U.S. Department of Transportation
Federal Railroad Administration

Argonne NATIONAL LABORATORY

# Natural Gas Locomotive Technology Workshop Report

Sponsored by the Federal Railroad Administration
Date: October 2–October 3, 2012
Location: Argonne National Laboratory, Lemont, IL
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# Executive Summary

The U.S. Energy Information Administration estimates that the supply of natural gas (NG) in America will last more than 100 years, thanks to hydraulic fracking of shale rocks. Fracking is a process by which natural gas is extracted from rock buried deep within the ground, and it has decreased the cost of NG (compared with diesel fuel) by more than 50 percent. Fuel usage accounts for 42 percent of the railroad (RR) industry's operational costs. Therefore, there is a significant potential cost-saving opportunity in using NG in locomotive engines.

To exploit this opportunity and address potential barriers, a workshop titled "Natural Gas Locomotive Technology" was convened on October 2 and 3, 2012, at Argonne National Laboratory in Lemont, IL. It was organized by the Federal Railroad Administration to develop a road map for the prospective use of NG in rail applications. It was attended by 55 participants spanning the railroad industry, locomotive manufacturers, OEM suppliers, and research and allied Federal organizations. The objectives of the workshop were to:

- Gauge the current level of interest in the use of NG as fuel for rail transportation,
- Identify pros and cons of using NG in rail applications,
- Identify the barriers in transitioning to NG use in rail transportation applications, and
- Develop a road map to address the potential issues.

The workshop presented the operational and safety regulations and practices currently in place for locomotive engines along with perspectives related to NG usage from different manufacturers, safety regulators, research groups, and the railroad industry. The presentations (listed in Appendix B) are attached to this report as separate files. Several topical categories were identified during a brainstorming session on the final day of the workshop and were further streamlined after discussions via teleconference calls in subsequent months. These include the following:

1. **OEM Concerns:** Gas supply connection types, gas injection methods, electrical connections, flow through multiple locomotives, tunnel operation, impact consequences, inspection rules, fueling time and proximity, NG infrastructure, compressed NG and liquefied NG (LNG) storage, etc.
2. **Safety:** Crashworthiness, tender car operation, vaporizer, communications, LNG usage education, safety and security of couplings, regulations, leakproofing, etc.
3. **Performance and Emissions:** Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET), dual-fuel modeling, single-cylinder engine research, exhaust speciation, lube oil studies, range issues, life-cycle cost, etc.
4. **Fuel:** Fuel standards, fueling infrastructure, head end power, tender car fueling, etc.
5. **Systems Engineering:** Economic modeling, vehicle dynamics, impact testing of tender cars, fatigue of components, track service-worthiness
6. **Standards:** Standardization for safety and interoperability, ISO-certified (International Organization for Standardization) containers as fuel tanks, LNG transport as a commodity, risk assessment, inspection and maintenance of tender cars, Auto Engine Start-Stop, etc.

# Contents

# 1. Introduction

## 1.1. Natural Gas as a Locomotive Fuel

The Energy Information Administration estimates that the supply of natural gas (NG) in America will last more than 100 years, thanks to hydraulic fracking of shale rocks. Fracking is a process by which natural gas is extracted from shale rock. President Obama's energy policy includes NG as one of the pathways to greater energy security and sustainability. The advantages of NG are well known; hence, it is extensively used for domestic purposes—building heat, stationary power, etc.—but it falls short as a transportation fuel because of its shorter range compared with diesel fuel. NG consists mostly of methane (90–95%) and other hydrocarbons such as ethane (3–4%), propane (2–3%), butane, and traces of $CO_2$ and nitrogen. America has several thousand miles of pipeline network distribution already in operation; therefore, access to the fuel is relatively straightforward.

