improve the current system, work would also need to be carried out to determine how to resource the activities that CVEF conducts, but which will cease as of mid-2015.

4. Lack of High Flow CNG Receptacle
One specific aspect that needs to be addressed in the short term is the development of a high flow, heavy duty receptacle profile for CNG refuelling for commercial trucks and buses. The ISO standards have recognized a standard receptacle profile design for situations where high flow fuelling is required. The current version of the CSA NGV1 standard has not adopted these requirements and therefore these components cannot be listed or certified as outlined in the NFPA 52 code. CSA Group has identified this work item. The Technical Subcommittee is being revitalized and CSA Group is looking for funding to complete this work item.

5. Container End of Life Management
As the initial wave of natural gas vehicles fitted with fuel containers that have a defined end of life date reach their limits, the North American natural gas vehicle industry is now struggling with how to identify, contain, and control these fuel containers so that they are taken out of service and rendered inoperative. There currently is a gap in the regulations and no system-wide method of enforcement is available that can manage or regulate compliance with the end of life requirement outlined in the standards. Also, it is not clear if retest and recertification of these expired fuel containers is safer than replacement since, in some cases, direct replacement parts are not available so new tank/bracket assemblies are being substituted. These substitutions may not be barrier tested and therefore it is not clear if the same impact resistance is maintained. Further safety studies will be required to categorize these risks appropriately.

With respect to enforcement, recommendations have been made to federal, provincial or state transportation departments to include container expiry dates as part of the vehicle registration record. When the annual licensing fees are processed, new vehicle licensing tags/stickers would be issued only when the containers are within their safe operation dates as indicated by the container expiry date.

The establishment of a national database for vehicle registrations for converted would facilitate tracking end of life of the vehicles and limit fuelling once the CNG cylinders have passed their end of life inspection date.

The technical need for a finite life limit for CNG cylinders should be evaluated based on the difficulty of achieving compliance and the significant safety issues that are encountered when expired cylinders must be replaced. Based on known information, it is clear that very serious accidents can occur when cylinders are thought to be defueled, but are not. It is also true that exact replacements are often not available, so changes to the fuel container can result in wholesale redesign and replacement of the entire fuel storage system.
6. Lack of Smart Technologies for Refuelling
It was the original intent of the NGV industry to approach the refuelling process using the same method as gasoline and diesel liquid fuel dispensers. With these conventional fuels, there is no communication between the dispenser and the vehicle when the nozzle is connected and the vehicle is being fuelled. The framework of standards was established to mitigate the risks that may occur during the fuelling process. In practice, however, incidents have occurred when components and subsystems have either been modified or adjusted to operate outside of required parameters. As is already done for hydrogen vehicles, the natural gas vehicle industry has now identified the opportunity to apply smart communication technologies to the vehicle - station interface which would limit or stop the flow of fuel in the event of an upset condition occurring.

One direction that is currently being considered includes the addition of a special flow limiting valve placed between the vehicle fuelling receptacle and onboard fuel containers. Additional sensors included in the fuel system would then identify when upset conditions occur that could put the vehicle fuel system at risk. When these conditions are detected, the flow limiting valve would close and flow would stop before any long-term damage could happen. Other approaches to managing this risk include wireless communication between the vehicle and the dispenser. In this case, when the vehicle sensors identify an upset condition, the vehicle would send out a message to the dispenser telling it to, “stop.”

In both cases implementation would be difficult because the existing vehicles and dispensing stations currently in the field would require “retrofit” before this technology could be implemented. These “retrofit” kits likely carry considerable cost and would be complex to install.

It has also been recognized that smart systems alone are still incapable of achieving a full fill except at cold ambient temperatures. Heat compensation in the form of active cooling of the gas is necessary to achieve fast fills and will increase the need for reliable and accurate dispensing systems.

7. Enhanced Understanding of Methane Emissions Issues
The development of methods to address methane emissions from both CNG and LNG applications is an area of potential future change. There is currently no understanding in the industry of when methane-specific requirements will be enforced and what the impact will be for CNG and LNG vehicles and stations. As previously mentioned, the technical subcommittees require information and technical data to support development of requirements, to carry out performance tests, and to develop pass/fail criteria that can be incorporated in certification programs for vehicle and station components and equipment. Further understanding needs to be developed on component- level methane emission requirements and their impact on vehicle level methane emissions.

8. First Responder Best Practice Document
A CNG and LNG alternative fuels vehicle first responder recommended best practice document is needed. Development of this best practice document could follow the
model set through the development of recommended practice documents for hydrogen and fuel cell vehicles (SAE J2990-1) and for hybrid and electric vehicles (SAE J2990). This work needs to be completed and implemented across North America. The availability of this type of best practice document would enhance existing local training efforts.

9. Current Approach Regarding Canadian Registration Numbers
In Canada, the pressure vessel code requires that all NGV fuel containers and pressurized fuel system components that are not part of a new OEM vehicle have a Canadian Registration Number (CRN). In addition, OEM replacement fuel containers are subject to CRN requirements. CRNs are established and managed at the provincial level, and provincial requirements and compliance demands vary across the country. This represents a barrier for component manufacturers marketing OEM replacement parts or parts into the aftermarket because the costs in terms of time and money associated with testing and application processing may outweigh any commercial gain.

Currently, no solution to this issue has been identified, however, all NGV fuel containers and other pressurized fuel system components, must be third party-certified to applicable CSA component standards. The required tests are the same as those needed to obtain CRNs. Manufacturers feel that providing certification should satisfy provincial requirements and allow for the elimination of the need for CRNs. This would apply to both CNG and LNG technologies.

10. Lack of Fuel System Installation Best Practice
As previously noted, there is no single industry best practice document that addresses the system design, component selection, system integration, manufacturing, and subsystem validation of the NGV fuel system. This results in significant variation in the quality and performance of aftermarket fuel systems, in particular. The industry has identified the need for an officially published and maintained best practice or guideline supported by a recognized agency such as CSA Group, SAE, NFPA, etc. In Canada, the CSA B109 Design and Installation Code provides the comprehensive basis for installation and inspection of these systems, but offers limited guidance on fuel system design and integration. CSA Group also intends to publish the next edition of the CSA B109 code that includes LNG fuel system design and installation requirements in March 2015.

11. Fuel Quality Standard for CNG & LNG
One of the foundational standards for all fuel dispensing and fuel burning technologies is the quality of the fuel. The reliability and performance of the critical components of the system is greatly reduced when poor or variable quality fuel is used. The trend for tighter engine tail pipe emissions and improved fuel economy and performance also demands that a stable and reliable fuel be supplied nationally by all dispensers to the vehicle. With conventional liquid fuels that are refined from crude oil sources, creation and implementation of fuel quality standards is a possibility and the standards can be enforced. With natural gas being sold primarily based on its energy content and maximum amounts of certain constituents, the variation in fuel composition can be relatively broad and CNG may not consistently satisfy the demands of the vehicle and engine OEMs. As a result, further fuel conditioning at the CNG refuelling station may
need to be considered in the future in order to have an enhanced standard fuel that could be used for vehicles.

There is currently new work by the SAE and ASTM to develop a transportation fuel best practice that would define special fuel blends for use by engine and vehicle manufacturers to certify their products to emissions standards and regulations set by EPA and other government bodies. Included in the scope of these activities is SAE 1616 – Recommended Practice for Compressed Natural Gas Vehicle Fuel. No work has been identified or initiated to turn these special fuel requirements into dispensed fuel quality standards.

For the fuel quality standards to be recognized in state, provincial or federal regulations, they must be first published as accredited national standards. Until such time, vehicle performance will vary across the different supply regions in the US and Canada which could adversely affect fleets operating NGVs in North America.

Oil content and oil fouling of controls has been a CNG issue for at least 20 years and some limits on the oil content are necessary. There is also the basic issue of incompatibility between the mineral oil used in older compressors and the synthetics used in new stations. These oils react to form solid deposits like tar and varnish that cannot be tolerated in precision control components. Some standard language is needed for the fuel composition standard to prevent both excessive oil content and the presence of incompatible mineral oils.

12. Harmonized CNG Home Refuelling Standard
There is currently no nationally recognized, harmonized standard for a home refuelling appliance. CSA Group is currently developing a harmonized set of performance and safety requirements that outline the design, installation, safe operation, and maintenance of CNG refuelling equipment that could be used for both residential and commercial fuelling. The standard is designed to allow this type of refuelling device to be categorized as an appliance and therefore be inspected and approved by the building inspectors and not the fire marshal. Similarly, the code coverage in North America will need to be modified to reflect use of these home refuelling appliances similar to that of other appliances powered by CNG.

13. LCNG Stations
CNG that is generated from a cryogenic supply of natural gas is not odorized and therefore additional sensors are necessary in and around the fuelling station. Standards specifically addressing the safety issues associated with odourless fuel or standards associated with onsite idolization need to be developed and recognized by the local AHJs.

14. Migrating Refuelling Infrastructure to P36 Pressure
As outlined, there are two service pressures used in North America – 3,000 psi (P30) which is the service pressure for the majority of NGVs in Canada and 3,600 psi (P36) which is used for all vehicles in the U.S. Having two different pressures has created a series of enforcement and maintenance issues that put the vehicle fuel containers at
risk if any type of illegal adaptor is used for refuelling. Migration to a single P36 level system needs to occur to ensure that lower pressure systems are not refuelled to higher pressures.

15. CNG “Virtual Pipeline” (Mother/Daughter) Systems

In Canada, there are no code requirements for CNG tankers and the defueling depots. There currently is coverage in Canada for LNG, LPG, and conventional liquid fuels for over the road carriage. In the past, the number of these virtual CNG pipelines (fleets of tube trailers supplying energy to remote locations) was small and there was limited demand from provincial authorities for a code to site and approve these systems. The AHJs cobbled together requirements from many different codes, but there is concern that doing this as a one-off approach is no longer the best approach. With the large disparity in price between diesel and CNG, the demand for these virtual pipelines continues to grow. There are now major trucked CNG projects operating in Nova Scotia, New Brunswick/Prince Edward Island, Ontario, and Saskatchewan. In each case, the fuel is being used for industrial applications. To date, none of these projects include a direct use of the trucked CNG as transportation fuel which is the traditional meaning of the term “mother-daughter” station in the NGV industry and is a model that is common in countries with limited pipeline infrastructure.

Given the increase in activity for industrial projects in Canada, the AHJs are asking for codes that provide performance and safety requirements for the tube trailers and trucks, the fuelling, the maximum emissions released from the different parts of the system, and defueling depots including emergency controls and countermeasures. In Canada, CSA Group manages these codes, in the US these codes and standards are supported by CSA, the Compressed Gas Association and NFPA.

E.6 Standards Governing Engines

Natural gas engines which are integrated by OEMs are subject to the same emissions standards as diesel and gasoline engines. The Canadian Environmental Protection Act, 1999 (CEPA 1999) transferred legislative authority for regulating emissions from on-road vehicles and engines to Environment Canada from Transport Canada’s Motor Vehicle Safety Act. This includes the authority to establish exhaust emission limits for on-road vehicles. The On-Road Vehicle and Engine Emission Regulations under CEPA 1999, came into effect on January 1, 2004.

With the integration of the North American automotive industry and seamless travel across the border between the countries, both Canada and the U.S. have agreed to work together to align vehicle emissions requirements for light- and heavy-duty vehicles. The new regulations adopted under CEPA 1999 continue the approach of aligning with the federal emission standards of the U.S. EPA.74

In the U.S., the California Air Resources Board (CARB) and U.S. EPA regulate fuel consumption and vehicle emissions as part of the Clean Air Act of 1990. There have been three sets of amendments for light-duty vehicles with progressively more stringent emissions requirements. Each of these amendments is referred to as a “Tier”:
Tier 1 standards were adopted in June 1991 with phase-in between 1994-1997.

Tier 2 standards were adopted in December 1999 with phase-in between 2004-2009.

Tier 3 standards, adopted in March 2014 with phase-in from 2017-2025. The Tier 3 requirements establish requirements for the vehicle and its fuel as an integrated system. The new regulations aim to reduce both tailpipe and evaporative emissions from on-road vehicles. The regulation also tightens gasoline sulphur limits, although that issue is beyond the scope of this paper.

Consistent with previous agreements related to Canada-U.S. harmonization, the Tier 3 requirements apply to vehicles used in Canada. In addition, alternative fuel vehicles including CNG and LNG vehicles are subject to Tier 3 standards.

E.7 Safety Incidents & Analysis

Over many years, CVEF has monitored and reported safety issues associated with the expansion of NGVs in North America. Incident information is maintained in a database and, as required, information is forwarded to the standards development organizations responsible for the respective codes or standards for review. Data on specific incidents can be obtained from CVEF.

As with any transportation fuel and technology, the natural gas vehicle industry in North America and around the world has had field safety incidents over the years. Generally, each incident has multiple root causes and solutions. The NGV incident database consists of a list of 49 incidents that have been reported and recorded. It should be noted that the database list does not include cylinder failures that have: (a) multiple root causes; (b) fundamental design issues such as stress rupture on composite cylinders; (c) ongoing research or investigation through CVEF; (d) durability and robustness issues of Type 4 cylinders that resulted from a failure in California; or (e) the research needed based on the Type 2 cylinder failure in Philadelphia. Information on these specific issues is noted below.

The incidents listed in the database is for serious incidents that are judged to have relevance to the CNG container standards of construction and use that are in effect for the U.S. A number of incidents occurred outside the U.S., but involved container designs and causes that relate to the U.S. products and market conditions. In some cases there is very comprehensive information available, but in other cases only news reports, photographs, and other correspondence is available. That said, in almost all cases, the information is complete enough to determine potential root causes.

In most incidents there are multiple root causes and, if any one cause were absent, the likelihood of an unsafe incident would be greatly reduced. These are potential root causes because in most cases a comprehensive failure analysis is not available. While the root causes are not confirmed, the fact that analysis shows that those root causes can be present and can contribute to severe incidents is sufficient reason to try and address the causes.

Some of the root causes have already been addressed through changes to the ANSI NGV2 standard and the NFPA 52 code, but many of these have not been addressed in FMVSS 303 OR
304. Some root causes have not been addressed and may require changes to NGV2, NFPA 52, and FMVSS.

A few of the incidents did not involve the container but had serious consequences and the same root cause could cause a container failure. Some related to the PRD system that is essential to the container system. The root causes are roughly ranked according to the number of incidents and the severity of actual consequences. Based on the incident findings, there are four significantly different levels of severity for failures of CNG containers.

1. The most severe failure is rupture of the container without warning. A number of these incidents have resulted in fatalities and serious injuries, although many others did not result in injury.

2. The intermediate severity is rupture with warning and these are all the result of vehicle fires. While these incidents are still very hazardous, emergency responders are trained and protected and there is time to clear a perimeter to protect the public. (A serious vehicle or structure fire may be either high or intermediate severity depending of the ability to evacuate.)

3. The least severe situation is a leak of natural gas. While a natural gas leak rarely has serious consequences, fire or explosion can occur. The odorant in CNG generally gives warning of a leak and is easily recognized.

Root Causes

1. Stress Corrosion Cracking of Glass Fiber Composite
   a. Ten container ruptures
   b. One fatality
   c. Two serious personal injuries
   d. All cylinders were made with commercial E-glass, not corrosion-resistant glass.
   e. All cylinders were made prior to NGV2-1998.
   f. NGV2-98 was modified to add an acid test but FMVSS 304 has not been changed.
   g. An acid spill is required.
   h. Periodic or even post-accident inspection does not provide protection.

2. Corrosive Cargo Drained Onto Containers
   a. Eight container ruptures
   b. One fatality
   c. Two serious injuries
   d. All cylinders failed due to acid stress corrosion cracking, see above.
   e. NGV2 states that containers are not expected to resist cargo
   f. NFPA 52 does not require that containers be protected from cargo

3. Overfilled Containers
   a. Nine incidents, nine container ruptures and one rupture disc failure
   b. Two serious injuries
   c. Two containers had no previous damage
   d. Eight containers had some level of composite damage before rupture
e. NFPA 52 does not require that dispenser fill controls be listed to a standard
f. ANSI NGV 4.1 does not require reliability, self-diagnostics or periodic verification of dispensers.

4. Installation Error
   a. Seven incidents, seven container ruptures and one vehicle fire
   b. Two serious injuries
   c. Location, mounting brackets or inadequate protection resulted in composite mechanical damage
   d. NFPA 52 requires installation in accordance with container manufacturer’s instructions
   e. FMVSS 304 and NGV2 do not require manufacturers to provide instructions
   f. Fire started with an exhaust fire but PRD installation resulted in rapid expansion before the driver could evacuate.

5. Multiple Service Pressures
   a. Seven incidents, seven ruptures
   b. Two serious injuries
   c. U.S. CNG vehicles have had service pressures of 2,400, 3,000 and 3,600 psi.
   d. These incidents involved filling of 2,400 psi or 3,000 psi vehicles at stations designed for up to 3,600 psi vehicles
   e. All incidents occurred since pressure-specific fill connectors have been required
   f. All standards presently allow all three service pressures.
   g. Virtually all new containers and vehicles are 3,600 psi
   h. FMVSS should permit only 3,600 psi

6. Isolation of Pressure Relief Device (PRD) from Fire
   a. Six incidents, six ruptures
   b. No serious injuries
   c. All PRDs required heat from the fire to activate
   d. Five vehicles were OEM, not conversions.
   e. NFPA 52 has been modified to call attention to the need to not shield PRDs
   f. FMVSS 303 does not address PRD shielding

7. Interconnection of PRDs to Multiple Containers
   a. Two incidents and two ruptures
   b. No serious injuries
   c. OEM buses with all containers interconnected

8. Failure to Vent Gas Through Valve in Service
   a. Seven incidents
   b. Four fatalities
   c. Three serious injuries
   d. Five involved cylinders fitted with solenoid valves
   e. NFPA 52 and ANSI NGV3.1 modified to require warnings and instructions
   f. Control by using service procedures has not eliminated the problem. A design control should be required to warn the technician.
9. Use of Compressed Air for Leak Testing
   a. Two incidents, one cylinder and one regulator
   b. Three fatalities
   c. One serious injury

10. Undetected impact damage
    a. Three incidents, five ruptures
    b. One fatality and one serious injury
    c. All Type 4 carbon cylinders
    d. NGV2-98 increased the severity of the drop test but it does not simulate stress rupture after impact. FMVSS 304 has no impact requirement.
    e. Fatality was due to concentrated point impact in operation and resulted in immediate rupture; NGV2 has no requirement for this level of impact resistance

11. Overfill resulting from solenoid valve malfunction
    a. Four incidents, four ruptures
    b. Three different designs of valve
    c. All Type 2 steel-lined containers
    d. Suspected dispenser inaccuracies in all four incidents
    e. Three ruptures in very hot weather, one in fire.
    f. NFPA 52-2013 requires detection of valve malfunction on new vehicles.
    g. Existing dispenser technology does not protect.

12. Excessive Hardness of Steel
    a. Eight incidents, eight ruptures
    b. Five Type 2, three Type 1
    c. Seem to result from skipping the tempering operation during manufacturing
    d. All processes included 100% hardness tests.

13. External metal corrosion
    a. Seven cylinders, seven ruptures
    b. Five Type 2, two Type 1
    c. Type 2 liners were also too hard.
    d. All were in areas of intensive use of de-icing salt
    e. No cylinder standard has requirements for resistance to de-icing salt corrosion

14. Lack of periodic inspection
    a. Two incidents, two ruptures
    b. One serious injury
    c. Primary root cause of one was exterior corrosion and the other a defective bracket design
    d. There is no national regulation requiring inspection

15. Low strength metal liner
    a. Two incidents, two ruptures
    b. Two serious injuries
    c. One aluminum Type 2 and one steel Type 2
    d. Properties are indicative of a possible slack quench in both cases
16. System designed with rupture disc PRD  
   a. One serious fire a service garage  
   b. No known injuries  
   c. Vehicle was overfilled due to improper temperature compensation  
   d. Incident would probably not have resulted in fire without the rupture disc.