Usage of NG in its "natural" (uncompressed) state in railroad (RR) applications is inconsequential: compressed NG (CNG) and liquefied NG (LNG) are the default states, with a higher priority for the latter (LNG) because its energy density is about five times higher. Therefore, onboard storage tanks need to be rated for very high pressure (>3600 psig) or for maintaining extremely low temperatures (-260˚F), either of which raises the tank cost by more than two orders of magnitude compared with diesel tanks. LNG is the preferred mode for freight trains because of refueling challenges, whereas CNG could be employed for switchers and commuter trains because of their frequent and routine stops and proximity to gas supplies. On-board storage of LNG requires a tender car (20,000 gallons) to meet the range requirements for typical locomotive operations: it is estimated that a locomotive can travel up to 800 miles before refueling.

Typically, intake fumigation of NG results in a power penalty of up to 20 percent. NG engine technology is dated relative to diesel technology; therefore, there is ample room for improvement, especially since it would be justified economically. The best way to address the "range anxiety" barrier, which is critical to enabling widespread market acceptance of NG/methane as a transportation fuel, is through **engine efficiency improvement**. Apart from the range issue, other barriers/challenges include safety concerns about crashworthiness, standardization of connections, and emissions control (NG is 23 times more potent as a greenhouse gas [GHG] than $CO_2$).

## 1.2. Workshop Motivation

Owing to the recent discovery of methods to extract NG in the United States, the cost of NG has decreased by more than 50 percent compared with the cost of diesel fuel. Fuel usage accounts for 42 percent of the RR industry's operational costs. Therefore, there is a significant cost-saving opportunity in using NG in locomotive engines.

To explore this opportunity and address potential barriers, a workshop titled "Natural Gas Locomotive Technology" was convened on October 2 and 3, 2012, at Argonne National Laboratory (ANL) in Lemont, IL. It was organized by the Federal Railroad Administration (FRA) to develop a road map for the use of NG in rail applications. It was attended by 55 participants spanning the RR industry, locomotive manufacturers, OEM suppliers, and research and Federal organizations. The objectives of the workshop were to:

- Gauge the current interest in the use of NG as fuel for rail transports,
- Identify pros and cons of using NG in railroad applications,

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- Develop a road map to address the issues.

The workshop presented the operational and safety practices and regulations currently in place for locomotive engines, along with perspectives related to NG usage from different manufacturers, safety regulators, research groups, and the railroad industry. The presentations (listed in Appendix B) are attached to this report as separate files.

## 1.3. Report Structure

The goal of this document is to present all the necessary information that was discussed during the workshop and follow-on conference calls so that a road map for **NG for locomotives** may be generated. The next section briefly describes the categories of topics identified as critical to successful NG usage in locomotives. These categories were identified during a brainstorming session on the final day of the workshop and were further streamlined after discussions via teleconference calls in subsequent months. The categories identified were OEM Concerns, Safety, Performance and Emissions, Fuel, Systems Engineering, and Standards. Group leaders provided the input for their respective categories. FRA hosted periodic conference calls on the dates listed below:

1. 11/7/2012 at 1:15 p.m.
2. 2/6/2013 at 1:15 p.m.
3. 3/6/2013 at 1 p.m.
4. 5/14/2013 at 10 a.m.

The appendices include the workshop logistics, the workshop agenda, and a list of attendees.

# 2. Summary of Recommendations

## 2.1. OEM Concerns

The main purpose of this workshop report is to ensure that the OEM concerns are recorded and used to develop a pathway for NG as an alternative fuel for locomotives. This section encapsulates the barriers, component definitions, standardization, and impact of unforeseen situations vis-à-vis accidents, logistics, etc. Some of the concerns identified by the railroad industry and the two major locomotive manufacturers, Electro-Motive Diesel (EMD) and GE, are as follows (additional details are provided in Table 1):

- Gas supply: connection types, location (front or rear), port injection, direct injection, flow requirements, flow through multiple locomotives, diagnostics
- Electrical: connection types, vaporizer specifications in the case of LNG
- Tunnel operation
- Inspection criteria
- Fuel Industry: fuel proximity to RR, fueling time, tank types
- Infrastructure investment
- Service and maintenance
- Safety
- CFR specifications
- Engine performance
- Emissions: GHGs (methane is 23 times more potent than $CO_2$)

The following sections elaborate on how best to address these concerns.