17. Multiple incidents of leaks in Type 4 containers  
   a. Unknown number of containers leaked  
   b. No known fires or injuries  
   c. From 1994 to 1997  
   d. Multiple causes from manufacturing defects to first practices  
   e. Enhanced testing with gas cycling in NGV2-1998 but no change to FMVSS 304

18. Internal corrosion of metal  
   a. One incident, one rupture  
   b. No known injuries  
   c. Container was stored outside without a plug in Jakarta  
   d. Similar but less severe internal corrosion has occurred in the U.S.  
   e. No standard has requirements for storage.

As noted, some industry incidents have resulted in updating and revisions to codes and standards or to specifications and procedures with other issues still being under review. During June 2014, industry initiated a workshop, through the CVEF, to identify critical issues facing the industry. Four problem statements were considered based on information in the incidents database. As a result of the workshop, six task groups have been formed to begin addressing the issues identified with effort being provided by industry on an in-kind basis. Participation in this activity is open to anyone in the industry by contacting CVEF. Additional workshops are proposed to update on activity and initiate work on additional issues yet to be addressed.

E.8 Organizations Involved in Safety in North America

Industry Associations

- **Canadian Natural Gas Vehicle Alliance (CNGVA)** ([http://www.cngva.org](http://www.cngva.org))
  The CNGVA promotes sustainable growth of natural gas vehicles, refuelling infrastructure, and renewable gaseous fuels for the benefit of Canada's economy and environment through education, dialogue with government at the federal, provincial, and municipal levels, and working in partnership with other associations active in transportation, municipal affairs, natural gas supply, alternative fuels, and advanced transportation technologies. The CNGVA is a federal not-for-profit corporation. The CNGVA has 45 corporate members whose areas of interest encompass on- and off-road applications including marine, rail, and high horsepower.

- **Clean Vehicle Education Foundation (CVEF)** ([http://www.cleanvehicle.org](http://www.cleanvehicle.org))
  CVEF is U.S.-based, non-profit national organization whose mission is to assess and guide alternative fuels including NGV activities and to build awareness for and foster deployment of alternative fuel systems including natural gas vehicles. CVEF programs rely on the support and participation of representatives from industry, government,
academia, customers, and other regional/state NGV coalitions to achieve its goals and objectives. CVEF programs and priorities are set by the CVEF Board of Directors with input from alternative fuel vehicle stakeholders.

The CVEF oversees two (2) industry groups: the Technology Committee (TC) and the Natural Gas Transit (and school bus) Users Group (TUG). The CVEF TC is chaired by an industry representative and membership is open to gas utilities, OEMs, equipment and service providers, government agencies, fleets, and other alternative energy technology experts. CVEF staff work to provide input, administrative support, and active membership on various SAE, ISO, ANSI, NFPA, and CSA committees.

The TUG is managed by CVEF under U.S. DOE contract to facilitate the exchange of information among natural gas bus users. Membership includes transit and school bus staff from small, medium, and large fleets across the U.S. Vendor participation is by invitation only and limited to reports and discussion on research activities, deployment, and/or demonstration programs. TUG activities include quarterly electronic newsletters, webcasts on subjects of interest to members.

CVEF plays a critical role with respect to technical leadership and incident investigation. Based on current funding, CVEF is scheduled to wind down its operations by mid-2015. The loss of this organization will create a very significant gap in the North American NGV industry in terms of technical leadership to identify gap and issue areas. The future of the incident database and related activities including investigating incidents and relaying relevant information to codes and standards committees is unknown at this time.

**NGVAmerica (NGVA) [http://www.ngvamerica.org]**

NGVA is a U.S.-based national trade association dedicated to the development of a growing a sustainable market for vehicles powered by natural gas or biomethane. NGVA has more than 200 member companies. Member companies include representation from producers, distributors and marketers of natural gas and biomethane, manufacturers and service providers related to natural gas vehicles, engines and equipment, and fleet operators.

NGVA is the national voice of the NGV industry focused on influencing legislative and regulatory outcomes, educating industry and consumers with data-driven information, and collaborating with industry allies and stakeholders to accelerate adoption of CNG and LNG vehicles.

**NGV Global [http://www.ngvglobal.org]**

NGV Global is an international, membership-based association focused on facilitating increased use of natural gas- and biomethane-powered vehicles globally. Membership in NGV Global includes national and regional natural gas vehicle associations including the CNGVA and NGVAmerica. NGV Global has liaison status with ISO and the Organization of Legal Metrology International (OIML). Through involvement in these activities, NGV Global seeks to globally harmonize industry standards to provide consistency of requirements between national markets and to remove trade barriers for industry.
Federal Regulatory Agencies

Â Transport Canada (http://www.tc.gc.ca)
Transport Canada is the Canadian national regulatory agency established to serve the public interest through the promotion of a safe and secure, efficient and environmentally responsible transportation system. This includes development and enforcement of safety regulations and standards, testing and promoting safety technologies, and introducing safety management systems to manage safety risks for all modes of transportation (air, marine, rail and road safety, as well as the safe transportation of dangerous goods) in a reliable and cost-effective manner. Transport Canada is responsible for proposing and enforcing laws and regulations to ensure safe, secure, efficient, and clean transportation. Specific to road safety, Transport Canada is governed by the Canada Motor Vehicle Safety Act and the Motor Vehicle Transport Act, and is responsible to establish and enforce national safety standards for vehicles, child safety and motor carriers, and commercial vehicles and their drivers.

Â Department of Transportation (DOT) (http://www.dot.gov)
DOT is the U.S. national regulatory agency, established by an act of the U.S. Congress in 1966, to serve the United States by ensuring a fast, safe, efficient, accessible, and convenient transportation system that meets national interests and enhances the quality of life of the American people. DOTs top priorities are to keep the traveling public safe and secure, increase their mobility, and have the U.S. transportation system contribute to the nation’s economic growth.

The DOT is comprised of 12 agencies with leadership provided by the Secretary of Transportation. The office of the Secretary oversees the formulation of national transportation policy and promotes intermodal transportation. Other responsibilities range from negotiation and implementation of international transportation agreements, assuring the fitness of U.S. airlines, enforcing airline consumer protection regulations, issuance of regulations to prevent alcohol and illegal drug misuse in transportation systems, and preparing transportation legislation.

NHTSA is the agency within the U.S. DOT established by the Highway Safety Act of 1970 to save lives, prevent injuries, and reduce economic costs due to road traffic crashes, through education, research, safety standards and enforcement activity. NHTSA sets and enforces safety performance standards for motor vehicles and equipment, investigates safety defects in motor vehicles, and provides grants to state and local governments to conduct local highway safety programs.

Â Federal Motor Carriers Safety Administration (FMCSA) (http://www.fmcsa.dot.gov)
The FMCSA is an agency within the U.S. DOT whose mission is to prevent commercial motor vehicle-related fatalities and injuries. Activities of FMCSA contribute to ensuring safety in motor carrier operations through strong enforcement of safety regulations, targeting high-risk carriers and commercial motor vehicle drivers, improving safety
information systems and commercial motor vehicle technologies, strengthening commercial motor vehicle equipment and operating standards, and increasing safety awareness.

Current inspections related to natural gas vehicles are for leaks of fuel from CNG and LNG vehicles. Additional inspections will now be carried out on PRDs for CNG vehicles and PRVs for LNG vehicles. Vent lines will be inspected, and a check made of the vehicle have shut off valves, appropriate labels, including a fuel port label with technical information on the fuel system. Checks will be made on whether the CNG fuel system has been inspected within the past 36 months, if any tanks are outside useful service life, and if tank shields are required and in place. For LNG vehicles, checks will be made that a fuel gauge is present which indicates when the tank is filled, that there is no discharge of LNG (not vapour) from the PRV or vent line, and that there is no frost on the tank. Out of service criteria have a hierarchy of major defects which requires that the vehicle is immediately taken out of service and minor defects such as labeling which will have out of service pending to be resolved by an inspector.

**Environment Canada** ([http://ec.gc.ca](http://ec.gc.ca))

Environment Canada is the Canadian regulatory agency responsible for preserving and enhancing the environment, renewable and natural resources. Environment Canada, through programs, policies, regulations and services coordinates and implement the Government of Canada’s environmental agenda. As noted earlier, this agency is responsible for regulating fuel consumption and vehicle emissions.

**U S. Environmental Protection Agency (EPA)** ([http://www2.epa.gov](http://www2.epa.gov))

The EP enforces environmental legislation passed by the U.S. Congress, and introduces and administers programs designed to protect human health and the environment based on best available scientific information. The U.S. EPA is the agency responsible for work with other nations to protect the global environment. As noted earlier, this agency is responsible for regulating fuel consumption and vehicle emissions as part of the Clean Air Act of 1990.

**Canada Border Services Agency (CBSA)** ([http://www.cbsa-asfc.gc.ca](http://www.cbsa-asfc.gc.ca))

The CBSA’s role is to manage the nation’s borders by administering and enforcing over 90 domestic laws that govern trade and travel, as well as international agreements and conventions. Vehicles imported into Canada must comply with all Canadian import laws and the requirements of the CBSA, Transport Canada, and Environment Canada. Per Transport Canada, a vehicle is defined as any vehicle capable of being or drawn on roads by any means other than muscular power exclusively or run on rails exclusively.

Information on importing vehicles into Canada can be found in Memorandum D19-12-1, *Importation of Vehicles* on the CBSA web site. Additional rules governing importation are contained in Transport Canada’s Registrar of Imported Vehicles (RIV) program ([www.riv.ca](http://www.riv.ca)).


Measurement Canada is an agency within Industry Canada responsible for ensuring the integrity and accuracy of measurement in the Canadian marketplace. Measurement Canada is responsible for developing and administering the laws and requirements that
govern measurement, evaluating, approving and certifying measuring devices, as well as investigating complaints of suspected inaccurate measurement. This is important to stations and fuelling station equipment to ensure consumers receive the product being paid for. Canadian regulations require inspection of fuel dispensing equipment and scales on a regular basis. Measurement Canada requires that dispensed natural gas be sold on a dollars per kilogram basis for legal trade. This unit applies to both CNG and LNG sales.


The Federal Trade Commission is a U.S. Federal agency established to protect consumers and promote competition. Motor vehicle trade between the United States, Canada, and Mexico is bound by the terms of the 1994 North American Free Trade Agreement (NAFTA); specific coverage of the automotive sector is contained in Annex 300A of Chapter 3: ([http://www.mac.doc.gov/nafta/naftatext.html](http://www.mac.doc.gov/nafta/naftatext.html)).

The FTC is also responsible for the fuelling stations; focused on protecting consumers and establishing rules, guidelines and requirements for disclosure (labelling, signage) of cost/benefit information that enables consumers to make educated choices and comparison.


NIST is a non-regulatory federal agency within the U.S. Department of Commerce. NIST is a national physical science laboratory responsible for promoting U.S. innovation and industrial competitiveness by advancing measurement science, standard and technology. With respect to alternative fuels, NIST is integrally involved with industry in determining the measurement standards for fuelling station dispensing equipment.

Regional Regulatory Agencies

- Interprovincial Gas Advisory Council (IGAC)
  The Interprovincial Gas Advisory Council is a council, established and maintained by CSA Group, to satisfy Standards Council of Canada (SCC) requirements for certification bodies to establish ongoing documented working relationships with applicable Canadian regulatory authorities in their field. All CSA Group gaseous fuel standards are processed through the IGAC for final approval.

- Provincial regulatory authorities

National Code Bodies

- ICC Codes- fire code; building code
- NFPA- NFPA 52
- CSA Group
- ASME
Standards Development Organizations

- SAE - OEM safety standards
- CSA Group - component station standards
- ASTM - gas composition for LNG/CNG; test procedures not specific standards
- Compressed Gas Association – industrial gas standards; LNG vehicle pressure vessel standards; industrial pressure relief device standards
- ISO
- ASME
- American Petroleum Institute
- American Society of Civil Engineers
- National Boiler Inspectors
- Factory Mutual

Testing Laboratories for Compliance with Safety Standards

- CSA Group
- Factory Mutual
- Intertek Laboratories
- UL
- Powertech
- Battelle
- GTI
F – Industry Training & Academic R&D Capacity

F.1 New Canadian Training Courses

The lack of up-to-date technical training in Canada was a major gap area identified through the Natural Gas Use in the Canadian Transportation Sector – Deployment Roadmap25 process carried out in 2010. One of the Roadmap’s recommendations underscored the importance of addressing this gap in order to ensure the capacity to sustain market development.

As a result, starting in 2012, work was undertaken by the industry in Canada with funding support from NRCan to develop eleven training courses. These courses target fleet and emergency first responders and encompass CNG and LNG applications. Development of the courses was completed in March 2014. The industry is now focused on developing appropriate models to make this training available across Canada in a consistent and sustained fashion. The listing of courses, audiences, length, and facility requirements is shown in Table 16.

<table>
<thead>
<tr>
<th>Course</th>
<th>Type</th>
<th>Audience</th>
<th>Duration</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 General Awareness</td>
<td>Workshop</td>
<td>All audiences</td>
<td>1/2 day</td>
<td>Any location</td>
</tr>
<tr>
<td>2 Fleet Operations Readiness</td>
<td>Workshop</td>
<td>Fleet personnel</td>
<td>1 day</td>
<td>At fleet’s site</td>
</tr>
<tr>
<td>3 First Responder Safety</td>
<td>Course</td>
<td>First responders</td>
<td>1/2 - 1 day</td>
<td>Gas-safe garage</td>
</tr>
<tr>
<td>4 Routine LNG Tank Inspection</td>
<td>Course</td>
<td>Mechanics</td>
<td>2 days</td>
<td>Gas-safe garage</td>
</tr>
<tr>
<td>5 Routine CNG Cylinder Inspection</td>
<td>Course</td>
<td>Mechanics</td>
<td>2 days</td>
<td>Gas-safe garage</td>
</tr>
<tr>
<td>6 Routine LNG Vehicle Service</td>
<td>Course</td>
<td>Mechanics</td>
<td>3 days</td>
<td>Gas-safe garage</td>
</tr>
<tr>
<td>7 Routine CNG Vehicle Service</td>
<td>Course</td>
<td>Mechanics</td>
<td>3 days</td>
<td>Gas-safe garage</td>
</tr>
<tr>
<td>8 CNG Vehicle Conversion*</td>
<td>Course</td>
<td>Mechanics</td>
<td>1-3 days</td>
<td>Gas-safe garage</td>
</tr>
<tr>
<td>9 CNG Refueling</td>
<td>Video</td>
<td>Refuellers &amp; drivers</td>
<td>10 minutes</td>
<td>N/A</td>
</tr>
<tr>
<td>10 LNG Refueling</td>
<td>Video</td>
<td>Refuellers &amp; drivers</td>
<td>10 minutes</td>
<td>N/A</td>
</tr>
<tr>
<td>11 LNG Bulk Transfer &amp; Offload</td>
<td>Video</td>
<td>Drivers</td>
<td>10 minutes</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* Pre-requisite to Course #8 is Course #7

Table 18 – New Canadian Training Courses

F.2 Existing Training - Vehicles

Of the existing training courses that are available, most courses focus on U.S. market needs and incorporate references to American codes, standards, and regulations.

Vehicle Technician – The ASE F1 test for vehicle technicians includes natural gas and was updated to include more cylinder installation content a few years ago. This course applies to American learners, although it should be noted that only a few states have requirements for trained technicians. In addition, as there is no best practices document for fuel system installation, there is also no common basis for technician training related to aftermarket conversions.

OEM Training – Available for selected fleet customers when new vehicles are purchased as well as for OE dealer representatives. This training is delivered in Canada and the U.S.
A Cylinder Inspector Training – Available in U.S., but not in Canada. CSA Group has a certified cylinder inspector exam and lists those who have achieved this certification on their website. More work needs to be done in this area as there are very few qualified CNG cylinder inspectors in Canada.

A Third Party Training – Third party training is available in the U.S. from two organizations – the Las Vegas-based, for-profit company NGVi and the West Virginia-based, not-for-profit National Alternative Fuel Training Consortium (NAFTC). NAFTC is, in part, funded by U.S. DOE and has a mandate to deliver training related to all alternative fuels and technologies. This organization works through a network of member organizations which are colleges and related organizations interested in training delivery.

As part of the work in Canada to develop up-to-date training, research was carried out to consider training delivery options. In this regard, the CNGVA is partnering with NAFTC and will be using modified, “Canadian-ized” versions of “ized” versions of six of NAFTC’s courses. These courses are technical in nature and are listed as Courses #3-8, inclusive, in Table 16.

A Vendor-Specific Training for Aftermarket Conversion – Various technology providers active in the area of aftermarket vehicle conversions offer training to shop personnel who are involved with installing their conversion kits. This training does not meet any particular third party standards.

F.3 Existing Training – Stations
The third party trainers NGVi and NAFTC both offer a limited amount of training for technicians who maintain refuelling station equipment. More typically, the expertise for maintaining CNG and LNG refuelling stations resides within the vendor community. Large companies who install stations also offer station service contracts. This approach addresses immediate needs, but provides only a modest contribution to increasing industry capacity with respect to having access to trained and experienced personnel.

With respect to the Canadian training courses in this area, the development of station maintenance courses had been under consideration, but were removed from the course development list due to concerns with liability and with accessing the deep technical knowledge needed related to equipment maintenance.

F.4 Existing Training – Emergency First Responders
NAFTC offers an emergency first responders course related to alternative fuels. A natural gas-specific version of the curriculum is to be used in Canada for first responder audiences. In addition, U.S. DOE has generic first responder training through its Clean Cities program. FCMSA has a light-duty natural gas vehicle program for first responders. They have also identified the need for a similar program for heavy-duty vehicles. FCMSA plans to develop this training over the next few years.

At present, there is no published third party standard or recommended best practice related emergency response situations involving CNG or LNG vehicles and stations. While OEMs have their own guidelines, this is a gap area in both Canada and the U.S.
F.5 Gap & Issue Areas

In addition to the gaps already noted, the other gap area is with respect to training for AHJs who review and approve: (a) CNG and LNG station applications; and (b) aftermarket conversions. Much of the institutional knowledge acquired in the 1990s during the first wave of natural gas vehicle adoption is no longer in place as staff retire. In addition, the use of LNG as a vehicle fuel is completely new to Canada and relatively new to many areas of the U.S. Further compounding the challenge for AHJs is the change in focus for market development from aftermarket light-duty vehicle conversions to factory-built medium- and heavy-duty vehicles that are subject to federal regulations. Many vocational vehicles such as refuse trucks come to the market via a multi-stage manufacturing process. The requirements associated with this process may not be well understood by provincial AHJs who have historically been involved with aftermarket conversions only.

F.6 Academic R&D Capacity

There is academic capacity in Canada that could be accessed for natural gas vehicle R&D. This point was highlighted in a 2010 report prepared by Dr. Andrej Sobiesiak of the University of Windsor who said, “capacity to conduct research on NGV is in place and it can be readilymobilized and utilized if funding is provided.” 76 The list below outlines known expertise, affiliations with industry, and past R&D efforts at the university level in Canada.

- **Carleton University** – Natural gas light-duty hybrid vehicle research underway at present.
- **University of Alberta** – Past work on natural gas fuelling in HCCI engines, both experimental and modelling, conducted by R. Koch and D. Checkel.
- **University of British Columbia** – Affiliated with Westport Innovations for natural gas engine-related R&D activities. Past work included effort on lean and stratified burn SI engines, dual direct fuelling in CI engines, both experimental and simulations involving S. Rogak, R. Evans, K. Bush, and M. Davy.
- **University of Calgary** – Past work on dual fuelling in CI engines carried out by G. Karim and I. Wierza.
- **University of Ontario Institute of Technology** – Daniel Hoornweg, Research Chair in Natural Gas as a Transportation Fuel. Also, analytical work on exergy analysis of natural gas vehicles conducted by M. Rosen and I. Dincer.
- **University of Saskatchewan** – In cooperation with the Saskatchewan Research Council, work has been carried out on intelligent control systems for natural gas vehicles and storage tanks led by R. Burton, M. Sulatisky, S. Hill, and B. Lung.
- **University of Toronto** – Work on direct injection natural gas engines with a glow plug including both experimental and modelling elements conducted by J. Wallace and M. Thomson, Director of NSERC-CREATE program, in Clean Combustion Engines section of engineering faculty.
- **University of Waterloo**
University of Windsor - Work on natural gas in cyclic variations, combustion completeness, exergy analysis, and durability in SI engines with both experimental and analytical effort conducted by A. Sobiesiak.

The AUTO21 academic network offers an opportunity for natural gas vehicle-related R&D, although none of the current projects funded by AUTO21 focus on natural gas. It should be noted that:

Â There were NGV projects in the initial round of AUTO21 funding 2000-2007.

Â Westport is represented on the AUTO21 Board of Directors.

Â AUTO21 could consider supporting projects on natural gas use in vehicles in its next round of funding provided such projects have Canadian industrial partners who commit financial support to the project proposal.

Â The AUTO21 Scientific Advisory and Research Management Committees are open for suggestions from NG interest groups to include NG projects in its Powertrains, Fuels and Emissions theme providing that such projects receive strong support by those NG interest groups.

F.7 New Canadian LNG Technology Development Centre

In addition to existing academic capacity and Canada’s AUTO21 research network, there is also a new initiative that will significantly increase Canada’s capacity with respect to LNG R&D through the creation of a global centre of excellence for LNG research. Westport and Hitachi High-Tech AW-Cryo, Inc. (HTAW) are partnering so as to establish a LNG Technology Centre headquartered in Vancouver. The LNG Technology Centre will be a consortium of local and international partners who represent the entire LNG value chain including academic institutions, government, research laboratories, regulatory agencies, fuel providers, systems integrators, engine and vehicle OEMs, suppliers, and end users.

*Figure 67 – Engagement Model for LNG Technology Centre*
Westport will leverage its extensive LNG knowledge base which has resulted in one of the largest intellectual property portfolios in the automotive sector. The company already works with OEMs around the world to develop products in markets with a significant demand for clean, low-emission engines, from automotive through to high horsepower applications.

HTAW is a new Canadian company formed from the partnership of Hitachi High-Technologies Corporation and Air Water Plant & Engineering Inc. With over 30 years of experience in transporting LNG by truck, rail and ship in Japan, HTAW has significant expertise and a strong safety record with respect to LNG handling. HTAW has existing manufacturing facilities in North America. The company produces LNG ISO containers, storage tanks, and cryogenic pumps.

**Purpose of the LNG Technology Centre**

The LNG Technology Centre will address issues faced by the entire LNG value chain which, if left unaddressed, could limit the growth of the LNG industry. The scope of work for the Centre will encompass key issues such as how to:

- improve the economics of LNG production;
- enhance storage strategies in tanks and on vehicles;
- reduce vehicle system cost;
- improve refuelling and bulk fuel transfer;
- minimize fugitive greenhouse gas emissions;
- improve the design of systems to ensure safety in the event of an accident;
- support the development of codes and standards for all applications;
- develop the businesses to provide the supply chain solutions; and
- provide the workforce required to staff LNG facilities.

The LNG Technology Centre’s mandate will be to create solutions to these and other challenges in order to increase adoption, along with the use and sales of LNG and LNG technologies. The pooling of resources, expertise and capabilities, training and education, and incubation and commercialization of LNG technologies will enable discovery, development, and commercialization of new, improved and existing technologies and resolution of LNG-related issues in a faster and more cost-effective way. The benefits will be manifested in more rapid, sustainable and broader market adoption of LNG, LNG technologies, and LNG-fuelled equipment.

**Facilities**

The LNG Technology Centre will be located at Westport’s existing LNG testing facilities at 1691 West 75th Avenue in Vancouver, with worldwide satellite locations engaged depending on project scope, funding sources, requirements, project participants and capabilities. This facility already provides:

- **Facility**
  - Up to 23,500 sq-ft office space available
  - 5,500 sq-ft of lab space available
  - Conveniently located near Vancouver International Airport
  - 20 minutes from FortisBC’s Tilbury LNG production plant

- **LNG system test bays**
• 5 small test bays with 15 hp hydraulic power available for actuation and 54kW of heated coolant available for vaporization
• 2 large test bays with 250 hp hydraulic power for actuation and 50kW of heated coolant for vaporization
• LNG or liquid nitrogen (LN2) capability
• Each bay has a methane gas detector tied into building safety system for LNG/CNG leaks
• Up to 1,000 kg/hr of gas reinjection capacity

➢ Prototype system assembly capability

➢ Onsite Cryogenic Fluid Storage
   • 12,000 gallons of LNG for system testing in horizontal ISO tank
   • 12,000 gallons of LN2 in vertical storage tank

➢ Vehicle fuelling station
   • 6,000 gallon capacity
   • LNG dispenser for trucks and test rigs

The LNG Technology Centre will have three main areas of activity:

1. Incubation, acceleration and commercialization
   For novel intellectual property (IP) generated either from the LNG Technology Centre's own R&D efforts or externally that are best developed as a standalone commercial venture, the LNG Technology Centre will:
   • develop IP protection and licensing policies;
   • incubate and accelerate LNG-related technology spin-off start-ups; and
   • encourage commercialization by its partners.

2. Research and Development
   The LNG Technology Centre will undertake research projects as determined by the Centre’s Director, Technology Advisory Group, and Board of Directors collaboratively with one or more of the Core Members and other industry, academic leaders, and government on a project-by-project basis. The Centre will collaborate with leading academic institutions, and host graduate and post-doctoral students, visiting academics and academics on sabbatical. Technological and regulatory issues of LNG and LNG-related technologies from extraction and production of LNG to long distance transportation and commercial applications will be addressed.

   The LNG Technology Centre will also provide LNG contract research and development services. The R&D activities will take place at the LNG Technology Centre in Vancouver, in a network of partner and subcontracted facilities and/or at academic institutions.

3. Training and Education
   The LNG Technology Centre will collaborate with the CNGVA and with academic institutions like the British Columbia Canada Institute of Technology (BCIT), industry, and government to support the education and training of people involved in making the
vision for LNG a practical reality: technicians, engineers, students, academics and tradespeople. Further, in collaboration with academic institutions, trades training bodies and industry, the LNG Technology Centre will develop best practices and the skills and qualifications required for LNG operations and activities. These efforts will attract and retain qualified talent pool, generate revenue, and attract external funding.

**Expected Benefits for Canada**

There are five broad areas of benefit for Canada associated with the LNG Technology Centre:

1. **Technology Creation**
   - Novel technologies for LNG addressing key issues for on-engine, off-engine, and stationary applications for on-road vehicles and off-road vehicles and vessels (mining, marine, rail, exploration and production, aerospace)
   - Incubation, acceleration and commercialization of spin-off technologies via partnership with network of venture capitalists, and mentorship and support from Westport’s and partners’ IP, legal, business, and corporate development teams

2. **Economic Benefits for Canada**
   - Further development of an industry around LNG technologies that can enable the broader use of LNG for transportation and other uses in the domestic market and internationally
   - Stimulate local and foreign investment into the LNG value chain from LNG Centre partners, and other funding sources
   - Strengthening supply chain and domestic LNG business
   - Potential decrease in cost of consumer goods due to decrease in freight transport costs and increased competitiveness resulting from development of LNG infrastructure for transportation

3. **Job Creation**
   - Creation of long term jobs in the LNG and cryogenic industries resulting from technology investments via existing companies, outlicensing and the creation of new spin-off companies across Canada
   - Retention of skilled labour force due to creation of local highly—skilled jobs in engineering—academics and technical trades from the creation, development and expansion of the LNG Technology Centre and Canadian companies

4. **Leadership and Competitiveness for Canada**
   - In partnership with institutions such as BCIT, the LNG Technology Centre will provide education and training for technicians, engineers, students, academics, tradespeople and executives
   - The LNG Technology Centre will form a unique consortium of leaders in LNG from industry and academia and will attract further talent from around the world
   - Vancouver will become a hub for LNG technologies innovation leveraging Westport’s expertise as a leader in the industry
5. Commitment to the Environment

- Expanding the use and applications for LNG, considered to be a cleaner, low carbon alternative fuel, to vehicles and vessels of all types and sizes
- Working with LNG Technology Centre consortium partners to eliminate fugitive emissions along the value chain
G – North American Context

G.1 Overview - U.S. Natural Gas Market
The Canadian natural gas market is highly interconnected with the U.S. natural gas market, and there are synergistic opportunities between Canada and U.S. as both countries seek to utilize natural gas and other clean energy resources for transportation applications.

A new era in natural gas production began impacting the U.S., Canada, and global markets around 2008 when new supplies from the “shale gas revolution” – arising from the confluence of advanced horizontal direction drilling, hydraulic fracturing, and microseismic monitoring – began flowing to the market in appreciable quantities. This breakthrough in natural gas production was the culmination of a series of technical and commercial advancements undertaken by the U.S. DOE, Gas Research Institute (now Gas Technology Institute, or GTI), Mitchell Energy & Development Corp., and others over the preceding two decades. The result has been an abrupt decline in U.S natural gas prices for more than five years as reported by the DOE Energy Information Administration (EIA) and a large increase in the estimate of the potentially-recoverable U.S. resource base, such as shown in Figure 69 by the Potential Gas

Figure 68 – Integrated North American Natural Gas Transmission System
Committee, an independent organization that provides biennial estimates of the U.S. natural gas resource base.  

![Figure 69 - Natural Gas Potential Resource per the Potential Gas Committee](image)

Increased natural gas production in the U.S. has sharply reduced the amount of natural gas that the U.S. imports (primarily from Canada by pipeline, and secondarily by imported LNG), as shown in Figure 70. In 2000, net imports equalled 18.8% of domestic U.S. gas production; by 2013, this figure had fallen to 5.5%. Conversely, exports from the U.S. (primarily to Canada and Mexico by pipeline) have increased.

![Figure 70 - U.S. Natural Gas Import and Export Volumes](image)
The U.S. consuming market is only beginning to fully respond to this major shale gas supply disruption. Figure 71 shows how natural gas was used in five different sectors of the U.S. economy in 2013. This usage primarily reflects past infrastructure investment. The transportation sector only accounted for about 0.1% of natural gas consumed in the U.S. While the U.S. had efforts and initiatives in the past to promote NGVs as a transportation option, these have been relatively modest efforts driven primarily by environmental benefits with little direct linkage to potential new demand growth for natural gas as a domestic resource. The other major natural gas consuming sectors are briefly summarized below, to provide context for the U.S. transportation application and U.S. natural gas R&D.

**Figure 71 - U.S. Natural Gas Use By Sector In 2013 in BCM**

**Power Generation use** is a major consuming sector for U.S. natural gas. Natural gas is used by traditional utility power generation as well as in large-scale independent power producers, onsite industrial, and small- and medium-sized commercial combined heat and power systems. The future outlook for natural gas use in the U.S. power generation sector is favourable, with expected older coal-fired and nuclear plant retirements, and greater economic and environmental incentives for high-efficiency, low-emission, natural gas-driven combined heat and power systems.

**Industrial use** of natural gas to satisfy process heating, steam generation, and onsite power generation needs (e.g., combined heat and power) is widely used by various manufacturing segments. About 89% of the natural gas consumed in the U.S. for industrial use is by: chemicals and plastics; petroleum refining; primary metals and fabrication; food and beverage; and paper, wood and printing.81

Figure 72 shows the DOE EIA 2014 Annual Energy Outlook for U.S. industrial natural gas demand, which projects an anticipated 39% increase from 2009 to 2030.
Commercial and residential use of natural gas represented about 35% of total U.S. consumption in 2013. On a go-forward basis, these sectors are expected to experience modest declines due to factors such as increased energy efficiencies.

Exports of LNG from the U.S. are expected to rapidly increase during the coming decade as new export facilities are brought online. DOE EIA’s 2014 Annual Energy Outlook projects that net exports from the U.S. may approach 100 BCM by 2025 – equal to 13% of estimated 2025 domestic U.S. consumption of 772 BCM. Figure 73 shows data from a recent Nexant study on the international market for LNG production. In this outlook, North American LNG exports rise to about 100 BCM after 2020 and largely hold steady over the subsequent twenty years.
G.2 Stakeholders Consulted
The following stakeholders were contacted in the context of preparing this section of the report on North American collaboration:
- Alabama Gas Corporation – Steve Robertson, Manager
- CenterPoint Energy – Jim Tilley, Sales Manager – Louisiana/Mississippi
- Clean Vehicle Education Foundation – Douglas Horne
- Southern California Gas Company – Cherif Yousse, Technology Development Manager
- U.S. DOE – Dennis Smith, National Clean Cities & Technology Deployment Director

G.3 Overview - Use of Natural Gas as a U.S. Transportation Fuel
The transportation sector is the other U.S. end-use sector that is expected to have very large growth in demand, at least in percentage terms. The rapidly-increasing use of natural gas in the U.S. transportation sector is driven not only by environmental factors, including pending IMO Emission Control Area requirements for marine vessels, but also driven by strong fuel price economics, domestic energy security interests, price forecast stability, infrastructure development inflection points, and other factors.

DOE EIA’s 2014 Annual Energy Outlook projects about 4 BCM of natural gas will be used in CNG and LNG vehicles by 2025, which is equivalent to displacing about 0.5% of traditional liquid fuel use. Figure 74 summarizes DOE EIA’s projection of the approximately 400% increase in the consumption of natural gas for transportation applications from 2013 to 2025 in the U.S. Some other parties project much greater consumption and achieving 2.6% displacement by 2025 (i.e. potential 2025 NGV market penetration of 635 PJ), with nearly 92% of this natural gas being consumed in heavy-duty vehicles. But while the use of natural gas as a transportation fuel is expected to rapidly increase in the U.S., Figure 74 illustrates that the price and overall growth in U.S. natural gas pipeline infrastructure will be driven by the other, much larger end-use sectors.

![Projected 2025 US Natural Gas Use By Sector](image)

Figure 74 - Projected 2025 U.S. Natural Gas Demand By Sector in BCM
Transportation-related use of natural gas in the U.S. includes CNG and LNG vehicles, but the U.S. differs from much of the rest of the world in the size of the vehicles being fuelled. At the end of 2012, there were over 16 million NGVs worldwide, with about 128,000 in the U.S. \(^{84}\) Approximately 97% of the U.S. vehicles are fuelled by CNG and 3% by LNG. \(^{85}\) While most of the 16 million NGVs worldwide are smaller vehicles, in the U.S. there is significant focus on natural gas use for buses, refuse trucks, over-the-road Class 8 trucks, and other medium- and heavy-duty vehicles. These types of vehicles typically consume at least 5 to 15 times more fuel than typical light-duty vehicles. The prevailing price savings for CNG of $0.37 - 0.45/litter equivalent of gasoline or diesel can provide a compelling payback for high fuel use vehicles consuming more than 30,000 litters of fuel per year.

Other industrialized nations such as Europe are also pursuing heavy-duty on-road vehicles. The European Union’s TEN-T initiative includes targets for refuelling infrastructure in key corridors for CNG, LNG, and other alternative fuels.

There is also growing market interest in the U.S. to use natural gas in large, off-road vehicles such as rail, marine, and mining applications, where the focus is primarily on LNG use. These large-consuming, off-road LNG applications could be supplied from natural gas utility peaking in the U.S., additional purpose-built merchant LNG fuel plants, and potential “excess” production capacity from the many new large-scale LNG export plants likely to be constructed over the next five years.

An expanding network of large NGV fleet fuelling stations is being constructed in the U.S. to supply CNG, LNG or both fuels. Some LNG stations also supply CNG that is made by pumping LNG to high pressure and vapourizing it. These stations are referred to as L-CNG stations. Figure 57 illustrates the approximately 1,400 CNG stations and 100 LNG fuelling stations (public and private) operating in the U.S. as of July 2014. \(^{86}\) These stations have been built by a variety of organizations such as natural gas local distribution companies, for-profit fuelling providers, and companies with large fleets including cargo transportation companies. Many additional fuelling stations are being developed or have been built and not yet commissioned.

Figure 75 – CNG & LNG Refuelling Stations as of July 2014 (Source: U.S. DOE)
U.S. CNG stations are typically rated to deliver CNG at 3,600 psi, and can be configured to provide either time-fill, fast-fill, or both. For example, a modern large-scale CNG fuelling station built in Houston, TX in 2013 is shown in Figure 58. This station includes 120 time-fill CNG fuelling lanes and a five-lane, fast-fill CNG dispensing area. This station offers a good example of a new trend in CNG station development in the U.S. which is the construction of high capacity CNG stations tailored to the access and refuelling needs of heavy-duty CNG trucks.

A modern large-scale LNG fuelling station built in Long Beach, CA is shown in Figure 59. U.S. LNG fuelling stations often provide the optional ability to warm (also referred to as “conditioning” or “saturation”) the LNG in order to provide sufficient on-board pressure to fuel spark-ignited engines, although some technologies to provide on-board LNG temperature-conditioning are being developed. Marine LNG bunkering facilities are being proposed or developed along the U.S. Gulf, West and East Coasts, along the Mississippi River, and in the Great Lakes. Current components and technologies used in the design and operation of CNG and LNG fuelling station are applied fairly consistently across the U.S. and Canada.

Many equipment suppliers active in North America have been developing new products for the U.S. and Canadian NGV markets. A large number of both OEMs as well as aftermarket suppliers have developed engines, storage tanks, compression equipment, liquefaction equipment, factory-built vehicles, and supporting components and infrastructure for passenger, trucking, mining, locomotives, ships and other transportation applications. Applications such as refuse,
school buses, and transit fleets have seen some of the greatest initial adoption, but Class 8 trucking applications are rapidly increasing. Marine applications are already commercial in terms of engine and tank technologies, although the choice of technologies is limited at present. Mining and locomotive applications are beginning to move from prototype demonstrations to early stage commercial.

G.4 U.S. R&D Efforts to Advance Natural Gas as a Transportation Fuel

Canada’s setting of its priorities for natural gas R&D efforts related to transportation can leverage synergies and related opportunities in the U.S., and strive to minimize overlap of duplicative R&D efforts. To provide some overall context, in 2011 the U.S. spent US$ 429.1 billion on total R&D while Canada spent US$ 24.3 billion and Mexico spent US$ 8.2 billion (equivalent to 2.85%, 1.74%, and 0.43% percent of GDP, respectively). 87

Within the U.S., many organizations are working to advance the efficient, economical, and environmentally-friendly use of natural gas as a transportation fuel through technical innovation, R&D, and demonstration. These organizations include governmental agencies (including federal, state and local agencies), regulated natural gas utilities, independent R&D organizations, transportation equipment OEMs, engine and vehicle OEMs, and other component manufacturers, natural gas producers, public policy and environmental groups, trade and industry associations, venture capital and angel investors, and others.

The U.S. federal government has historically expended a relatively limited portion of its R&D funds on energy-related R&D. For example, as illustrated in Figure 67,88 in 2012 the federal government expended only 1.7% of its non-defense budget on energy-related R&D 89 (vs. for example 22.2% on health and 6.3% on space flight). In addition, only a small portion of U.S. federal energy-related R&D funds have historically been focused on natural gas. One analysis indicates that only 5% of U.S. federal energy-related R&D expenditures from 1950-2010 were for natural gas R&D, as compared to 48%, 23% and 15% for nuclear, coal and renewable energy R&D, respectively. 90 And even more specifically, only a small portion of U.S. federal natural gas-related R&D funds have historically been focused on utilization in all forms (including as transportation fuel), as illustrated in Figure 61 which shows R&D funds spent by the U.S. Department of Energy (DOE) from 1978-2010. 91 Given this past situation and the opportunity to advance domestically-fuelled NGVs, additional U.S. federal funding for NGV R&D is being promoted. In April 2013, for example, the American Gas Association, American Public Gas Association, GTI, and NGVAmerica urged the U.S. Congress to provide $30 million for NGV R&D 92, and other organizations such as MIT have called for support for natural gas RD&D 93.
The primary U.S. federal agency funding source for R&D related to natural gas and more specifically NGVs is and has been the U.S. DOE through DOE’s Office of Energy Efficiency and Renewable Energy (EERE), Advanced Research Projects Agency – Energy (ARPA-E), National Energy Technology Laboratory (NETL) and other departmental agencies. The DOE issues R&D solicitations multiple times per year. Representative topic areas are summarized below. Agencies such as ARPA-E do not directly break-out R&D funds focused on natural gas. It is noteworthy that ARPA-E requested that its budget for FY 2014 transportation R&D for all types of technologies, including electric, be increased from US$138.3 to US$196.6 million. In addition to its R&D funding solicitations related to natural gas and NGVs, the DOE also:

- Issued via ARPA-E the major $30 million "Methane Opportunities for Vehicular Energy" (MOVE) program in February 2012.
- Administers the Clean Cities program, which spearheads local initiatives to implement alternate fuels (Figure 13) through a network of close to 100 coalitions.
- Maintains an Alternate Fuels Data Center (AFDC) website that summarizes alternative fuel vehicle information across the U.S.
- Annually publishes the Transportation Energy Data Book which summarizes data on CNG, LNG, and other alternative fuel vehicles, as well as well-to-wheel emissions assessments.
and use of domestic petroleum and natural gas,” but contains no specific language regarding the use of natural gas as a transportation fuel.  