## 2.2. Safety

The Pipeline and Hazardous Materials Safety Administration (PHMSA) develops and maintains the regulations on the transportation of hazardous materials by rail contained in Title 49 of the Code of Federal Regulations, Parts 100–185. FRA works with PHMSA to enforce the safe transportation of hazardous material by rail. Currently, NG cannot be transported by rail unless the rail carrier obtains a Special Permit. However, a Special Permit is not required for the use of NG as fuel for the locomotive; instead, classification of the locomotive as a vehicle that carries NG, or any other material being used to fuel attending locomotives, is subject to FRA's statutory and regulatory authority related to locomotives contained in the Federal RR safety statutes. (See 49 U.S.C. §§ 20701–20703 [formerly known as the Locomotive Inspection Act].) The Locomotive Inspection Act, in part, prohibits a RR from using a locomotive or tender unless the equipment is in proper condition and safe to operate without unnecessary danger of personal injury. Moreover, there are safety issues that must be addressed in order for NG to be a true alternative to diesel fuel. Safety of the fuel handling and other operations associated with NG-powered locomotives must be evaluated to demonstrate that the rail network's level of safety is maintained. This can be done through collaborative research activities between the regulators, equipment manufacturers and suppliers, and the RRs. Safety research topics such as those discussed below should be investigated.

### 2.2.1. Risk Analysis

An assessment of the risks associated with the use of NG as a locomotive fuel will identify the critical areas of the system that can compromise safety. This knowledge will allow regulators, manufacturers, and end-users to develop appropriate regulations, technologies, and operating practices that can mitigate those risks. Stakeholders need to understand fully the potential risks that NG fuel systems pose to RR employees, first responders, passengers, and the infrastructure as a whole. Risk analysis research will provide valuable data as the safety of NG locomotive systems is evaluated.

### 2.2.2. Regulations and Standards Review

To understand how safety can potentially be compromised by the use of an alternative fuel such as NG, it is important to understand which regulations and safety standards apply. The design and performance standards and regulations of the NG fuel system and components must be evaluated for their applicability to rail equipment and for use in the RR environment. A regulations and standards review will identify areas of potential deficiency in the standards and regulations so that amendments may be made appropriately.

### 2.2.3. Structural Integrity

The crashworthiness of the full NG locomotive system must be evaluated. Using the data and results from the risk analyses, the structural safety of the locomotive-tender system can be analyzed. This analysis will include, at a minimum, evaluating the survivability of CNG and LNG tanks and the integrity of locomotive/fuel-tender connections and collision protection structures. Safety can be demonstrated through structural analyses and testing of the individual components of the NG fuel system and the locomotive-tender system as a whole.

### 2.2.4. Emergency Preparedness and Response Training

FRA is concerned with reducing the occurrences and severity of accidents/incidents in the RR environment. The research activities discussed above will yield important results that can be used to appropriately develop emergency preparedness requirements and response training for RR employees and first responders for those rail systems operating NG-fueled locomotives. However, the safety research areas discussed are only a few of those that must be investigated as NG is evaluated as a viable alternative for rail transportation.

## 2.3. Performance and Emissions

The Performance and Emissions category will be led by Argonne National Laboratory in partnership with GE, EMD, and West Virginia University. The important subtasks are briefly described below.

### 2.3.1. Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET)

**Data gathering**

Argonne has developed a full life-cycle model called GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) to fully evaluate the energy and emission impacts of transportation fuels. The model allows researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis. The fuel pathways in GREET already exist for road and air transportation. Currently, however, there is no information on transportation by rail in the GREET model; therefore, the following information is needed to accurately develop a GREET model for rail applications:

1. For locomotive engines with diesel fuel: fuel quality and energy use (could be in Btu/ton-mile) for different operations (baseline for comparison purposes);
2. For electric locomotives: electricity use in kWh/ton-mile for different operations (this information is always asked for and easier to add on the front end);
3. Energy use differences, if diesel locomotives are to be switched to LNG, CNG, and Di-Methyl Ether (DME); and
4. Emissions of locomotive engines with diesel, CNG, LNG, and DME.