Operates a number of national laboratories, some of which are active in NGV R&D (such as Argonne National Laboratory).

Some other U.S. federal agencies fund R&D related to NGVs to a lesser extent, such as the U.S. Department of Transportation (including the Federal Transit Authority, or FTA, and the Federal Railroad Administration, or FRA); the Department of Defense (DoD), National Science Foundation (NSF), and others. Recent bi-annual Broad Agency Announcements issued by the FRA have included some natural gas-related solicitation topics among a range of topics, to make available approximately US$2.0 million during FY2014 for all federal railroad R&D. Research solicited by other DOT agencies such as the Federal Highway Administration, the Federal Motor Carrier Safety Administration, the National Highway Traffic Safety Administration, and the Maritime Administration have not historically included significant NGV technology R&D, but rather typically assessed potential regulatory impacts, operational best practices, and other issues. Federal agencies with large R&D budgets (including for example the DOE, DoD, and NSF) periodically issue Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) grant solicitations, and some of these solicitation topics may occasionally be relevant to the development of NGV-related materials or components.

Other U.S. federal policy drivers to promote public transportation applications of alternate fueled vehicles include the Clean Fuel Fleet Program, Clean Fuels Grant Program, and the Fuel Cell Bus Program. These programs generally help fund the purchase of NGVs and NGV-related infrastructure rather than funding NGV technology R&D.
Leading state, regional and local governmental agencies that fund R&D and demonstration programs related to NGVs include the California Energy Commission (CEC), which invested US$4 million in natural-gas-related transportation R&D in 2013, California Air Resources Board (CARB), South Coast Air Quality Management District (SCAQMD), San Joaquin Valley Air Pollution Control District, and New York State Energy Research and Development Authority (NYSERDA). Many of these organizations often issue multiple R&D solicitations per year related to NGVs, although some of these solicitations primarily offer NGV purchase rebates or fueling infrastructure development grants. Other state, regional, and local governmental agencies periodically offer grants to help fund the purchase of vehicles and infrastructure.

Regulated natural gas utilities have historically provided some funds for natural gas R&D including for transportation applications. But historically U.S. utilities have only applied 0.1% of sales to R&D as compared to an average 2.5-3.0% by other U.S. industries. Utility-funded natural gas R&D was dramatically reduced during 1998-2004 when the Federal Energy Regulatory Commission eliminated a previously-approved surcharge for U.S. natural gas industry R&D.

Some utility-provided R&D funds are directed through GTI, a U.S. 501(c)(3) non-profit independent R&D organization which was established in 2000 through the merger of Gas Research Institute and the Institute of Gas Technology (founded in 1941). GTI performs and manages more than USD $50 million in annual R&D efforts in natural gas including R&D to apply natural gas as a transportation fuel. As part of this effort, GTI administers the activities of Utilization Technology Development, NFP (UTD), which as of 2013 was funded by a number of large natural gas utilities or affiliated organizations (e.g. APGA Research Foundation), and their research program related to NGVs underway in 2012-2013 included the projects listed below. Other U.S.-based independent R&D organizations that perform R&D related to NGVs include for example Southwest Research Institute and Battelle Memorial Institute.

| 1 | Improved efficiency for stoichiometric combustion with cooled exhaust gas recirculation |
| 2 | Low-cost and scalable CNG cylinder |
| 3 | Development & commercialization of ultra-low emission heavy-duty natural gas engine |
| 4 | Evaluation of natural gas-based electric vehicle charging station technology |
| 5 | Side-by-side station evaluation of compressor/booster two-bank fast fill storage system |
| 6 | Design and development of time fill CNG metering system and controls |
| 7 | Natural gas vehicle costs benchmarking and reduction pathways |
| 8 | Truck-trailer integrated CNG storage design study |
| 9 | Ultimate CNG FuelMule mobile fueling vehicle field test |
| 10 | Vertical well CNG storage investigation |
| 11 | NGV fueling appliance prototype testing and evaluations |
| 12 | Free piston linear motor compressor design |

Table 19 - Transportation-Related R&D Projects Led by GTI for 2012-13
Private industry such as transportation equipment OEMs, engine and vehicle OEMs, and other component manufacturers has significant NGV R&D underway, primarily related to product development and refinement. Many of the largest of these companies operate throughout Canada and the U.S., and there may be opportunities to focus certain private industry NGV R&D at specific Canadian test sites that have unique capabilities or other attributes. Managing competitive sensitivities is, of course, a key issue with respect to OEM-related R&D activities.

The U.S. venture capital community has provided only limited investments in NGV R&D to date. By contrast, most U.S. VC energy-related investment has been targeted towards wind, solar, biofuels, and energy smart and efficiency technologies. Increased interest from these investor groups has been seen in the past several years as evidenced by their attendance and participation at regional and national NGV industry conferences and events.

Public policy, industry and environmental organizations in the U.S. such as the Clean Vehicle Education Foundation, American Clean Skies Foundation, and the Carbon War Room evaluate or advance the use of NGVs, but generally have not funded or coordinated R&D related to NGVs.

The primary R&D focus areas for NGVs that directly consume natural gas as fuel has focused on the following key challenges:

1) Improving the driving range and vehicle performance, where progress has been made for example by developing more lightweight composite CNG tanks and additional high-horsepower engines. For example, a number of heavy-duty vehicles are now available with 570 to 660 diesel litre equivalent capacity of CNG, yielding range possibilities of 950 to 1600 kilometers (depending on storage volume and fuel economy).

2) Lowering the first cost for OEM vehicles, where progress has been made principally by increases in production volumes, a more integrated supply chain (e.g. body manufacturers extending their area of focus to include fuel system installations), and product design innovation (e.g. part count consolidation/reduction and other strategies to consolidate or simplify components or systems).

3) Reducing greenhouse gas contributing emissions and criteria pollutants from the source to the point of use (tailpipe) via improvements in combustion control, exhaust after treatment approaches, advanced material selection, reduction of venting, and other technology applications.

Representative areas of NGV R&D related to the above and reflected in public U.S. R&D solicitations include for example:

- Development of lower-cost, lightweight natural gas storage tank technologies
- Development of conformable natural gas storage tank technologies
- Development of adsorbed natural gas storage technologies, to reduce on-board CNG storage tank size and operating pressure
- Development of improved CNG cylinder valves (both automatic and manual) to overcome potential safety and operational concerns
- Development of improved algorithms or technologies to prevent overpressure or underfilling of CNG cylinders, and to compensate for the heat of compression
- Development and demonstration of low-emission engines, including larger or different engines, that utilize compression ignition (and other non-spark-ignited means) or spark-ignition
- Development of hybrid electric-natural gas engine power trains for Class 3-8 vehicles
- Development of alternative, low-cost sensors to ensure engine fuel quality (e.g. methane concentration, heating value, water dewpoint, hydrocarbon dewpoint, compressor oil content)
- Development of low-cost, novel technologies for methane gas detection in stationary and mobile use
- Development of improved analysis and modelling of potential natural gas releases within enclosed maintenance facilities, to help guide regulatory development
- Development of potential additional language or topics to help guide regulatory development in new applications (e.g. railroad, mining, marine)
- Development of economical, novel CNG home refuelling appliances (HRAs)
- Development of more economical processes and equipment to purify and integrate landfill-derived, digester-derived and other renewable biogas with CNG and LNG
- Development of improved alternative fuel training materials for first responders and others
- Development of innovative and economical liquefaction technologies, including small-scale liquefaction

G.5 U.S.-Canada R&D Collaboration on Natural Gas as a Transportation Fuel

The remarkable, transformative change in North American natural gas production is spurring a wave of innovation and demand responses to apply natural gas as a transportation fuel. Canadian and U.S. researchers, planners, administrators, regulators, and others have a unique opportunity to collaborate in advancing technical R&D and demonstration because of their proximity, interconnected manufacturing base and infrastructure, co-location in the global center of shale gas production, energy security concerns, and other synergies.

The leading NGV technical issues or R&D needs identified by North American government, industry, and others include, but are not limited to, those listed above and those further described below:

- Improved emission and mitigation techniques to minimize natural gas releases at NGV fueling stations and vehicle methane tailpipe emissions (e.g., new vehicle catalyst formulations).
- Additional analytical efforts to better understand the current and future role that NGVs may have on atmospheric methane concentrations.
Improved cost-effective techniques for ensuring fuel quality requirements to satisfy engine and vehicle specifications and yield high consumer satisfaction. Work in this area would include the development of low-cost sensors for detecting methane concentration, heating value, water dewpoint, hydrocarbon dewpoint, compressor oil carryover, etc. These advanced sensors can also be used for quality assurance of bio-methane derived fuel from landfills, wastewater treatment plants, and digester plants.

Development of advanced sorbents and membranes for fueling station fuel quality assurance.

Advanced natural gas storage technologies including compressed gas cylinders (e.g., high-performance materials, conformable designs, lower costs), low-pressure adsorbed natural gas materials (e.g., metal organic framework [MOFs]), and high-performance LNG storage. Advanced adsorbent materials can be used for low-pressure storage of compressed natural gas – with attendant benefits of using lower-pressure containers and fueling infrastructure – and to capture LNG boil-off gases at LNG fueling stations and on-board vehicles; however, full system approaches are needed that solve issues surrounding bed contamination, thermal management for acceptable fill and discharge rates, detection and/or odorization techniques, and state of charge measurement.

Next-generation natural gas and hybrid powertrains (engines and fuel cells) with greater efficiency and near-zero emissions, including the development of advanced natural gas fuel injectors for large vehicles including dual-fuel natural gas/diesel fuel injection systems. Also needed are advanced natural gas-driven generators that can be used as range extenders for battery-dominant electric vehicles (e.g., transit and shuttle buses), as well as changes to engine and emissions monitoring controls for hybrid platform integration.

Advancements in fueling infrastructure, including new methods for large-scale natural gas energy storage, enabling remote fueling operations for off-site and off-road vehicles, and small-scale distributed liquefaction. Further investigation is also needed to determine cost-effective options for integrating the North American natural gas delivery system with NGV station infrastructure in order to optimize infrastructure for use to supply the transportation market; for example, technologies that increase the availability of high pressure gas at CNG station sites could be used to lower the cost of compression required.

Advancements in dispensing large volumes of CNG and LNG more quickly, accurately, and completely for improved vehicle range performance and customer satisfaction. Next-generation off-road vehicles such as rail and marine require substantially higher fuel transfer rates than on-road vehicles which will demand advancements in fuel dispensing, metering, ergonomics, and fluid dynamics.

Cost-effective home fueling systems to expand light-duty commuter NGV use. There are currently multiple efforts underway to develop new approaches to home fueling and other distributed small fleet fueling needs, such as novel piston arrangements, novel integrated linear motor driven compressors, hydraulic drives, liquid piston compressors,
and other technical approaches. In addition, a standard for certifying Home Refueling Appliances is currently being developed (CSA NGV 5.1).

- Advancements in renewable natural gas production and processing to meet stringent vehicle fuel and natural gas pipeline injection requirements. The main emphasis in this area is on new methods for using adsorbents and membranes for cost-effective and reliable gas clean-up. In addition, more reliable and cost effective real-time online monitoring techniques are needed to ensure gas quality specifications are being adhered to.

- Intelligent refueling for CNG vehicles where there is a communications protocol established (similar to hydrogen refueling, but in a less complex manner) so that data is shared between the vehicle and the station in order to optimize CNG refueling.

- Odorization of LNG

<table>
<thead>
<tr>
<th>Technology Issue/Need</th>
<th>Timeline</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Lower-cost, lighter-weight storage tanks (CNG)</td>
<td>Medium Term</td>
<td>Medium</td>
</tr>
<tr>
<td>2. Lower-cost, lighter-weight storage tanks (LNG)</td>
<td>Long Term</td>
<td>High</td>
</tr>
<tr>
<td>3. Conformable storage tanks (CNG)</td>
<td>Medium Term</td>
<td>Medium</td>
</tr>
<tr>
<td>4. Conformable storage tanks (LNG)</td>
<td>Long Term</td>
<td>High</td>
</tr>
<tr>
<td>5. Adsorbed natural gas media and tanks (CNG)</td>
<td>Long Term</td>
<td>High</td>
</tr>
<tr>
<td>6. Novel, superior LNG tank insulation technologies and other high-performance LNG storage technologies</td>
<td>Long Term</td>
<td>High</td>
</tr>
<tr>
<td>7. Improved, higher-reliability CNG cylinder valves</td>
<td>Near Term</td>
<td>Low</td>
</tr>
<tr>
<td>8. Improved algorithms, technologies or intelligent communications systems to optimize CNG tank refuelling capacities, including managing the heat of compressions</td>
<td>Medium Term</td>
<td>Medium</td>
</tr>
<tr>
<td>9. Additional low-emission natural gas engines (covering additional engine displacement capacity needs)</td>
<td>Near Term</td>
<td>Medium</td>
</tr>
<tr>
<td>10. Advance high-pressure natural gas fuel injectors for both compression-ignition and spark-ignition engines</td>
<td>Medium Term</td>
<td>Medium</td>
</tr>
<tr>
<td>11. Hybrid electric-natural gas engine power trains, including for Class 3-8 vehicles</td>
<td>Near Term</td>
<td>Low</td>
</tr>
<tr>
<td>12. Low-cost, novel sensors to monitor engine fuel quality</td>
<td>Medium Term</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Low-cost, novel sensors for stationary and mobile gas detection</td>
<td>Medium Term</td>
</tr>
<tr>
<td>---</td>
<td>-------------------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>14.</td>
<td>Cost effective, novel home fueling systems and home refuelling appliances (HRAs)</td>
<td>Medium Term</td>
</tr>
<tr>
<td>15.</td>
<td>Improved, economical processes to purify and integrate landfill-derived, bio-gas-derived, and renewable gas with CNG and LNG fuelling stations</td>
<td>Long Term</td>
</tr>
<tr>
<td>16.</td>
<td>Cost effective, novel liquefaction technologies, including for small-scale distributed LNG production</td>
<td>Medium Term</td>
</tr>
<tr>
<td>17.</td>
<td>Improved processes to minimize methane emissions from NGV tailpipes and natural gas emissions from NGV fuelling stations</td>
<td>Medium Term</td>
</tr>
<tr>
<td>18.</td>
<td>Improved analytic analysis of the role NGVs may have on global atmospheric methane concentrations</td>
<td>Long Term</td>
</tr>
<tr>
<td>19.</td>
<td>Advanced, economical sorbents and membranes to better ensure fuel quality at fuelling stations, including methane capture and recovery</td>
<td>Medium Term</td>
</tr>
<tr>
<td>20.</td>
<td>Natural gas-driven generators that can act as range-extenders for battery-dominant electric vehicles</td>
<td>Long Term</td>
</tr>
<tr>
<td>21.</td>
<td>Improved analytic analysis of best-practices to integrate the North American natural gas distribution system with CNG and LNG transportation market</td>
<td>Medium Term</td>
</tr>
<tr>
<td>22.</td>
<td>Economical, reliable, and safe high-volume CNG and LNG dispensing and measurement technologies for high horsepower applications</td>
<td>Near Term</td>
</tr>
<tr>
<td>23.</td>
<td>Improved analytic analysis of the potential natural gas releases within maintenance facilities, to inform best-practices in facility design</td>
<td>Near Term</td>
</tr>
<tr>
<td>24.</td>
<td>Odorization of LNG</td>
<td>Long Term</td>
</tr>
</tbody>
</table>

**Table 20 – Representative Leading NGV Technology R&D Issues and Needs**

Potential specific strategic collaboration and common interests in NGV R&D and scientific research between Canadian and U.S. government, industry, and academic researchers may include opportunities to:
Develop a North American database of current vehicle, engine, and component OEMs related to NGVs, in order to foster additional cross-border commercial relationships (such as Cummins Westport Inc.) and include an assessment of primary private-industry centers for NGV R&D.

Expand the sharing of federal, state, and regional NGV R&D technology roadmaps and public strategic plans through conferences, meetings, and other means between the U.S. R&D organizations listed above and Canada’s National Research Council Canada (NR C), Sustainable Development Technology Canada (SDTC), Canadian Energy Research Institute (CREI), Natural Gas Technology Centre (NGTC), Climate Change and Emissions Management Corp. (CCEMC), Alberta Energy Research Institute (AERI), and other organizations and laboratories.

Expand strategic relationships and communication between leading educational institutions, such as co-sponsored, alternating-location topical conferences.

Foster increased collaboration between the Canadian Gas Association (CGA) and American Gas Association (AGA) in relation to natural gas for transportation.

Leverage Canada’s strong aerospace industry expertise, including for example its significant materials testing capabilities (paralleling for example Lockheed Martin’s 2013 entrance in the LNG tank manufacturing business).

Leverage Canada’s strong cold weather testing capabilities to increase the knowledge base related to cold weather issues to improve NGV and for refuelling station performance in cold climates.

Potential specific strategic collaboration and common interests in NGV demonstration efforts between Canadian and U.S. organizations may include opportunities to:

Evaluate and target specific NGV applications that have some of the greatest technical synergies between Canada and U.S. such as:

- Marine, such as to exploit synergies in LNG bunkering developments on the coasts and in the Great Lakes;
- Rail, due to the interconnectedness of the North American rail system; and
- Mining, based on similarities between Canadian oil sands mining operations and surface coal mining in the U.S.

Leverage best practices from the U.S. DOE’s Clean Cities program, such as by encouraging Canadian-U.S. sister city dialogues

Potential specific strategic collaboration and harmonization of Canadian and U.S. regulations, standards and economic development planning may include opportunities to:

Aid in the development and harmonization of regulations, standards, and best practices related to:

- Marine LNG bunkering and operations (e.g. ferry operations in nearby cities, such as Vancouver and Seattle);
- Locomotive and rail operations including tender car design, refuelling, and operation;
- LNG facility design, construction, and operation including refinement of Quantitative Risk Assessments for related production and distribution facilities in North America.

Expand strategic relationships and communication between geographic Centers of Excellence in energy and materials, e.g. Calgary, Houston, Chicago, Denver

In summary, while NGV and fuelling infrastructure technologies are mature enough to satisfy and support a flourishing market in Canada and the U.S., there are significant opportunities to improve fuel efficiency, reduce emissions, lower equipment acquisition and operating costs, expand product offerings, and apply other innovations to make the overall cost of NGV ownership more attractive, reduce emissions, and increase North American energy security. Judicious setting of priorities for natural gas R&D in Canada in the context of North American and other efforts can allow innovators to develop and benefit from key intellectual property for technologies and expand cross-border and international trade in this growing market. The results of this new R&D focus can build upon a foundation of innovation in Canada and the U.S. Despite extremely limited past public-sector funding for natural gas R&D in North America, both countries received relatively more patents related to natural gas than to other energy technologies (when compared to other countries) according to one analysis of energy-related patents issued globally from 1970 through 2009. 123

![Table 21 – Cumulative 1970-2009 Patents by Energy Technology & Country](image-url)
H – Refuelling Infrastructure

H.1 Introduction
While a leading near-term opportunity for natural gas as a vehicle fuel is in return-to-base and regional corridor fleets that can justify an investment in their own refuelling infrastructure, it is expected that some publicly-accessible infrastructure will be necessary to enable broad adoption for natural gas vehicles. This is particularly true for smaller fleets that cannot justify their own refuelling facilities or for larger fleets that happen to travel off a set route from time to time. The following content has a primary focus on issues related to publicly-accessible stations, while also noting challenges associated with current station technologies.

H.2 Overview of Issue Areas
Key issues that will affect refueling for natural gas vehicles relate to point of sale simplicity for public stations, communications, and the development of a standardized unit of measure for fuel sales.