This information will be gathered from locomotive manufacturers, end users, and publications. This is not intended to be a testing exercise. If the information on the engines or locomotives using the alternative fuels does not exist, the data will be generated by scaling up heavy-duty truck data in a manner appropriate for this task.

**Model development**

The energy use of a diesel locomotive will be used to develop the energy use for the GREET model. Once that is done, a model for each engine type will be developed and implemented in the GREET model. Finally, the emissions factors for the energy usage of the various fuel types will be developed and implemented in the GREET model.

**GREET modeling of potential railroad fuels**

After the RR model is developed, CNG, LNG, and DME will be evaluated against diesel and electricity, using the most promising fuel pathways. A final report will detail the well-to-wheels energy consumption, emissions, and GHG effects on the locomotive performance of each fuel pathway.

### 2.3.2. Dual-Fuel Modeling

Depending on the level of funding and the industry's timeline, two options are proposed for dual-fuel modeling.

(1) (Simplified): Develop high-fidelity dual-fuel models for a single-cylinder locomotive engine and validate them with experimental data. (2) (More detailed): In addition to option 1, develop high-fidelity dual-fuel chemical kinetic mechanisms for use in 3-D computational fluid dynamics (CFD) modeling of locomotive engine combustion. Validation of these models will require generation of some fundamental combustion data experimentally, possibly with shock tubes, rapid-compression machines, or constant-volume combustion vessels (with possible DOE-EERE collaboration here). Final CFD validation would be done with endoscopic in-situ imaging in the single-cylinder engine.

### 2.3.3. Single-Cylinder Engine Research

Combustion research in a single-cylinder research engine needs to be performed. Dual-fuel combustion imaging technologies will be acquired to support modeling efforts.

## 2.4. Fuel

Work in the Fuels category will be led by Caterpillar/EMD in partnership with GE, with input from the class 1 RRs, tender car manufacturers, and fuel suppliers. The important subtasks are briefly described below.

### 2.4.1. Fuel Standards

NG is a naturally occurring resource; thus, the composition of NG in its original state is not controlled and contains undesirable constituents, as well as acceptable constituents at unacceptable levels. NG usually needs to be processed after production at the well to remove undesirable constituents and to control the concentration of acceptable constituents before the gas is introduced into the distribution system. If the constituents of NG used as a fuel in engines are not controlled, the heating value of the fuel may be too high or too low, causing engine output to be affected; in extreme cases, the fuel system may not be able to control the rate of heat addition or the engine combustion may be intermittent or cease altogether. If the levels of species concentration for more highly reactive fuel constituents are not controlled, some engine technologies may exhibit uncontrolled rapid combustion that causes catastrophic engine damage as a result of "knocking combustion." If all constituents other than methane (the primary constituent in NG) were removed, the combustion characteristics of the fuel would be well controlled, but the cost of the fuel would be undesirably increased because of the cost of processing it to this high level of purity. Thus, the goal is to specify fuel constituent levels (or fuel characteristics indicative of constituent levels) which provide a fuel that will provide well-controlled combustion in all the available engines with minimum fuel cost to the consumer. A CNG/LNG fuel specification is under development by the Truck and Engine Manufacturers Association (EMA). It is recommended that the RR industry consider adopting the EMA specification in order to ensure simplicity and consistency across the NG engine market.

### 2.4.2. Fuel Temperature at Fill

In applications where energy storage requirements for NG exceed approximately 10,000 MJ (~125 gal or 500 liters of LNG), storage of the fuel as a cryogenic liquid is desirable in order to take advantage of the much higher density of LNG relative to CNG. LNG is stored in equilibrium with the gas above it and the pressure of that saturated mixture is a function of the temperature of the LNG. Thus, the temperature of the LNG that is supplied must be controlled in order to be able to provide adequate margin to the pressure at which the tank must vent to avoid an overpressure event. However, the lower the temperature (providing more margin), the more expensive the fuel will be for the consumer; so, a temperature should be determined that provides adequate storage life with minimal cost. Modeling the heat transfer and pressure build rate, as well as validation using actual tender cars, is necessary to be sure the fill temperature will provide adequate margin to boiling, or adequate delivery pressure, if the vapor pressure of the LNG is used to provide the fuel system pressure.

### 2.4.3. Fuel Infrastructure

Larger NG liquefaction plants can reduce the unit cost of liquefaction. However, the increased production levels mean fewer plants, requiring more transportation, and a cost is associated with the transportation of the LNG. Example models should be developed to help understand the best size for LNG plants to optimize the processing versus transportation costs.

### 2.4.4. Fuel Tender Power

The LNG tender cars can have significant power requirements for pumping and gasification. These power requirements should be documented for a range of tender applications and best practices developed for power transmission to the tender cars or power generation on the tender cars.

### 2.4.5. LNG Tender Car Filling

Because of the large quantity of cryogenic liquid that will need to be transferred to the fuel tenders, filling equipment that can transfer safely at a high flow rate will need to be specified. Cavitation, buildup of static electricity, and cryogenic burns to skin are examples of undesirable conditions that should be studied, and best practices should be developed to help the industry specify equipment that is common across the RRs and that provides safe infrastructure and infrastructure interfaces.

## 2.5. Systems Engineering

The Systems Engineering category will be led by Sharma & Associates, Inc., in partnership with FRA, OEMs, and RRs.

### 2.5.1. Economic Modeling: Efficiency Benefits of Increasing Locomotive Range and Impact on the Railroad Transport Network

It is proposed that energy studies be conducted to assess the effects of NG implementation on rail operations. The model would include, for example, a direct operational-range comparison between a diesel-fueled and an NG-fueled system with all else being equal. Additionally, the change in the fuel supply network would be analyzed to identify the initial capital costs and long-term return on investment of the implementation of NG fuel stations, as well as the peripheral structures/processes needed.

### 2.5.2. Train and Vehicle Dynamics: Simulations of Locomotives with In-Train Tender Cars; Normal and Abnormal Operation

In-train and vehicle dynamics performance of the tender car is of paramount importance to operational safety. The fuel tender car(s) logistically have to be placed next to the locomotives, which are all likely to be in the head-end position where high draft and buff forces generally occur. Alternatively, if distributed power is used, the tender car and the associated locomotive may be in the rear third of the train where the most severe slack action events occur. Train dynamics will be simulated for selected grades, curves, train makeup, and train handling conditions to determine the level of in-train forces and evaluate the train's stability against derailment potential.

A vehicle dynamics simulation of tender cars will be conducted for Association of American Railroads (AAR) Chapter XI track-worthiness performance regimes. These simulations will be used to assess whether tender cars should be evaluated with full-scale on-track testing.

### 2.5.3. Impact Performance of Tender Cars

A test plan will be developed that might mirror current AAR M-1001 specifications for longitudinal-impact car design testing. Additionally, there will be a need to instrument specific components of the test car for measurement of accelerations, displacement, and forces that can be compared with component design specifications to assess the likelihood of damage due to impact. Also, a risk analysis will be done for the fuel and fueling-related components to assess the probability of damage or rupture and the resultant hazards per component. All components aboard a tender car must comply with the test specifications that are developed.

Fittings protection under rollover conditions will also be reviewed, considering past and current research and recommendations by FRA and the railroad industry.

A Pareto chart that will rank the components by risk will then be developed. Finally, plans will be drawn up to allow the industry to inspect for impact damage prior to component or system failure and to remediate any issues that occur in the field as a result of impact.

### 2.5.4. Fatigue Due to Vibration of Tender Car Components

The tender car may carry various fuel conversion and supply subsystems. The reliability and life cycles of these systems have to be proven under severe acceleration and vibration conditions. A test plan will be developed for measurement of accelerations, displacement, and forces that can be compared with component vibration design specifications to assess the likelihood of damage due to vibration. A life-cycle analysis of each component will be done and will take into account generally accepted operating vibrations due to track input; those results will be compared with each component's vibrational design specification.