Transactional Issues

a. Point of sale simplicity and common experience at all facilities
In the past, NGV retail stations tended to be stand-alone operations that were not integrated with other retail forecourt operations. Card lock facilities were introduced at some locations in the 1990s but these usually required a separate card and the transactions were typically compiled by the gas utility.

It would be beneficial to the industry if the point of sale experience were made (at least superficially) identical to the purchase of other fuels. This would reduce transaction time and improve efficiency for end user. It would also eliminate the perception that NGV is a “special case” which would, in turn, promote acceptance and uptake of the fuel. Work is needed to scope out this issue and to identify whether there are any specific R&D-related barriers or areas of further technology development that are required.

b. Communication between vehicle and station
Communication between the vehicle and station leads to faster and more complete fills. Wireless, low energy systems have been available since the 1990s, but no effort has been made to standardize the equipment and reduce costs through economies of scale. There are several benefits that come with the use of such systems, particularly for fleet owners including:

i. The vehicle can provide detailed information about its state of fill (pressure, temperature, and volume). This would enable the station to deliver a precise temperature compensated fill without the need for secondary measurements, and/or complex or inherently inaccurate calculations. This provides complete fills in a shorter time, improving productivity and vehicle range.

ii. The vehicle identification information communicated to the station could easily include commercial transaction information that could authorize the fill and enable a simple “fill and go” transaction.
iii. The vehicle identification information could include odometer and age information that can be used to flag maintenance and testing requirements.

The hydrogen industry has developed a standard for vehicle-station communications that could be used as a starting point to determine what R&D work would be required to establish a “smart vehicle” and/ or “smart station” that would improve CNG fills.

C. Uniform unit of sale and energy conversion factors
This problem is fundamentally tied to the interests of the end user and their ability to understand the economic benefits of natural gas as a vehicle fuel at point of purchase. Measurement Canada requires that natural gas be sold on a cents per kilogram basis or a dollars per truckload basis. Mass is considered to be the most accurate way to measure natural gas as a vehicle fuel. The problem with this approach is that it leaves the end user with the challenge of having to do calculations in order to understand the energy equivalent pricing for comparison with diesel or gasoline.

In the U.S, there is an agreed upon unit for natural gas sales called the, “gasoline gallon equivalent” based on a set conversion factor. Industry in the U.S. is now working to secure recognition for a “diesel gallon equivalent” as the basis for natural gas that displaces diesel as a vehicle fuel.

Work is needed to: (a) determine the appropriate standard conversion factors for natural gas that replaces gasoline and diesel fuel; and (b) develop a rationale for using a “gasoline litre equivalent” or “diesel litre equivalent” as the basis for natural gas sold as a transportation fuel in Canada.

Refuelling Process for Dual Fuel Vehicles
At most NGV stations it is necessary for dual fuel vehicles or pilot ignition vehicles, where diesel is used to ignite the natural gas, to fill with one fuel at one location and then to have to move to another location to fill with the second fuel. This requires extra time and often requires two separate commercial transactions. Since convenience is a significant factor (often at least as significant as price) this two-step process often leads to skipping out on the less convenient fill.

In the past this problem has been compounded by the fact that the two refuelling receptacles might not necessarily be located in the same position relative to one another – so a station layout that meets the needs on one vehicle may not meet the needs of another. The solution to this problem involves standardizing the relative location of the refuelling receptacles, developing guidelines for station layouts, and creating safety standards for simultaneous dual refuelling operation. Such measures would improve convenience and productivity, reduce the likelihood of skipping the second fuel, usually NGV, and ultimately improves acceptance.

Off-Pipeline Stations
There will be instances when it will be necessary to develop stations in locations that are not well served by the natural gas grid. Most often this refers to locations that are remote from a major pipeline. However, even within a region with a reasonably well developed natural gas distribution system, there can be instances when other factors make it cost prohibitive to develop a tie-in at the ideal station location.
In these cases, customized solutions for high volume “mother/daughter” facilities can provide a fueling solution. These systems are already being built for off-pipeline industrial facilities in Canada with early projects now in place in Nova Scotia, Ontario, and Saskatchewan. The NGV industry can benefit from the adoption of the technologies and best practices being developed for such systems. It would be useful to study the limitations and benefits of these systems in order to apply learnings in a manner that promotes commercial sustainability for natural gas in the transportation sector. Some areas for further development include:

a. **Optimal storage configurations**
   Typically the gas is delivered in high volume, multi-tube bulk storage trailers that hold more than 250,000 standard cubic feet (scf). It should be possible to design automatic manifold systems that use cascade strategies to provide a significant number of vehicle fills without the need for a compressor at the daughter station location. Modeling of systems would be able to predict optimal storage manifold designs.

b. **Making the best use of the high, but falling, inlet pressure**
   In many cases much of the gas on board the trailer (as much as one third of it) will need to be recompressed to NGV pressures. Since the last gas on the trailer will be at low pressure, and standard reciprocating compressors require a relatively constant inlet pressure, this means it is necessary to regulate all of the gas to a relatively low pressure to remove it from the trailer. Clearly this wastes the energy of much of the pre-compressed gas. For high consumption stations, the amount of energy wasted can be significant. There are many possible strategies that can be employed to mitigate this loss. A study to model these strategies and identify the best among them should lead to improved economics of these systems.

c. **Ruggedized bulk trailers**
   The tube trailers for these systems will operate in environments that are typically harsher and more remote than for most NGV stations. The bulk tube trailers will be subject to vibration and impact loads inherent in over-the-road use. Therefore it would be useful to conduct a risk assessment and develop strategies to mitigate potential hazards and reliability issues.

**Electrically Constrained Stations**
There are times when a natural gas refuelling facility will a) be located off the electrical grid, b) in a location with a low quality electrical supply, c) require an amount of electricity that is cost prohibitive to tie-in, or d) require compressor prime movers of a size that makes natural gas engine drives preferable to large electric motors. These situations can arise in remote rural locations as well as in populated urban areas, either of which may have stringent noise and emissions regulations.

Although gas-driven NGV compressors have been used in some cases for high horsepower applications, there may be opportunities to improve economics for smaller applications if the following challenges can be reliably mitigated or overcome:

- Maintenance costs
- Vibration reduction
• Noise attenuation
• Emission controls
• Initial capital cost

In these cases it is also possible to use an electric motor-driven NGV compressor in conjunction with a natural gas driven electric power generator. Such a system could also provide power for the local community. The overall economics of such a system should be explored to determine possible economic benefits.

Managing Moisture Content in Fuel
Pipeline quality gas typically contains up to 7#MMSCE meaning that 7 pounds of water can be present in 1 million cubic feet of natural gas. In cold climates, it is possible for this water in the natural gas to condense, freeze, and affect vehicle performance. In addition, the NGV refuelling process involves sudden and large pressure drops that can create extremely low temperatures.

The amount of moisture present in pipeline quality natural gas may be acceptable for household appliances and furnaces, but requires the installation of a properly-sized dryer to ensure a clean, dry supply of fuel is available as vehicle fuel. Information on the gas supply moisture content can be obtained from the local gas utility and should be verified before specifying a dryer unit or designing a compressor station for use in a CNG vehicle application.

The dryer in such a system should be equipped with a dew point meter and a monitor that can be used to ensure that the gas exiting the dryer has been adequately dried. An additional layer of protection may be to add a dew point meter right on board the vehicle. This is because it is possible for trace amounts of moisture to gradually accumulate in storage vessels and increasing the dew point slowly over time.

It would be useful to conduct a literature search and a supply industry review to determine if low cost, robust dew point meters, suitable for mounting on board the vehicle are commercially available, and their effectiveness.

Managing Heat During the Refuelling Process to Improve Settled CNG Fill Pressure
In fast fill applications, vehicles fail to achieve a full fill due to the high temperatures that develop inside on board storage CNG tanks during the refuelling process. In the most extreme cases, the increase in temperature can encroach upon the maximum allowable operating temperature of the cylinder material.

Fundamentally these high temperatures are the result of two effects. The first effect is that as the gas pressure drops during the early stages of the fill (as it travels from pressurized parts of the station to low pressure in the near empty CNG fuel storage cylinder), the gas temperature drops, and so, the gas picks up extra heat from the surrounding environment. The second effect is that, as the fill cycle progresses, the gas temperature increases as pressure increases. So, the addition of heat during the early stages of the fill manifests itself as higher temperatures toward the end of the fill.

For the most part, the fast fill of an empty cylinder from storage will not result in high temperatures. The worst case scenario is the filling of a partially full (~1/3 full), large volume
tank (or group of tanks), from a compressor on a warm day. Under these circumstances it is not unusual to see in-tank temperatures well in excess of 110 degrees Fahrenheit. When the temperature on board the vehicle is significantly higher than ambient, then a temperature compensation algorithm that is based on ambient temperature will underfill the vehicle. Vehicle filling algorithms have been written in a way that estimates the final fill temperature - and so, determine an “overfill” margin. However, there are many variables that can throw these calculations off to a significant extent.

The mechanisms by which excess heat may be added to the gas during the fill process are fairly well understood and there are several potential options to mitigate this effect. For example, bulk tube trailers and vehicles with large storage volumes that are filled directly from a compressor, may require active strategies such as refrigeration (chilling - or active removal of heat) to keep final fill temperatures in the ambient range.

It would be very useful to develop an overview report that describes the different potential scenarios, discussing the temperature profiles and outcomes so that high temperature scenarios can be identified. The paper would identify those situations under which excessive temperatures can arise and outline the various solutions that are either in use, or that offer good potential. These solutions may involve communication between the vehicle and the station, insulating pipe in cold sections, rejecting heat in hot sections, the use of very late stage backpressure control, and employing various methods of active chilling. Each scenario and strategy could be evaluated based on the costs, the effectiveness of improving fill pressure, and protection of cylinder integrity.

**Strategies to Manage Boil-Off from LNG Stations**

Boil off from LNG stations creates several problems. It represents a potential for degradation of the purity of the product, loss of revenue, and negative impact on the environment. There are examples in the industry to address the boil off gas issue. For example, a nitrogen system can be used to collapse LNG vapours, so as to ensure that there is no boil off from an LNG refueling station. American company Blu announced in August 2014 that it had installed a boil off gas capture system at its Nampa, Idaho refueling station which would capture, warm, and then inject the natural gas into the local pipeline system.\(^\text{124}\)

Given the early stage of development for LNG as a vehicle fuel, the industry lacks access to a good base of knowledge about the full range of potential issues, as well as the current state of the art for mitigating or dealing with boil off. In addition to the two strategies noted above, there may also be technology options to use boil off gas including in methane fuel cells or small gen sets. A summary report based on a literature search and industry interviews would be helpful to increase understanding of this issue and how it can be best addressed.

**High Capacity Nozzles for Off-Road Applications Including Marine, Rail, and Mining Trucks**

At this point in time the largest nozzles designed specifically for NGV applications are those designed for transit buses. It is clear that solutions must either be identified, or developed for some of the larger vehicle applications being considered such as marine, rail, and mining trucks. The bulk CNG business tends to utilize large (1 and 1½”) hydraulic fittings. A survey report is required by the industry to identify what, if any, commercial products exist and what additional R&D or demonstration work is needed to achieve commercialization.
I - State of Critical Technologies

The following section provides analysis and insight related to the critical technologies and issues associated with:

- Section C - Engine development and vehicle integration
- Section D - On-board vehicle fuel systems
- Section E - Safety, codes, and standards
- Section F - Industry training and academic capacity
- Section G - North American collaboration opportunities
- Section H - Refuelling infrastructure

This analysis builds on the more detailed information provided in each of the previous sections.

Engine Development and Vehicle Integration

General Background

Growth opportunities for natural gas engines and vehicles clearly lie in the medium- to heavy-duty market segment. The key to the expansion of natural gas engine availability is a clear technology path that simultaneously lowers the cost premium of engine and fuel storage systems and critically provides a long term horizon for continued improvements in performance, efficiency, emissions, usability, and reliability. With development costs exceeding $20 million per new engine, OEMs will require strong market signals in order to make this level of investment. Customer acceptance on a broad scale is required and is starting to appear in on-highway heavy duty engine applications, with more truck models than ever before. For example, Kenworth now has natural gas engines included in first launch plans rather than being considered as possible later additions.

Off-highway applications for natural gas engines have also been gaining traction recently. Typically, the volume of fuel used is much larger than for on-highway applications and supports a positive business case for natural gas use. Given the size and cost of the parent diesel engine, incremental costs for natural gas variants can be relatively small, and lead to a stronger value proposition for the engine developer. In addition, increasingly stringent emissions regulations are a strong driver, especially in the case of marine applications, resulting in an increasing number of vessels being designed with natural gas in mind.

State of Maturity of the Technologies

There are three technologies pathways for natural gas engines for on-road vehicles:

- Spark-ignited engines using 100 % natural gas with reduced complexity for emission control compared with diesel, but also with lower thermal efficiency.
- Diesel pilot ignition with fumigated natural gas, which offer fuel flexibility to revert to 100% diesel operation.
- Diesel pilot ignition with direct injected natural gas, which use a small quantity of diesel injected as an ignition source. This results in a dedicated natural gas engine with fuel efficiency essentially equivalent to diesel. Operation of this technology on 100% diesel results in significantly reduced power for “limp home” emergency situations.
These three technologies each has varying fuel efficiencies, incremental costs, fuel flexibility, and technology complexity, depending on the vehicle application, duty cycle, and power and torque requirements.

**Spark-Ignited Engines**
Comparing all three pathways, the spark-ignited engines are the clear leader in technology maturity with four generations of product development experience. These engines are produced by Cummins Westport which is a joint venture between Cummins and Westport Innovations. They employ the same architecture as their diesel counterpart minus the common rail diesel injection system, and minus much of the complex diesel emission control system which includes diesel particulate filters, and urea-based SCR systems. Instead, emissions are controlled to very low levels with a conventional three-way catalyst system which is the same type of system that has been used over decades to control spark-ignited gasoline engines. This has resulted in a robust technology which is being widely adopted in many vehicle applications including buses, refuse vehicles, and heavy-duty trucks. There are two engines in production at present with this technology. The Cummins Westport ISL G 8.9 L covering about 250 – 320 HP which has been in production for many years, and is used in buses and refuse trucks. The second engine is the more recent Cummins Westport ISX12 G which is an 11.9 L engine, used in heavy duty trucks up to 400 HP.

There are two gaps in the spark-ignited engine portfolio. One gap represents lower power and torque, targeting the medium truck and school bus segment. The other gap is in the higher power range of 450 HP and above. The gap at the lower end is in the process of being filled with the new Cummins Westport ISB G 6.7 L engine which will be available in 2016. This segment is also served with the Ford Triton V-10 bi-fuel natural gas engine, which is based on a gasoline engine conversion, and by the GM 6.0 L V-8 Vortek bi-fuel and dedicated natural gas engine, which is also converted from the gasoline base engine.

The gap in the higher horsepower range has no contender at present and the terms of the Cummins Westport joint venture preclude this company from offering an engine above 12 L. Cummins’ previously announced plans to produce a 15 L spark ignition natural gas engine greater than 400 HP have been paused to wait for market pull. In addition, very recently, Volvo decided to terminate plans to produce a 13 L HPDI engine in cooperation with Westport Innovations. This is a significant gap to fill and may require government/industry funded demonstrations to support the case for commercialization. (refer to opportunity (n) on page 163) This approach was successfully used in 2006 through a project funded by NRCan, Transport Canada, Sustainable Development Technology Canada, and industry stakeholders to demonstrate Westport’s HPDI technology in heavy-duty trucks operating along the Highway 401 corridor in Ontario. Following this demonstration project, Westport commercialized the product including achieving EPA and CARB certification. The first significant support for the technology was in California via the Clean Ports Plan which was a joint initiative of the Ports of Los Angeles and Long Beach requiring that older, high emission trucks be retired and
replaced with lower emission technologies including natural gas for use in port drayage operations.

However, technology is a continuously moving target. While the Cummins Westport spark ignition technology can be considered mature at the present time, advances in diesel technology continue to move in the direction of improved fuel economy. There are two implications for natural gas related to this development. One is that, being a derivative of the diesel engine, some of the improvements in technology for the diesel engine may trickle down to the natural gas engine, providing the opportunity for improved performance. The other is that, if the gap in fuel efficiency between diesel and natural gas widens significantly based on improved diesel efficiency, this will encroach on the cost advantage which natural gas has over diesel. Currently the SI natural gas engines are about 15% less fuel efficient than their diesel counterparts, but if that difference grows, the price advantage enjoyed by natural gas will become less attractive on a dollar per kilometer basis. It is, therefore, critical that the spark ignition technology continues to advance in step with the diesel.

The natural gas spark ignition technology is by no means maxed out, and there are many opportunities for improving performance and fuel efficiency of these engines to match those of their diesel counterparts (refer to opportunities (a),(c),(d),(f),(g),(l),(m) on page 162-163 which follows). Matching, or even coming close to matching, diesel technology improvements will maintain market attractiveness for natural gas engines, not only because of the cost per kilometer economic advantage, but also because experience has shown that lifecycle costs of heavy duty natural gas vehicles can be lower than those of diesel vehicles in certain applications.

There is, however, a significant hurdle to overcome in this technology path. The advent of on-board diagnostics (OBD) will significantly raise the bar in terms of complexity and sophistication, together with OEM integration and collaboration to access diesel monitor parameters for re-calibration to natural gas requirements. First implementation on diesel engines began in 2007 with relatively simple engine manufacturer diagnostics, and full implementation of OBD was required by 2013. Normally, natural gas engines have OBD phase in requirements later than the conventional fuel, and the phase in commences in 2013 with engine manufacturer diagnostics. Full OBD compliance for natural gas engines is required by 2018.

Once implemented, the natural gas engines will benefit from improved robustness and performance, with enhanced fuel economy, vehicle uptime as well as improved in-use emissions. OBD implementation is therefore a good thing for natural gas engines, but the complex technology demands may create commercial and supply chain barriers to smaller engine development companies. OEMs active in this field estimate that full OBD implementation on the first natural gas engine families may cost as much as $7 million. When OBD II systems were developed initially for light duty vehicles, the basic R&D was done on a pre-competitive basis shared by OEMs/government. Perhaps a similar approach for medium- and heavy-duty natural gas engines could ease the burden for cost effective implementation.
**Fumigated Diesel Pilot Ignition**
This type of dual fuel technology involves fumigating the natural gas into the air intake creating a fuel/air ratio which is ignited in the cylinder with diesel pilot injection. The amount of diesel used depends on the load and speed of the engine. This technology path offers fuel flexibility so that the engine can run either on a diesel/natural gas mix or on 100% diesel if natural gas is not available. Given the current state of natural gas fuel infrastructure, the ability to run on diesel creates market attractiveness. However, since the original diesel system is retained, complete with diesel particulate filter and the NOx SCR emission control system, the vehicle must be emissions certified on both fuels to show that the installation of the natural gas system has not affected emissions when running on diesel only. This means that the emissions certificate of compliance will be issued on the basis of the “dirtiest” fuel, so the emissions advantages of natural gas may not be realised in dual fuel applications due to the certification requirements.

This technology path has been adopted by aftermarket converters following market attractiveness for fuel flexibility and reduced fuel costs. However, emissions certification on both fuels creates significant cost barriers for new or intermediate age vehicles. As a result, all vehicles to date that have been certified using dual fuel technology are certified as older outside useful life vehicles where the certification requirements are less rigorous. The implementation of OBD requirements would create a significant challenge for small volume aftermarket converters, suggesting that dual fuel technologies will likely be confined to outside useful life vehicles.

Currently, natural gas substitution levels with this technology range from 50–70%. If the substitution level could be improved to about 90% (refer to opportunity (e) on page 163 that follows) then the market share may improve, providing opportunities for the entry of larger volume manufacturers who could afford to convert newer vehicles.

**Diesel Pilot Ignition with Direct Injected Natural Gas**
This technology path has been commercialized by Westport Innovations and has been successfully implemented in many truck applications including in an estimated 200 highway tractors in Canada. The high pressure direct injection technology requires LNG fuel, has gas substitution levels of about 90%, and is a dedicated natural gas engine with the diesel pilot acting essentially as a spark plug. Its market position lies in the higher horse power range (> 400 HP) of Class 8 trucks. The original diesel emission control system remains essentially the same using diesel particulate filters and urea-based SCR emissions control technology.