On the basis of the performance of the subsystems and components, procedures will be developed to be used by the industry to inspect for vibration damage prior to component or system failure and to remediate any issues that occur in the field as a result of vibration.

### 2.5.5. Track and Service-Worthiness of Tender Cars

A test plan will be developed to comply with AAR's current Chapter XI testing specifications. Testing will be accomplished per these requirements just as any new car build needs to comply. It will be up to the AAR/FRA to allow for any exemptions from the testing due to "previously approved and existing" equipment scenarios.

## 2.6. Standards

Safety and operational standards for LNG- or CNG-powered locomotives have not been established. Industry, FRA, and AAR must adopt a collaborative approach to apply, evaluate, write, and/or amend the appropriate regulations or standards to facilitate the integration of LNG and CNG fuel (in tender cars) and NG locomotives into North American RR operations. Gaps in understanding of existing standards and required changes to regulations were identified during the workshop. Filling these gaps will require the following:

- Investigation of regulatory changes needed to allow LNG and CNG to be transported as a commodity without a Special Permit; and
- Standardization in the following areas to allow interoperability:
  -Locomotive and tender car connections
  -Refueling connections and procedures
  -Fuel distribution and shutoff protocols
  -Safe operating , maintenance, and repair procedures
  -Designs for LNG tender cars
  -Designs for CNG tender cars
  -Designs for dual-fuel locomotives
  -Guidance on placement of fuel tenders on trains

The recommended approach to reaching solutions for these issues requires an analysis of currently applicable codes, standards, and regulations to identify areas in need of further development. This analysis will reveal areas for technical advancements or regulatory changes to accommodate the integration of LNG and CNG as locomotive fuels.

**Table 1: Research & Development Topic Priorities**

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| 1 | OEM Concerns | | | | | | |
| | | Gas supply connection type and location:<br>-Port injection/carburetion (low pressure <10 bar)<br>-Front and rear connections<br>-Fluid, electrical connections<br>-Vaporizer reheat<br>-Diagnostics, power<br>-Gas flow rate requirements<br>-Flow-through for multiple locomotives | | | | | |
| | | Operation in tunnel: Significant knock challenge; Research needed to model impact, develop mitigation and maximize performance | | | | | |
| | | What is the impact on existing operation and inspection rules? | | | | | |
| | | Fuel industry:<br>-Fuel proximity to RR<br>-Fueling time | | | | | |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| **1** | **OEM Concerns** | | | | | | |
| | | Railroads:<br>-Infrastructure investment<br>-Impact to operation, including service, maintenance, and overhaul<br>-Safety and service protocols | | | | | |
| | | Onboard CNG storage: under-frame enclosure requirements for tank protection; CFR 49 Part 238 appendix D, which specifies damage tolerance requirements for diesel fuel locomotive tanks | | | | | |
| | | Recommending a final CNG pressure fill standard of 4500 psi. Conventional on-road tanks are rated at 3600 psi, but typical fill hardware is rated at 4500 psi for rapid fill with cool-down to 3600 psi nominal pressure. With moderate-rate fills, 4500 psi nominal pressure nets 15% more storage in the same volume | | | | | |
| **2** | **Safety** | | | | | | |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| | | Crashworthiness of full system (all equipment). Survivability of tanks and cylinders, consequences, collision protection | | FRA | Safety | | Analyses of fueling system: tender, fuel delivery system, locomotive |
| | | Tender car operation | Need for today's demos | Class 1 | Standardization | | |
| | | Vaporizer fluid | Need for today's demos | Class 1 | Standardization | | Propose to use propylene glycol as standard |
| | | Communication protocol between the tender car and locomotive | Need for today's demos | Class 1 | Standardization | | Class C and Class D protocol |
| | | Appropriate regulatory framework: what regulations apply, should apply, or need amending | | FRA | | | |
| | | Full educational package on LNG safety in railway use | | Class 1 with FRA support | Safety and education of first responders | | |
| | | Safety and security of flexible couplings for fuel delivery: Can a reliable leak-proof connection be devised for a RR application? | | OEM | | | |
| **2** | **Safety** | | | | | | |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| | | CNG tank type (Types 1, 2, 3, 4 available). Currently looking into Types 1 and 3 built to UN standards (Type 1 tanks exposed and Type 3 tanks in protective enclosure) | | | | | |
| **3** | **Performance & Emissions** | | | | | | |
| | | **GREET: G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation | | Argonne | To evaluate energy and environmental emissions (especially GHG) impacts due to NG usage in locomotives | Since 1996, GREET has been used extensively for vehicular applications but never for rail applications. A new rail model needs to be developed for this study. | Data pertaining to existing locomotive technology such as fuel quality, energy use, and emissions output for different operating conditions will be gathered. This information will be solicited from the industry and publications. These precursors will serve as input to a newly developed RR GREET model. This model can be customized for different engine/locomotive configurations. Finally, CNG and LNG impact will be evaluated against |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| | | | | | | | diesel and electricity by using the most promising fuel pathways. |
| **3** | **Performance & Emissions** | | | | | | |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| | | Dual-fuel modeling | | OEMs, with Argonne support | Lack of high-fidelity models to enable development of cleaner dual-fuel locomotive engines | The chemical kinetics associated with dual-fuel combustion are not well characterized. New models/analytical tools have to be developed and validated both at the basic science level and on engine platforms. | Depending on the level of funding and the industry's timeline, two options are proposed. (1) (simplified): Develop high-fidelity dual-fuel models for a single-cylinder locomotive engine and validate with experimental data. (2) (more detailed): In addition to option 1, develop high-fidelity dual-fuel chemical kinetic mechanisms for use in 3-D CFD modeling of locomotive engine combustion. Validation of these models will require generation of some fundamental combustion data experimentally, possibly with shock tubes, rapid-compression machines, or constant-volume combustion vessels (with possible DOE-EERE collaboration here). Final CFD validation would be done with endoscopic |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| | | | | | | | in-situ imaging in the single-cylinder engine. |
| **3** | **Performance & Emissions** | | | | | | |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| | | Single-cylinder engine research: Subject to EMD's approval to use engine facility<br>**Stage 1:** NG port injection<br>**Stage 2:** NG HPDI<br>**Supporting Research Tools:** Optical visualization of dual-fuel combustion | | OEM, with Argonne support | Argonne has an operational single-cylinder locomotive engine. Data acquired will be shared with the partners. | Argonne has proactively invested in getting NG distribution to its test facility. However, low-pressure (150 psig) NG is the only option available at this point. For Stage 2 work, a high-pressure gas compression installation is needed. | Stage 1 research can commence as early as March 2013. Argonne has all research instrumentation needed to deliver engine performance and emissions data. Additionally, a Visioscope will be used to acquire in-cylinder combustion images to provide temporal and spatial combustion data. Upon installation of a high-pressure NG supply unit, Stage2 work will be attempted. |