While the technology is well-advanced, in 2013 Westport decided to exit from in-house manufacturing in favour of entering into a cooperative venture with Volvo Trucks. Volvo planned to launch 13 L LNG trucks in North America using the Westport HPDI technology. Very recently, however, Volvo announced that these plans are now on hold citing the modest pace of natural gas infrastructure development for long haul trucking over the past year.

Volvo is adapting to the pace of the North American CNG/LNG market, but will continue to offer the VNM and VNL heavy duty truck platforms equipped with factory installed Cummins Westport engines. This change in strategy negatively affects the availability of
the HPDI engine in the North American market and is particularly detrimental to the development of the Class 8 natural gas highway tractor market in Canada given that truck weights are, on average, higher in Canada.

This new emerging gap area suggests the need for stronger market signals in order for the private sector to justify the level of investment required for OEMs to develop new engine products.

**Marine**

Over recent years, the market for LNG-powered vessels has expanded considerably driven by fuel savings, but also by implementation of new emissions control requirements in Emissions Control Areas (ECA) which apply within 200 nautical miles of the east and west coasts of North America as well as in the Great Lakes. There is a ready supply of high-powered marine LNG engines, and the technology continues to improve. Wartsila in Finland has developed a new marine 2-stroke dual fuel engine which features a lower cost LNG and gas handling system operating at pressures below 10 BAR. The diesel pilot fuel amounts to only 1% of the total fuel, and stable operation on gas can be achieved across the entire load range which means there is no need to switch to diesel at low loads. In addition, no additional NOx abatement systems are required for this natural gas technology.

From the perspective of commercial LNG-powered vessels, the technology is reasonably mature and there is an expanding number of engine options. The critical area needing to be addressed lies in the regulatory arena. There is a considerable amount of work that needs to be done to adapt current regulations to accommodate LNG-powered vessels and LNG bunkering. Modifying the existing regulatory framework in both Canada and in the U.S. is therefore very important.

**Rail**

Locomotive engines are predominantly supplied by two suppliers, GE and EMD. Both companies are running prototype natural gas engines at this time. Commercial offerings of both engines are expected in 2015 with effort being driven by more stringent emissions regulations which will come into effect for new locomotives in 2016.

As with the marine sector, the critical area needing to be addressed lies in the lack of rules and regulations in relation to using natural gas as a railroad fuel. Work is in progress with LNG fuel tenders being developed to supply fuel to locomotives, but more work is necessary to identify other required changes to the regulatory framework and related to the logistics of operating LNG-powered locomotives.

**Mining Trucks**

GFS Corporation offers an EVO-MT 7930 fully integrated LNG conversion used in CAT 793B mine haul trucks. CAT is also working on an OEM prototype engine which will be in use in an Arizona mine in late 2014. Since these applications are all high fuel users, the market is expanding with no obvious critical barriers at this time.
R&D Opportunities

R&D opportunities for natural gas engines relate to improving the performance and fuel efficiency together with reducing product costs. As diesel engines improve their fuel efficiencies, natural gas engines have to keep up in order to maintain their per kilometer cost advantage. In other cases, the barriers to growth relate to gaps in codes and standards and the need to adapt current regulations. There is also a need to improve vehicle refuelling capability with smart vehicle/station interactions and faster fuel delivery especially for larger vehicles.

The R&D opportunities needed to address the current issues relating to critical technologies are summarized as follows:

| a) Vehicle Systems and Driver Aids | Optimisation of diesel technologies for use in natural gas engines such as waste heat recovery, start stop systems, and intelligent driver aids and telematics. |
| b) On-Board Diagnostics | The advent of heavy-duty OBD systems is imminent for natural gas engines with simpler engine manufacturer diagnostics required in 2013, and full OBD compliance by 2018. Full OBD implementation on the first natural gas engine families could run as high as $7 million to $8 million. This significant technical challenge will likely need cost sharing and cooperation as pre-competitive development. |
| c) Dedicated Natural Gas Engine Design | Combustion optimization, air handling and, specific to dual fuel engines, after treatment system development |
| d) Ion Current Sensing for SI Combustion Analysis and Control | Improved cycle-by-cycle and cylinder-to-cylinder control |
| e) Micro-pilot Port Injected Gas Engine Systems | For use in fumigated dual fuel systems to improve diesel substitution form the current 50 – 70% level to about 90% |
| f) Advanced SI Engine Concepts | Capitalize on advances in gasoline engine systems applied to natural gas engines such as increased levels of boost pressure, higher EGR tolerance, and engine downsizing. Coupled with direct injection, it is possible to significantly increase power and torque to levels approaching modern gasoline and diesel engines. |
| g) Advanced Ignition Systems | This includes dual coil, corona or plasma discharge ignitions systems, and pre-chamber ignition concepts |
| h) Gas Seals | Development of low cost, high performing sealing technology. |
| i) LNG Fuel Level Sensing | Improved accuracy is required, but also because they are housed inside the tank, meaning that any sensor failure will lead to a costly repair and re-vacuum of the tanks. |
| j) Fuel Quality Sensing | For LNG systems, real time on-board determination of fuel quality would allow feed-forward and feed-back control mechanisms to optimize combustion. |
| k) Fast Acting Wide Range Lambda Sensors | For dual fuel engines which operate over a wide range of air/fuel ratios. |
| l) Hydrogen as a Natural Gas Combustion Enhancer | Recent work on gasoline engines, which could be adapted for natural gas engines, involves generating hydrogen and CO in
one engine cylinder through rich combustion which is then passed to all cylinders through the EGR circuit. This could be great R&D work for academic institutions.

m) **Tailpipe Methane Conversion** - If catalyst formulations could be developed without excessive precious metal content, such catalysts would find widespread use across highway, rail, and marine applications.

n) **Demonstration of New Technologies** - Government can play a key role in supporting the development, evaluation, and demonstration of new technologies in a pre-competitive environment to support the long term viability of natural gas systems.

o) **Rail Applications** - More work needs to be done to identify changes that are needed to the regulatory framework in order to accommodate LNG locomotives, such as LNG tender cars.

p) **Marine Applications** - Given that LNG is a new fuel in the North American marine sector, there is a considerable amount of work that needs to be done to adapt current regulations and review processes in order to accommodate LNG-powered vessels and LNG bunkering.

---

**Natural Gas Vehicle On-Board Fuel Storage**

**General Background**

On-board fuel storage has always been a challenge for natural gas vehicles given the much lower energy density of CNG and LNG compared to liquid fuels. There are two basic storage technologies to consider:

- CNG is typically stored at 3600 psi in purpose-designed cylinders employing technologies appropriate to the vehicle application depending on weight, cost, and space limitations. Compression increases the gas density by about 200 times that of natural gas at normal temperatures and pressures.

- LNG is stored as a liquid in cryogenic containers at -162 degrees Celsius at low pressures (similar to propane) achieving densities of 600 times that of natural gas at normal temperatures and pressures.

There are many trade-offs to be considered when selecting a particular storage technology for vehicle applications. All light-duty vehicles use CNG. In addition, CNG is increasingly being used for medium- and heavy-duty vehicles. Several cylinders are required in heavy-duty applications to get adequate vehicle range, which affects total vehicle weight and available space.

LNG is well-suited for heavy duty long haul truck applications since the LNG tanks occupy less space on the truck compared with CNG tanks for the same vehicle range. However, LNG is a time sensitive fuel and must be used on a regular basis to prevent build-up of gas pressure in the tanks over time leading to possible venting of gas to the atmosphere. Matching the use of LNG with the duty cycle of the vehicle where the vehicle is largely in continuous use will eliminate venting, and cool down techniques can reduce the temperature of the LNG which, in turn, can slow increases in pressure.
State of Maturity of Technologies

CNG Fuel Systems Options & Trade-Offs
The technology for manufacturing each of the four types of CNG tanks available on the market is well-established. There are trade-offs in the selection of tanks depending on the vehicle requirements.

Â Type 1 tanks are all metal with least cost, but maximum weight. These tanks are best for applications where cost is the significant factor and the increased weight is not problematic.

Â Type 2 tanks have a metal liner with a composite wrap around the center of the tank. The liner takes 50% and the composite takes 50% of the stress created by pressurization. These tanks are lighter, but more expensive than Type 1, and are not commonly used in heavy-duty applications.

Â Type 3 tanks have a metal liner, which takes a small amount of the total stress, with a composite wrap over the whole cylinder. These tanks are lighter, but more costly than Type 1 or 2 tanks, and are favoured in medium- and-/heavy-duty applications where cost is a major factor and fuel system weight is an important factor in minimizing payload impact.

Â Type 4 tanks are fully composite wrapped, lightest in weight, and the most expensive. These types of tanks are favoured in vehicles using larger diameter tanks ( > 21 in.) where weight and cost are both major considerations.

While vehicle tank technology is well-established, fuel storage tanks remain the largest single cost of CNG vehicle applications, and are a critical area to address in terms of reductions in cost and addressing weight impacts. There are also critical safety issues with respect to use of automatic valves and pressure relief devices which are addressed in the Section E – Safety, Codes, and Standards.

Fuel Economy Impact of Fuel System
As noted in the Section C - Engine Development and Vehicle Integration, it is critical to maintain fuel economies of the heavy-duty natural gas engines to be competitive with their diesel counterparts. The current spark-ignited natural gas engines result in a 15% decrease in fuel economy compared to diesel engines, but this fuel economy penalty increases when the complete truck is considered because of the increased weight of the cylinders as well as the aerodynamic drag that is created, for example, by the placement of the cylinders in behind the cab installations. Some progress has been made in the design of cylinder containment to be within the aerodynamic envelope of the truck, and the gap between the cab and trailer has been reduced. However, it is clear that this is a critical area to be addressed through joint efforts between the fuel storage system supplier and the vehicle manufacturer to create more integration of the fuel system into the aerodynamic design of the truck. Eventually, this should lead to on-line manufacturing of CNG trucks.

Fill Quality
Another critical area to be addressed lies in the fill quality for CNG vehicles. During fast filling of a vehicle, the heat of compression increases the gas temperature in the cylinders. If the station is not equipped with temperature compensation, then the station will shut off delivery of the
fuel at a service pressure in the cylinder which is substantially above ambient temperature. When the gas temperature cools to ambient, the cylinder pressure is reduced, resulting in less than full fills. There are various ways in which this can be addressed including:

- **A gas cooling system could be installed at the station to cool the compressed gas.** This approach is in use in Spain. However the cost of installation is apparently significant.

- **An alternative approach is to take control of the filling through the development of an on-board pressure management system on the vehicle.** Many of the parameters required to manage pressure and temperature in the tank, and shut off filling when the right amount of energy has been delivered to the tank, already exist on a natural gas vehicle. However, R&D will be required to determine a method of measuring the temperature of the gas in the tanks reliably, develop a smart valve to shut off the gas at the dispenser when the correct fill conditions have been reached, and develop the control algorithms.

This would be a reliable way to ensure correct filling of the vehicle independent of the station. There are also safety benefits associated with the implementation of a smart fill system. If a vehicle is filled to 3,600 psi at a station not equipped with temperature compensation, or by operator error, in winter conditions, then overpressure of the cylinder can occur if the vehicle is subsequently moved into a heated service bay. This could result in triggering the pressure relief device which may then vent the entire content of the cylinder into the building. This issue is discussed further in the Safety, Codes, and Standards section.

**Dispensing Rates**
There are also issues which need to be addressed with consistency in dispensing rates from station to station. The time required to fill a truck with CNG should be as close to diesel as possible. Time spent on filling is time not on the road. The industry should work to provide consistent fast fill times across all stations.

**Opportunities for Improved CNG Storage**
Storage could be improved by employing higher cylinder pressures of 5,000 psi which would give about a 28% increase in storage capacity. However, this would require an increase in cylinder wall thickness, adding weight and cost to cylinders and to the vehicle. Fuel system components would also increase in cost, and the infrastructure system would have to adapt to higher pressures. This is not a promising approach.

An alternative approach is to employ high surface area adsorbents to store the gas at reduced system pressures in a thin walled tank. Adsorbed natural gas (ANG) systems, however, have been investigated in R&D projects over many years, none of which have been able to overcome the basic issues of competitive cost, weight of adsorbent, reliability, and impact of gas quality on durability. Inconsistent fuel composition is one of the major challenges of ANG systems. Never the less, intensive R&D in this area has recently being conducted by the U.S. DOE. While some projects are showing promise, no success stories have yet emerged. In some cases, the barrier is caused by the risks associated with commercialisation.
BASF is developing high efficiency natural gas adsorbents based on a metal organic framework (MOF) approach, rather than using a conventional activated carbon approach. While their plans are to introduce a low pressure ANG system into the market (which would be the key to passenger car applications using home refuelling appliances), their current system is being demonstrated on heavy-duty trucks using MOF adsorbent in a high pressure CNG tank pressurised to 3,600 psi. In this respect, therefore, the MOF adsorbent is being used as a range extender. Using a high pressure system also allows the vehicles to be refuelled at existing CNG stations which, at this stage in development, is helpful to gain experience, provide visibility, and demonstrate durability. There is certainly interest in this approach by some fleets and tests are underway. Credibility in the approach is enhanced by the involvement of a major chemical company.

LNG Fuel Systems
A study on the safety of LNG tanks was recently carried out by Transport Canada. From a safety perspective, it was concluded that the double walled design of LNG tanks made from high strength stainless steel make them significantly more difficult to puncture than a diesel tank, and also protected against tank rupture from high temperatures created by fire. The double wall design also provides a “crush zone” of protection to the critical inner shell.

There are issues, however, with first responder exposure to LNG vehicle accidents. After a LNG vehicle fire is extinguished, the potential for cryogenic burns remains. Education is needed for example, to take care that no spillage of LNG from righting a vehicle can affect personnel in the vicinity. Also, as odorant cannot be added to LNG, there is no obvious detection of gas leaks. The presence of gas detectors on LNG vehicles should be part of a commercial vehicle safety inspection.

The most critical issue related to LNG vehicles is the lack of sufficient infrastructure to fuel the vehicles. There is an opportunity for governments to support demonstration projects involving LNG trucks operating in regional corridors with a high-level objective similar to what has been set in the European Union (E.U.) via the TEN-T program which requires LNG refuelling stations every 400 kilometers along four major truck transport corridors in the E.U.

R&D Opportunities
The R&D opportunities needed to address the current issues relating to CNG and LNG fuel systems are summarized as follows:

| a) Lower Cost CNG Systemic Approach | Development of lower cost CNG storage systems. This should include a fresh eyes investigative approach to the system as a whole including tanks, valves, and PRDs as one system. Opportunities should be explored to reduce complexity and decrease the number of components, including the possibility of eliminating some tank valves. Treating the tank, tank valve, and PRD as one system could lead to more efficient, safer, and less costly systems. |
| b) Vehicle Integration and Fuel Economy | Integration of CNG and LNG fuel storage systems into the aerodynamic design of trucks through cooperative efforts between the fuel system supplier and the vehicle manufacturer. This can significantly improve |
the fuel economy of the truck to keep pace with diesel developments, and enhance the GHG performance of the vehicle.

c) **CNG Fill Quality** - Development of an on-board pressure management system involving smart fill receptacles, and possible smart stations to control the amount of energy delivered to the tank. This will result in improved fills for CNG vehicles.

d) **CNG Dispensing Rates** - Consistent dispensing rates need to be improved from station to station to provide fast fill rates as close to diesel as possible.

e) **MOF Adsorbed Natural Gas Storage** - The BASF approach to adsorbed natural gas storage using metal organic framework (MOF) adsorbents should be monitored. Currently this approach is showing most promise, although low pressure adsorbed storage systems have not yet been demonstrated in the field. Only a range extender approach is in field trial at the present time.

f) **Other Adsorbed Natural Gas Systems** - Considerable work is in progress with developing various adsorbent systems in ARPA-E projects supported by the U.S. DOE. These projects should be monitored to assess possible breakthroughs in technology.

g) **LNG Infrastructure** - The development of LNG corridors should be accelerated as there is insufficient LNG fuelling infrastructure currently in place to support operation of long haul heavy duty LNG trucks. Demonstration of viable LNG truck routes will provide the catalyst to create customer demand, and OEMs to develop and offer the required high power natural gas truck engines.

**Safety, Codes and Standards**

**Background**

As the natural gas vehicle market continues to grow in North America, safety, and the need for updated codes and standards becomes increasingly important to ensure that the market reaches a similar level of maturity to that of the conventional gasoline and diesel fuels. That level has not yet been reached, although considerable progress has been made.

Safety is an important aspect of alternative fuel implementation. The overall approach to safety needs to include everything from production at the wellhead through fuel station operation to engine and vehicle integration, vehicle maintenance, gas-safe service facilities, and training of personnel to dispense fuel, service vehicles, and respond to emergencies.

Experience is growing in the use of natural gas as a transportation fuel, and with that comes an expanding knowledge base revealing critical safety gaps which need to be addressed. These gaps are highlighted below.

**State of Maturity**

A number of critical issues have been identified requiring resolution.
Use of ECE R 110 Components
Most of the high volume CNG valve manufacturers are now based in Europe and Asia. These countries recognize ECE R110, which is a European design and installation code for natural gas vehicles. However, North America has chosen not to recognize ECE R 110 which has less rigorous standards than those of North America. Some of these components are finding their way into the North American market especially in aftermarket applications where approvals are provided by provincial AHJs and not federally. Some AHJs have approved these components being unaware of the differences between ECE R 110 and North American requirements. New work is commencing in Europe to update ECE R 110 and harmonise with ISO 15500 standards to the extent possible. Therefore, in the future we would expect to see new products designed and certified to meet the North American requirements become more available.

Pressure Relief Devices
There are issues with premature activation of PRDs resulting from improper specification of the trigger, using, for example, a 3,000 psi PRD in a 3,600 psi system. This is a result of a lack of training of personnel.

There are also cold climate issues related to changes in the trigger threshold caused by moisture migration, and freezing/thawing cycles, which can create internal changes to the physical structure of the PRD. This can be dealt with through appropriate maintenance service intervals requiring PRD inspection and replacement.

Temperature-related premature activation can also occur as a result of over-pressurisation/over-densification of the fuel system caused by refuelling to a pressure higher than that specified by the temperature compensation curve. This curve defines the maximum fill pressure which can be dispensed at any given ambient temperature. If the ambient temperature is low, the fill pressure must also be low so that if the ambient temperature increases, as in the vehicle being moved indoor, then the higher pressure created will not exceed the specified settled pressure. Exceeding this value can cause premature PRD activation within an enclosure and render the vehicle inoperative. Over-pressure is also an issue with tank valves as described below.

Failure of PRDs to activate when required also occurs and is usually related to improper placement of the PRD in the system. This is particularly critical with large tanks where exposure of a tank to a fire may occur in an area remote from the PRD. Technology is being developed to address this issue based on “long trigger” detection designed to provide increased coverage of the container surface for thermal detection and activation of the PRD.

Tank Valve Failures
Over-pressurisation of tanks can also occur when a tank valve fails to open to supply fuel to the engine. This occurs in applications having multiple tanks and multiple tank valves as part of the fuel system. Because the solenoid valve is a one-way check valve that is designed to fail closed, the tank with the inoperative valve remains at full pressure and is not allowed to defuel during normal vehicle operation. If the vehicle continues to operate with undetected failure, additional fuelling could lead to over-pressurization of this tank. Failure to open has also been observed with manual tank valves. In this case, the tank is isolated and unable to be defueled or fuelled, causing the vehicle to be inoperative, or in multi tanks systems, creating reduced vehicle range.
Vehicle Maintenance Facility Code Gap
There is currently no specific set of code requirements for indoor facilities used for NGV maintenance and repair, storage and parking, loading, and refuelling in Canada. CSA Group has proposed to the Canadian natural gas vehicle industry the development of a unique code that specifically addresses requirements for facilities used for NGV storage, maintenance, and loading, and for indoor refuelling for NGVs.

Safe Vehicle De-fuelling
There is currently no standard or code language included in the Canadian regulatory structure outlining the need for defueling prior to moving the vehicle indoors for any of the situations above.

Current Status of Actions to Resolve Critical Issues with PRDs and Tank Valves
It is clear that the whole issue of PRD placement, premature and failed activation, and tank valve failures need to be re-visited, not only to resolve individual issues, but also to look at the tank, tank valve, and PRD as a complete system requiring revisions to codes and standards. This work has commenced with a critical issues workshop organized in June 2014 by the Clean Vehicle Education Foundation which is associated with NGV America.

The outcome of the workshop was the formation of six Task Groups to address many of the issues described above. The six Task Groups are:

1- Indoor release modelling – SANDIA - The modelling study will determine the impact of indoor gas release in various configurations of buildings to determine if ignitable mixtures can be created.

2- Over pressure filling of CNG Cylinders – short term education - This task has been completed and a technical bulletin has been released to station and vehicle operators, which provides a table showing the maximum pressures which can be dispensed at any given ambient temperature.

3- Over pressure filling of CNG Cylinders – solution development - This is a long-term task group which will work with CSA Group to support development of a listing standard for CNG dispensers that includes temperature compensation. The task group will also explore possible pressure control by the vehicle versus pressure control by the fuel dispenser.

4- Cylinder valve issues - This will include reliability, failure detection, safe removal, and international labelling harmonization. A best practices document will be developed and submitted to CSA for possible changes to the CSA 3.1 standard, and coordinate international harmonization with NGV Global and ISO as needed.

5- Pressure activated PRD use and issues - This group will address the over-pressure issues describes above in coordination with Task Group 3

6- PRD installation and venting issues - This group will address installation, placement, and venting issues. The intent is to develop a best practice document that will consider vehicle type to differentiate between typical installations, and also look at the issues on a systemic basis.
The work of the six Task Groups is to be ongoing until December 2015.

Leakage and Permeation of Natural Gas
This is another critical area requiring evaluation. Natural gas can exhibit slow leak rates from fittings and components, but also permeate through elastomers such as flexible hoses, and also Type 4 storage tanks which are composite wrapped. The ANSI PRD 1 standard for leakage is much lower (0.7 NC/hr) than that of the ANSI NGV 3.1 standard for other components (20Ncc/hr), and they are therefore in conflict. However, these standards were developed in the 1990s when the industry was just emerging. It is now believed that these conservative leak rates may be far too low for current large and complex CNG fuel systems. This is especially true for the large Type 4 tanks now being installed in heavy duty vehicles which have much larger surfaces to allow permeation. While these inconsistencies between the discreet leak rate for components versus the leak rate from the vehicle as a whole are being reviewed by CVEF, there is no current allocation of financial resources to address this fuel system leakage issue for the North American natural gas vehicle industry.

LNG Vehicles
Currently, there are no North American standards for either vehicle or station LNG components. While work is in progress to develop standards such as the LNG fuelling nozzle and receptacle (LNG 1) and the onboard vehicle tank (LNG 2), many gaps exist where more work needs to be done, but resources are constrained. This is a critical area requiring allocation of financial resources to close the gaps as defined in Section E. It will be difficult for LNG to expand as a viable transportation fuel without the standards to support the industry.

Internationally, ISO 12614 has been published for LNG vehicle components, which parallels ISO 15500 for CNG components. However, this standard has not yet been adopted as a nationally recognized requirement and will need a new initiative to pursue it.

In Canada, the CSA Z276, Annex D, outlines the requirements for permanent outdoor LNG refuelling stations. However, with interest rising in mobile LNG refuelling as a strategy to enhance infrastructure development, revisions are being developed to address mobile LNG stations which will be incorporated in the 2015 edition of the Z276 Code.

Incidents & Gap Analysis Findings
The CVEF has for many years maintained a database of incidents occurring with CNG and LNG vehicles. The value of analysing the root cause of these incidents is to provide the opportunity for revision of existing codes and standards to minimize recurrence of such incidents and to improve overall safety. The output from incident investigations has led to the identification of a number of gaps requiring new standards or revision to existing standards. The R&D opportunities created by these gaps are included in the list below.

R&D Opportunities

a) The issues surrounding PRDs, tank valve failures, and vehicle safe refuelling are being addressed by CVEF Task Groups. There is a need to track these developments and apply the outcomes to revisions of Canadian standards as appropriate.
b) **Leakage and permeation of natural gas from components and whole vehicles.**  
There is a need to correct inconsistencies and create new standards

c) **There are many gaps in LNG vehicle component and station standards** which need to be addressed. This critical area requires financial resources to close the gaps necessary to maintain a viable LNG transportation fuel option

d) **Incorporation of mobile LNG stations** into the CSA Z276 Code

e) **End of life management of CNG tanks**

f) **Smart technologies for refuelling** which would mitigate upset conditions which put the vehicle fuel system at risk

g) **Lack of a best practice document on fuel system installation** to enhance CSA B109 and NFPA 52 codes which were originally written to address the needs of aftermarket converters. This document will be designed for aftermarket converters

h) **Challenges related to CRNs for CNG tanks in Canada**

i) **Lack of a high flow CNG receptacle**

j) **No standards for home refuelling appliances or LCNG stations**

k) **Infrastructure migration in Canada** for stations to exclusively dispense CNG fuel rated at 3,600 psi maximum pressure

l) **Ensuring that fuel station dispensers meet temperature compensated fuelling protocols**

m) **Codes related to mother/daughter station systems**

n) **Need for dispensed fuel quality standards to cover contaminants** as well as fuel composition

o) **Update NGV 4.1 dispensing systems standard for CNG** Creation of a CNG/LNG first responder recommended practice document

p) **Improved system related to incident reporting** and providing feedback on lessons learned to North American codes and standards committees

---

**Canadian Natural Gas Vehicle Industry and Academic R&D Capacity**

Two critical lack of capacity issues need to be recognized, both of which are hampering the further development of the natural gas vehicle industry in Canada:

1. Training
2. Fundamental R&D of innovative concepts

**Training**

There are instances where incidents could have been avoided had sufficient training been in place. This applies to fuel station operators dispensing fuel, to vehicle maintenance technicians, and to CNG/LNG station maintenance engineers. At present, ongoing CNG and LNG training is only offered in the U.S. by two providers - the NGV Institute (NGVi) located in Las Vegas and by the National Alternative Fuels Training Consortium (NAFTC). OEMs, engine manufacturers, and station providers also offer
initial training related to their products in Canada. Toronto-based Centennial College offers a light—duty aftermarket conversion course, but this course is out-of-date.

In 2012 with funding support from NRCan, the CNGVA developed the following eleven training courses:

<table>
<thead>
<tr>
<th>Course</th>
<th>Type</th>
<th>Audience</th>
<th>Duration</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Awareness</td>
<td>Workshop</td>
<td>All audiences</td>
<td>1/2 day</td>
<td>Any location</td>
</tr>
<tr>
<td>Fleet Operations Readiness</td>
<td>Workshop</td>
<td>Fleet personnel</td>
<td>1 day</td>
<td>At fleet’s site</td>
</tr>
<tr>
<td>First Responder Safety</td>
<td>Course</td>
<td>First responders</td>
<td>1/2 - 1 day</td>
<td>Gas-safe garage</td>
</tr>
<tr>
<td>Routine LNG Tank Inspection</td>
<td>Course</td>
<td>Mechanics</td>
<td>2 days</td>
<td>Gas-safe garage</td>
</tr>
<tr>
<td>Routine CNG Cylinder Inspection</td>
<td>Course</td>
<td>Mechanics</td>
<td>2 days</td>
<td>Gas-safe garage</td>
</tr>
<tr>
<td>Routine LNG Vehicle Service</td>
<td>Course</td>
<td>Mechanics</td>
<td>3 days</td>
<td>Gas-safe garage</td>
</tr>
<tr>
<td>Routine CNG Vehicle Service</td>
<td>Course</td>
<td>Mechanics</td>
<td>3 days</td>
<td>Gas-safe garage</td>
</tr>
<tr>
<td>CNG Vehicle Conversion*</td>
<td>Course</td>
<td>Mechanics</td>
<td>1-3 days</td>
<td>Gas-safe garage</td>
</tr>
<tr>
<td>CNG Refueling</td>
<td>Video</td>
<td>Refuelers &amp; drivers</td>
<td>10 minutes</td>
<td>N/A</td>
</tr>
<tr>
<td>LNG Refueling</td>
<td>Video</td>
<td>Refuelers &amp; drivers</td>
<td>10 minutes</td>
<td>N/A</td>
</tr>
<tr>
<td>LNG Bulk Transfer &amp; Offload</td>
<td>Video</td>
<td>Drivers</td>
<td>10 minutes</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* Pre-requisite to Course #8 is Course #7

**Table 22 – New Canadian Training Courses**

The audiences for these courses are fleet operators and emergency responders. Two of the eleven courses are information-oriented and do not require demonstration of specific competencies. The remaining nine courses are technical and competency checks are required in order to pass the course. The CNGVA is in the process of implementing these courses, so as to make them available across Canada. Three distinct approaches will be used for training delivery include workshop sessions for information-oriented courses, hands-on technical training in gas-safe facilities, and online interactive videos. Once these courses are available, it will be important to conduct outreach to the provincial AHJs and to secure recognition for Course #8 – Light Duty Aftermarket Conversions given that four of the provinces currently have regulations requiring this type of training for technicians who service natural gas vehicles.

**Fundamental R&D and Innovation**

The innovation chain begins at the university level. The development of innovative concepts and advanced technology at academic institutions is critical to the emergence of improved performance natural gas vehicles as earlier described. Several of the R&D opportunities listed in Section D, for example, would be ideal for investigation at the university level to develop the advanced technologies necessary for natural gas vehicles to improve their performance relative to diesel.
Unfortunately there are few academic institutions in Canada with the capability, experience or facilities to carry out this work. One of the most experienced universities in this field is the University of Toronto. There are also new gas-safe test facilities available at the University of Ontario Institute of Technology in Oshawa, ON including a climactic chamber that can accommodate testing of a Class 8 highway tractor. More proactive engagement of the academic community across Canada is needed. In this regard, a helpful first step would involve working with one of the universities to convene a natural gas for transportation update session at which the highlights of this study could be disseminated and discussed.

R&D Collaboration in a North American Context

The goals for R&D initiatives to support natural gas vehicle use are similar in the U.S. to those in Canada including:

- Improving driving range and vehicle performance.
- Lowering first costs for OEM vehicles by increasing production volumes, developing a more integrated supply chain, and by product design innovation.
- Reducing greenhouse gas emissions from the source to point of use using exhaust after-treatment, advanced material selection, improved fuel economy, and reduction in venting.
- Providing guidance for regulatory development in new applications such as rail, mining, and marine.

Building on opportunities to improve fuel efficiency, reduce emissions, lower equipment acquisition and operating costs, expand product offerings, and apply other innovations will support the goal of making the overall cost of NGV ownership more attractive while also reducing emissions. Collaborative setting of priorities for natural gas R&D in Canada in the context of the North American market can allow innovators to develop and benefit from key intellectual property for technologies and expand cross-border and international trade in this growing market. The results of this new R&D focus can build upon a foundation of innovation in Canada and the U.S.

RD&D Opportunities

Opportunities for collaborative RD&D between Canada and the U.S. can be divided into three categories:

<table>
<thead>
<tr>
<th>#1 - R&amp;D and scientific research between Canadian and U.S. government, industry, and academic researchers</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Develop a North American database of current vehicle, engine, and component OEMs related to NGVs, in order to foster additional cross-border commercial relationships (such as Cummins Westport Inc.) and include an assessment of primary private-industry centers for NGV R&amp;D.</td>
</tr>
</tbody>
</table>
b) Enhance the sharing of federal, state, regional, and private sector NGV R&D technology roadmaps through conferences, meetings and workshops.

c) Improve strategic relationships and communication between educational institutions through organizing regional topical conferences.

d) Foster increased collaboration with and between the Canadian Gas Association (CGA) and American Gas Association (AGA) in relation to natural gas for transportation.

e) Leverage Canada’s strong aerospace industry expertise in materials and testing.

f) Leverage Canada’s unique cold weather testing capabilities to increase awareness of cold weather issues, and improve cold weather performance of engines, vehicles, and stations.

#2 - NGV demonstration efforts between Canadian and U.S. organizations

a) Evaluate and target technical synergies in both countries such as Great Lakes and coastal marine LNG bunkering developments, rail opportunities throughout the North American rail system, and mining applications related to Canadian oil sands and American coal

b) Leverage best practices from the U.S. DOE’s Clean Cities program, such as by encouraging Canadian-U.S. sister city dialogues.

#3 - Harmonisation of Canadian and U.S. regulations, standards, and economic development planning

a) Share information to harmonize standards for marine bunkering and operations

b) Share information on rail operations, including experience with tender car design, refuelling and operation

c) Share experience with LNG facility design

d) Enhance communications and relationships between major centers having experience in energy and materials, such as Calgary, Houston, Chicago and Denver.
J – Recommended Priority Actions

The priority R&D opportunities and action items resulting from this study have emerged and are listed below in call-out box format. As previously noted, there is no separate listing of infrastructure priorities as these areas of need are considered to be reasonably well-addressed in the safety, codes and standards priorities listing that follows.

These by-section lists have been derived based on the individual sections of the report, but with some filtering in order to define the list of primary priorities for each section.

In the case of engine development and vehicle integration, a brief summary regarding potential supportive R&D activities that could be carried out at the academic level is also being provided. Unlike on-board fuel storage where there is a fair amount of activity including several projects that have been undertaken related to low pressure adsorbent and conformable fuel systems through DOE’s ARPA-E program, there is limited engine development work going on at the university level. This is despite having capacity in this area in Canada including, for example, expertise at the University of Toronto that could be accessed in order to assess various concepts and their applicability to natural gas engine development at the pre-commercial stage.

The by-section listings of priorities are then followed by a “top ten” overall list of R&D priorities. This second list is intended to identify strategic issues that need to be addressed in order to move the NGV industry forward and to ensure the long term competitiveness of natural gas as a transportation fuel given the continuously evolving and improving technologies for gasoline and diesel vehicles.

J.1 Priorities for Engine Development and Vehicle Integration

COMMERCIAL R&D PRIORITIES:

**Advanced SI Engine Concepts:** Capitalize on advances in gasoline engine systems applied to natural gas engines such as increased levels of boost pressure, higher EGR tolerance, and engine downsizing. Coupled with direct injection, it is possible to significantly increase power and torque to levels approaching modern gasoline and diesel engines.

**Dedicated Natural Gas Engine Design:** Combustion optimization, air handling and, specific to dual fuel engines, after treatment system development.

**Demonstration of New Technologies:** Government can play a key role in supporting the development, evaluation, and demonstration of new technologies in a pre-competitive environment to support the long term viability of natural gas systems.

**Rail Applications:** More work needs to be done to identify changes that are needed to the regulatory framework in order to accommodate LNG locomotives, such as LNG tender cars.

**Vehicle Systems and Driver Aids:** Optimisation of diesel technologies for use in natural gas engines such as waste heat recovery, start stop systems, and intelligent driver aids and telematics.
**On-Board Diagnostics:** The advent of heavy-duty OBD systems is imminent for natural gas engines with simpler engine manufacturer diagnostics required in 2013, and full OBD compliance by 2018. Full OBD implementation on the first natural gas engine families could run as high as $7 million to $8 million. This significant technical challenge will likely need cost sharing and cooperation as pre-competitive development.

**Ion Current Sensing for SI Combustion Analysis and Control:** Improved cycle-by-cycle and cylinder-to-cylinder control.

**Tailpipe Methane Conversion:** If catalyst formulations could be developed without excessive precious metal content, such catalysts would find widespread use across highway, rail, and marine applications.

**LNG Fuel Level Sensing:** Improved accuracy is required, but also because they are housed inside the tank, meaning that any sensor failure will lead to a costly repair and re-vacuum of the tanks.

**Fuel Quality Sensing:** For LNG systems, real time on-board determination of fuel quality would allow feed-forward and feed-back control mechanisms to optimize combustion.

**Gas Seals:** Development of low cost, high performing sealing technology.

**Marine Applications:** Given that LNG is a new fuel in the North American marine sector, there is a considerable amount of work that needs to be done to adapt current regulations and review processes in order to accommodate LNG-powered vessels and LNG bunkering.

**Micro-Pilot Port Injected Gas Engine Systems:** For use in fumigated dual fuel systems to improve diesel substitution form the current 50 – 70% level to about 90%.

**Fast Acting Wide Range Lambda Sensors:** For dual fuel engines which operate over a wide range of air/fuel ratios.

**SUPPORTING ACADEMIC PRIORITIES:**

**Advanced Ignition Systems:** This includes dual coil, corona or plasma discharge ignitions systems, and pre-chamber ignition concepts.

**Hydrogen as a Natural Gas Combustion Enhancer:** Recent work on gasoline engines, which could be adapted for natural gas engines, involves generating hydrogen and CO in one engine cylinder through rich combustion which is then passed to all cylinders through the EGR circuit. This could be great R&D work for academic institutions.
J.2 Priorities for Natural Gas Vehicle On-Board Fuel Storage

**Lower Cost Systemic Approach:** Development of lower cost CNG storage systems. This should include a fresh eyes investigative approach to the system as a whole including tanks, valves, and PRDs as one system. Opportunities should be explored to reduce complexity and decrease the number of components, including the possibility of eliminating some tank valves. Treating the tank, tank valve, and PRD as one system could lead to more efficient, safer, and less costly systems.

**LNG Infrastructure:** The development of LNG corridors should be accelerated as there is insufficient LNG fuelling infrastructure currently in place to support operation of long haul heavy duty LNG trucks. Demonstration of viable LNG truck routes will provide the catalyst to create customer demand, and OEMs to develop and offer the required high power natural gas truck engines.

**CNG Fill Quality:** Development of an on-board pressure management system involving smart fill receptacles, and possible smart stations to control the amount of energy delivered to the tank. This will result in improved fills for CNG vehicles.

**Vehicle Integration and Fuel Economy:** Integration of CNG and LNG fuel storage systems into the aerodynamic design of trucks through cooperative efforts between the fuel system supplier and the vehicle manufacturer. This can significantly improve the fuel economy of the truck to keep pace with diesel developments, and enhance the GHG performance of the vehicle.

**Dispensing Rates:** Consistent dispensing rates need to be improved from station to station to provide fast fill rates as close to diesel as possible.

**MOF Adsorbed Natural Gas Storage:** The BASF approach to adsorbed natural gas storage using metal organic framework (MOF) adsorbents should be monitored. Currently this approach is showing most promise, although low pressure adsorbed storage systems have not yet been demonstrated in the field. Only a range extender approach is in field trial at the present time.

**Other Adsorbed Natural Gas Systems:** Considerable work is in progress with developing various adsorbent systems in ARPA-E projects supported by the U.S. DOE. These projects should be monitored to assess possible breakthroughs in technology.

J.3 Priorities for Safety, Codes and Standards

**The issues surrounding PRDs, tank valve failures, and vehicle safe refuelling** are being addressed by CVEF Task Groups. There is a need to track these developments and apply the outcomes to revisions of Canadian standards as appropriate.
There are many gaps in LNG vehicle component and station standards which need to be addressed. This critical area requires financial resources to close the gaps necessary to maintain a viable LNG transportation fuel option.

Infrastructure migration in Canada for stations to exclusively dispense CNG fuel rated at 3600 psi maximum pressure.

Smart technologies for refuelling which would mitigate upset conditions which put the vehicle fuel system at risk.

Ensuring that fuel station dispensers meet temperature compensated fuelling protocols.

Lack of a high flow CNG receptacle.

Need for dispensed fuel quality standards to cover contaminants as well as fuel composition.

Incorporation of mobile LNG stations into the CSA Z276 Code.

Codes related to mother/daughter station systems.

Update NGV 4.1 dispensing systems standard for CNG Creation of a CNG/LNG first responder recommended practice document.

Improved system related to incident reporting and providing feedback on lessons learned to North American codes and standards committees.

No standards for LCNG stations.

Challenges related to CRNs for CNG tanks in Canada.

Lack of a best practice document on fuel system installation to enhance CSA B109 and NFPA 52 codes which were originally written to address the needs of aftermarket converters. This document will be designed for aftermarket converters.

End of life management of CNG tanks.

Leakage and permeation of natural gas from components and whole vehicles. There is a need to correct inconsistencies and create new standards.
J.4 Priorities for R&D Collaboration in a North American Context

The potential areas for collaboration between Canada and the U.S. can be grouped into three broad categories:

- **Collaborative scientific research and enhanced information sharing between government, industry, and academia**

  Develop a North American database of current vehicle, engine, and component OEMs related to NGVs, in order to foster additional cross-border commercial relationships (such as Cummins Westport Inc.) and include an assessment of primary private-industry centers for NGV R&D.

  Enhance the sharing of federal, state, regional, and private sector NGV R&D technology roadmaps through conferences, meetings and workshops.

  Improve strategic relationships and communication between educational institutions through organizing regional topical conferences.

  Leverage Canada’s unique cold weather testing capabilities to increase awareness of cold weather issues, and improve cold weather performance of engines, vehicles, and stations.

  Leverage Canada’s strong aerospace industry expertise in materials and testing.

  Enhance communications and relationships between major centers having experience in energy and materials, such as Calgary, Houston, Chicago and Denver.

  Foster increased collaboration with and between the Canadian Gas Association (CGA) and American Gas Association (AGA) in relation to natural gas for transportation.

- **Joint NGV demonstration efforts to address technical issues and to enhance North American competitiveness**

  Evaluate and target technical synergies between Canada and the U.S. related to Great Lakes and coastal marine LNG bunkering developments, rail opportunities throughout the North American rail system, and mining applications related to Canadian oil sands and American coal. Multi-modal pilot projects involving the use of LNG in marine, rail, and/or on-road trucking also present an opportunity for collaboration and demonstrating how greater use of natural gas can provide economic, environmental, and competitiveness benefits for both countries.

  Leverage and extend best practices from the U.S. DOE’s Clean Cities program, such as by encouraging Canadian-U.S. sister city dialogues.

- **Focused effort to harmonize regulations, standards, and economic development planning**
**J.5 Overall R&D Priorities**

The overall R&D priorities across all sections of natural gas vehicle implementation are listed below as the top ten priorities that are both strategic and most likely to succeed in overcoming significant barriers to growth and sustainability of the industry.

In developing this overall list, both cost effectiveness and likelihood of achieving desired outcome were taken into consideration. The top ten R&D priorities are the following:

1. **Apply advanced SI engine concepts to natural gas engines.** Capitalize on advances in gasoline engine technology by applying these concepts to natural gas engines such as increased levels of boost pressure, higher EGR tolerance, and engine downsizing. Coupled with direct injection, it is possible to significantly increase power and torque to levels approaching modern gasoline and diesel engines.

2. **Invest in research that addresses lowering the cost of CNG fuel systems by taking a systemic approach to fuel system design.** This recommendation would also encompass the integration strategies for lower cost fuel storage technologies when available. This should include a “fresh eyes” investigative approach to the system as a whole including tanks, valves, and PRDs as one system. Opportunities should be explored to reduce complexity and decrease the number of components, including the possibility of eliminating some tank valves. Treating the tank, tank valve, and PRD as one system could lead to more efficient, safer, and less costly systems.

3. **Fund demonstrations of new technologies.** Government can play a key role in supporting the development, evaluation, and demonstration of new technologies in a pre-competitive environment to support the long term viability of natural gas systems. A range of areas of R&D need identified in this study could be suitable for demonstration.

4. **Monitor results achieved related to the issues surrounding PRDs, tank valve failures, and vehicle safe refuelling** that are being addressed by CVEF Task Groups. There is a need to track these developments and apply the outcomes to revisions of Canadian standards as appropriate.

**Share information** on rail operations, including experience with tender car design, refuelling and operation.

**Share information** to harmonize standards for marine bunkering and operations.

**Share experience** with LNG facility design.
5. **Fund the development of LNG vehicle component and station standards** on a harmonized North American basis via CSA Group. This critical area requires financial resources to close existing gaps and to ensure that the codes, standards, and regulatory framework keeps pace with market developments.

6. **Apply vehicle systems and driver aids that are used for diesel technologies to natural gas technologies.** The application of optimized diesel technologies to natural gas engines can improve performance and enhance the value proposition for natural gas. The application of waste heat recovery and start stop systems, as well as intelligent driver aids and telematics are some of the options in this area.

7. **Apply smart vehicle-station communication systems so as to improve CNG fill quality.** Development of an on-board pressure management system involving smart fill receptacles, and possible smart stations would improve control over the amount of energy delivered to the vehicle’s tanks. This would result in improved CNG fills.

8. **Evaluate and identify R&D priorities of mutual interest between Canada and the U.S. related to Great Lakes and coastal marine LNG bunkering, rail locomotives, and mining applications related to Canadian oil sands and American coal.** Multi-modal pilot projects involving the use of across LNG in marine, rail, and on-road trucking applications presents an opportunity for collaboration and benefits verification for both countries.

9. **Resource R&D work that supports the development of dispensed fuel quality standards** in order to identify contaminants and desired fuel composition.

10. **Leverage existing Canadian academic expertise and networks, so that advanced natural gas vehicle and station technologies can be developed in partnership with industry.** To raise awareness and connect academic researchers with industry, it is recommended that NRCan include a focus on networking and information sharing with the academic community at an upcoming event, so as to initiate this important dialogue.
Appendices

Appendix A - Spotlight - Aftermarket Conversions of Existing Vehicles

New EPA regulations relating to the conversion of existing engines and vehicles has reduced the technical and commercial burden on developers of aftermarket systems to convert vehicles including heavy-duty vehicles to use natural gas in the US. Depending on the model year of the engine to be converted, systems may be verified as compliant with these new rules through a reduced level of testing and demonstration to confirm that the original certified emissions are not exceeded. In the case of Outside Useful Life engines (OUL) the new rules permit conformity through submission of technical descriptions of the systems and the approval of such descriptions by EPA, see Table below:

<table>
<thead>
<tr>
<th>Age Category</th>
<th>Demonstration Requirement</th>
<th>Exhaust Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>New, &lt; 2 years old</td>
<td>Full Certification</td>
<td>FTP data, OBD Data</td>
</tr>
<tr>
<td>Intermediate, &gt; 2 years old but Inside Use</td>
<td>Meet Standards, Provide Technical Description</td>
<td>FTP data, OBD Scan</td>
</tr>
<tr>
<td>Useful Life</td>
<td>Provide Technical Description</td>
<td>Provide Technical Description, Dyno/Vehicle Data, OBD Scan</td>
</tr>
</tbody>
</table>

Table 23 - Summary of Conformity Requirements For Aftermarket Conversions

EPA designated Outside Useful Life engines (OUL) are classified as follows:

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Gross Vehicle Weight</th>
<th>Vehicle Mileage / Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium Heavy Duty Diesel Engines</td>
<td>19,500 – 33,000 lbs</td>
<td>185,000 miles, 10 years</td>
</tr>
<tr>
<td>Heavy Heavy-Duty Diesel Engines</td>
<td>&gt;33,000 lbs</td>
<td>435,000 miles, 10 years, 22,000 hours</td>
</tr>
</tbody>
</table>

Table 24 - Outside Useful Life Engine Classifications

A number of companies have started to take advantage of these new regulations to offer customers an option to operate existing vehicles with natural gas without the commitment to buying new vehicles for their fleet.

American Power Group (APG) provides dual fuel conversions for Outside Useful Life engines across a range of OEM engines. Conversions cover ratings of 350 to 600 hp for model year 1993 to 2009 engines from Caterpillar, Volvo, Cummins, Detroit Diesel, Daimler, and Mack.

Clean Air Power has dual fuel retrofit products available in the US for Caterpillar C10, C12, and C15 engines, with ratings up to 500 hp for heavy duty applications. These engines are all offered via EPA’s Outside Useful Life regulations, and by CARB Retrofit certifications which require full original new certification data to 1998 levels in gas operation. Clean Air Power also recently announced that it is developing a dual fuel version of both the Volvo D13 and Mack MP8 engine range for use with model year 2010 to 2013 versions of the diesel engines as a retrofit solution for newer Volvo and Mack vehicles. Complete with EGR, SCR, and DPF emissions controls, the dual fuel solutions are targeted at 2010 emissions levels of 0.2g/bhp NOx and 0.01 g/bhp PM.
The product plan calls for compatibility with the Volvo I-Shift and Mack mDrive fully automatic transmissions.

D2G offers its DualFlex+ system on Detroit Diesel Series 60 engines up to model year 2006.

EcoDual had been offering dual fuel conversion systems for Model Year 2004 to 2009 Cummins ISX and ISM engines, but recently there has been news that the company has stopped delivering products and has ceased business altogether, although industry news suggests that the management team may be looking to restructure the business.

According to their website, Power Solutions International have suggested that they will be offering a dedicated natural gas engine (spark-ignited) in the 11 – 15 litre range, but have not released specifications or ratings, nor details of whether it will be offered through OEM channels or as a repower option for existing vehicles.

Omnitek recently announced the availability of a repower engine solution on Mack E7 up to model year 2006. These repower engines adopt spark-ignition technology for dedicated natural gas operation.

Given the current limited range of engine options for new vehicles, natural gas retrofit systems could be an opportunity to increase the early adoption of natural gas as a transportation fuel in Canada. This is particularly relevant to applications requiring larger engine sizes (> 13 litre) and horsepower (500+), where there is little visibility to near term new product offerings for the on-highway market.
### Appendix B - OBD Requirements Summary

Summary table taken from fact sheet produced by International Council on Clean Transportation (ICCT):

<table>
<thead>
<tr>
<th>System and §66.010-18 reference</th>
<th>General</th>
<th>Thresholds after 2015</th>
<th>Details</th>
<th>Continuous monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel System Monitoring (g) 1</strong></td>
<td>The OBD system must monitor the fuel delivery system to verify that it is functioning properly. The individual electronic components (e.g., actuators, valves, sensors, pumps) that are used in the fuel system have special monitoring provisions.</td>
<td>NO(_x)(_y) +0.3 PM: 0.03 +0.02 NMHC: 2.0X CO: 2X</td>
<td>Fuel system pressure control Fuel injection quantity Fuel injection timing</td>
<td>Fuel system pressure control (continuously monitored unless new hardware needed) Feedback signals (continuously monitored) Continuous monitoring would be defined by manufacturer according to in-use performance requirements</td>
</tr>
<tr>
<td><strong>Engine Misfire Monitoring (g) 2</strong></td>
<td>The OBD system must monitor the engine for misfire causing excess emissions.</td>
<td>NO(_x)(_y) +0.3 PM: 0.03 +0.02 NMHC: 2.0X CO: 2X</td>
<td>Misfire monitored at idle (MY 2010-12) and continuously (MY 2013+)</td>
<td>For MY 2013+, OBD monitors continuously for engine misfire under all positive torque engine speed and load conditions</td>
</tr>
<tr>
<td><strong>EGR System Monitoring (g) 3</strong></td>
<td>OBD monitors the EGR system for low flow rate, high flow rate, and slow response malfunctions. For engines equipped with EGR coolers (e.g., heat exchangers), the OBD system must monitor the cooler for insufficient cooling malfunctions. The individual electronic components (e.g., actuators, valves, sensors) have special monitoring provisions.</td>
<td>NO(_x)(_y) +0.3 PM: 0.03 +0.02 NMHC: 2.0X CO: 2X</td>
<td>EGR flow rate, high and low, including leaks EGR response rate EGR feedback signals EGR Cooling System Performance</td>
<td>EGR flow rate (high and low, continuously monitored) EGR feedback signals (continuously monitored) EGR response rate and cooling monitoring would be defined by manufacturer according to in-use performance requirements</td>
</tr>
<tr>
<td><strong>Turbo Boost Control System Monitoring (g) 4</strong></td>
<td>The OBD system must monitor the boost pressure control system for under and over boost malfunctions. For engines equipped with variable geometry turbochargers (VGT), the OBD system must monitor the VGT system for slow response malfunctions. The OBD system must monitor the charge air cooler system for cooling system performance malfunctions, if available. The individual electronic components (e.g., actuators, valves, sensors) that are used in the boost pressure control system must be monitored in accordance with the comprehensive component.</td>
<td>NO(_x)(_y) +0.3 PM: 0.03 +0.02 NMHC: 2.0X CO: 2X</td>
<td>Under and over boost malfunctions Slow response (VGT systems only) Charge air undercooling Feedback signals</td>
<td>Under and over boost malfunctions (continuously monitored) Feedback signals (continuously monitored) VGT response rate and charge air cooling monitoring would be defined by manufacturer according to in-use performance requirements</td>
</tr>
<tr>
<td><strong>Non-Methane Hydrocarbon (NMHC) Converting Catalyst Monitoring (g) 5</strong></td>
<td>The OBD system must monitor the NMHC converting catalyst(s) for proper NP HC conversion capability. Conversion on the DPF is not included.</td>
<td>NA</td>
<td>NMHC Conversion Temperature for proper PM filter regeneration Exothermal monitor strategy</td>
<td>Monitoring would be defined by manufacturer according to in-use performance requirements</td>
</tr>
<tr>
<td><strong>SCR and Lean NO(_x) Catalyst Monitoring (g) 6</strong></td>
<td>The OBD system must monitor the SCR and/or the lean NO(_x) converting catalyst(s) for proper conversion capability. The individual electronic components (e.g., actuators, valves, sensors, heaters, pumps) in the active/intrusive redundant injection system must be monitored.</td>
<td>NO(_x)(_y) +0.3</td>
<td>Conversion efficiency Reductant delivery performance (e.g., urea injection, separate injector fuel injection, post injection of fuel, air assisted injection/mixing) Reductant quality Reductant quantity Feedback control</td>
<td>Conversion efficiency and reductant quality monitoring defined by manufacturer according to in-use performance requirements Reductant delivery performance and quantity, on Feedback signals are continuously monitored</td>
</tr>
</tbody>
</table>
## Appendix B: OBD Requirements Summary (cont’d)

<table>
<thead>
<tr>
<th>System and $86.010-18 reference</th>
<th>General</th>
<th>Thresholds after 2013</th>
<th>Details</th>
<th>Continuous monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx Adsorber / Lean NOx Trap (LNT) System Monitoring (g7)</td>
<td>The OBD system must monitor for proper performance. The OBD system must monitor the active/intrusive injection system for proper performance. The individual electronic components (e.g., injectors, valves, sensors) that are used in the active/intrusive injection system must be monitored.</td>
<td>NOx: &lt;0.3</td>
<td>Adsorption and conversion efficiency. Reductant delivery for NOx adsorber systems that use active/intrusive injection (e.g., in-cylinder post fuel injection, in-exhaust air-assisted fuel injection). Feedback control.</td>
<td>Reductant delivery and feedback signals are continuously monitored. Adsorption and Conversion efficiency monitoring defined by manufacturer according to in-use performance requirements.</td>
</tr>
<tr>
<td>DPF System Monitoring (g8)</td>
<td>The OBD system must monitor the DPF for proper performance. For engines equipped with active regeneration systems that use an active/intrusive injection (e.g., in-exhaust fuel injection, in-exhaust fuel/air burner), the OBD system must monitor the active/intrusive injection system for proper performance. The individual electronic components (e.g., injectors, valves, sensors) that are used in the active/intrusive injection system must be monitored.</td>
<td>PM: 0.05/0.04 NMHC: 2X</td>
<td>Filtering performance; this includes PM threshold reading capabilities and a temporary option for pressure differential reading methods before 2013. Regeneration frequency. Regeneration completion. Missing, removed DPF. Insufficient action for regeneration. Feedback control (continuously monitored).</td>
<td>OBD monitoring is defined by manufacturer according to in-use performance requirements. PM filter monitoring based on differential pressure requires continuous monitoring.</td>
</tr>
<tr>
<td>Exhaust Gas Sensor Monitoring (g9)</td>
<td>The OBD system must monitor for proper output signal, activity, response rate, and any other parameter that can affect emissions, all exhaust gas sensors, including: oxygen sensors, air-fuel ratio sensors, NOx sensors, and other sensors used for emission control system feedback (e.g., EGR control/feedback, SCR control/feedback, NOx adsorber control/feedback) and/or as a monitoring device. The OBD system must monitor the heater for proper performance of heated oxygen sensors.</td>
<td>Air-Fuel ratio sensor upstream of device: NOx: &lt;0.3 PM: 0.03/0.02 NMHC: 2X CO: 2X Air-fuel ratio sensors downstream of aftertreatment devices NOx: &lt;0.3 PM: 0.05/0.04 NMHC: 2X CO: -- NOx sensors: NOx: &lt;0.3 PM: 0.05/0.04 NMHC: 2X CO: --</td>
<td>Sensor performance (sensor voltage, resistance, impedance, current, response rate, amplitude, offset). Circuit continuity or out of range signals. Feedback faults that cause an emission control system to default out of closed loop. Insufficient performance of the sensor for use for other OBD monitors. Heater performance. Circuit faults (continuously monitored). Feedback control (continuously monitored).</td>
<td>Sensor performance monitoring based on differential pressure requires continuous monitoring. Circuit integrity and feedback function is monitored continuously.</td>
</tr>
<tr>
<td>Variable Valve Timing (VVT) system monitoring (g10)</td>
<td>The OBD system must monitor the VVT system on engines so equipped for target error and slow response malfunctions. The individual electronic components (e.g., actuators, valves, sensors) that are used in the VVT system must be monitored.</td>
<td>NOx: &lt;0.3 PM: 0.03/0.02 NMHC: 2.0X CO: 2X</td>
<td>Target error: checks for deviations from target. Slow response</td>
<td>VVT target and response rate monitoring is defined by the manufacturer according to in-use performance requirements.</td>
</tr>
</tbody>
</table>
Bibliography


“Is Natural Gas a Viable Alternative to Diesel For The Trucking Industry”, American Trucking Association


Endnotes

1 http://www.nrcan.gc.ca/media-room/speeches/2013/1877


3 http://www.albertaolimagazine.com/2013/06/the-100-2013/ - The 100 largest oil and gas producers in Canada, Alberta Oil Magazine’s Top 100 ranking for 2013


8 Cryostar’s Smal Scale LNG: http://www.cryostar.com/web/small-scale-lng.php


10 GE unveils LNG-in-a-Box System http://online.wsj.com/article/PR-CO-20130417-911585.html


13 http://www.fortisbc.com/NaturalGas/Business/NaturalGasVehicles/Pages/default.aspx


26 “MCI Natural Gas Systems Training,” June 25, 2014

27 “MCI Natural Gas Systems Training,” June 25, 2014

28 “MCI Natural Gas Systems Training,” June 25, 2014


37 Vehicles equipped with Westport 15 litre engines will have both a LNG blue diamond and a CNG blue diamond as both forms of the fuel can be found on the vehicle.


R. Judd and C. Y. Law, ANG Technology, Germanischer Lloyd


Saddle Creek Transportation, “Compressed Natural Gas Project,” 2014

Saddle Creek Transportation, “Compressed Natural Gas Project,” 2014

Saddle Creek Transportation, “Compressed Natural Gas Project,” 2014


American Trucking Association – “Is Natural Gas a Viable Alternative to Diesel For The Trucking Industry”


The Case for LNG Fueling Solutions for Drilling and Completion – Linde, 2014

Natural Gas for Transportation: Industry Led Opportunities – David Hill, Encana, October 2010

LNG as Marine Fuel – Poten & Partners


http://www.epa.gov/obd/regtech/420d06006.pdf

http://www.epa.gov/obd/regtech/420d06006.pdf


http://iopscience.iop.org/0022-3727/44/2/022001/fulltext/


http://www.psf.mit.edu/library1/catalog/reports/2000/06ja/06ja003/06ja003_full.pdf


83 “FSU” means Former Soviet Union


86 http://www.afdc.energy.gov/locator/stations/


http://arpa-e.energy.gov/?q=arpa-e-programs/move

http://www.eere.energy.gov/cleancities/

http://www.afdc.energy.gov/fuels/natural_gas.html


http://www.transportation.anl.gov/fuels/index.html

https://www.fra.dot.gov/Page/P0562

http://www.fmcsa.dot.gov/safety/research-and-analysis/research-projects

http://www.nhtsa.gov/Research


http://www.arb.ca.gov/research/veh-emissions/veh-emissions.htm

http://www.aqmd.gov/grants-bids

http://www.valleymair.org/RFPs/RFP.htm


http://www.gastechnology.org/Solutions/Pages/NGVs.aspx


121. http://www.cleanskies.org/