| | | Exhaust speciation: analysis of volatile, semi-volatile and particulate matter-bound organics and all inorganics of exhaust emissions | | | | | |
| | | Lube oil studies (focusing on NG-fueled locomotive engines) | | | | | |
| **3** | **Performance & Emissions** | | | | | | |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| | | Other R&D topics:<br>-Development of on-board, in-use emissions measurement systems<br>-Advanced laser ignition systems | | | Industrial input needed to proceed further | | |
| | | Performance and range issues | | | What volume of gas is needed (and at what pressure) to provide adequate range for a locomotive? | In buses, range varies greatly with ambient temperature, as the gas density and hence calorific value changes. In some cases, the tanks provided offer insufficient range for a day's bus service at higher temperatures. For a locomotive to have a useful range, it will likely be necessary either to store a large volume of gas or to store it at extremely high pressures. Both approaches have their own issues. | |
| **3** | **Performance & Emissions** | | | | | | |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| | | Life cycle cost | | | Economic incentive for switching to NG | While the fuel itself is (currently) cheaper than diesel, the costs of fixed and moving equipment to accommodate LNG/CNG, and the life of such systems, need to be considered. The compressors, etc., at CNG filling stations have a finite life and need replacing at relatively short intervals—another cost to be considered. | |
| **4** | **Fuel** | | | | | | |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| | | NG fuel standards for locomotives | | OEMs | Required for engine reliability | Some fuel may contain HHCs or inerts | Set standard, require fuel vendors to meet the standard. |
| | | Minimum methane number | | | | | A gas standard already exists and could be adopted. |
| | | Minimum and maximum LHV | | | | | ISO 6974-6 |
| | | Temperature at fill | | | | | |
| | | NG fuel infrastructure ("micro" LNG plants) | | Fuel and infra-structure suppliers | Required for this program | Potential lack of commonality | Set a standard for fuel (see above) and fill interface. |
| | | Head-end power: location (locomotive vs. tender), fuel (dual vs. spark-ignited or other), passenger prime mover fuel (dual fuel or LNG) | | FRA | Required for this program | Potential lack of commonality | Set a rule to ensure commonality, probably requiring tender to be self-powered. |
| | | Tender car fueling | | Fuel and infra-structure suppliers | Required for this program | Potential lack of commonality | Set a standard for fuel (see above) and fill interface in the tender car |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| **5** | **Systems Engineering** | | | | | | |
| | | Economic modeling: efficiency benefits of increasing locomotive range and impact on RR transport network | | OEM and Class I | Required for understanding effects of NG implementation | Lack of economic justification for implementation | Due diligence in economic modeling |
| | | Vehicle dynamics: simulations of locomotives with in-train tender cars; normal and abnormal operation | | FRA, with OEM support | Required for understanding the service in-train load environment | Lack of performance history | Vehicle dynamic modeling |
| | | Impact testing of tender cars | | FRA, with OEM support | | Lack of performance history | Impact testing |
| | | Fatigue due to vibration testing of tender-car components | | FRA, with OEM support | | Lack of performance history | Fatigue and vibration testing |
| | | Track and service-worthiness of tender cars (squeeze?) | | FRA, with OEM support | | AAR interchange requirements | "Chapter-XI-like" testing |
| **6** | **Standards** | | | | | | |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| | | Standardization for safety and interoperability: (1) Locomotive/tender connections: gas, coolant, electrical-fluid leakage, quick disconnect vs. permanent testing of connections; (2) fueling connections (refueling); (3) design standards; (4) safe operating, maintenance and repair procedures; (5) placement in trains and consists | | FRA, AAR, RRs, locomotive and tender-car developers | Research program needed to assess all options; applications of standards | RR/AAR/FRA cooperation needed; interchange requirements, technology, LNG safety education | Gap analysis needed to assess options in consultation with stakeholders and AAR TAG activities |
| | | Identification and standardization of safety control systems and communications | | AAR, locomotive and tender-car developers | Application of standards | Interchange requirements, technology, LNG safety education | AAR TAG activities |
| | | Identification and standardization of on-board fuel distribution system and emergency shutoff systems | | FRA, AAR, locomotive and tender-car developers | Application of standards and regulations (FRA/AAR) | Technology dependence, interchange requirements | AAR TAG activities |
| **6** | **Standards** | | | | | | |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| | | Use of ISO containers as fuel tanks and for transportation of LNG | | Tender-car developers, FRA | Assessment for tender car use to be examined; upcoming demonstrations may use this system | Safety assessment | Review of current regulations for LNG as commodity. Gap analysis for use of LNG tank as fuel tank |
| | | Investigate the impact of the current regulation of LNG transport as a commodity | | AAR | Regulating LNG as a commodity is the first step to regulating it as a fuel source. | Long time-line | Resources to be allocated for review of current regulations (Permit to Reg) |
| | | Risk assessment of process from well to implementation of NG in locomotives. Complete evaluation and assessment. | | FRA, AAR, locomotive and tender-car developers | Use of existing GHG tools (Argonne-GREET) | | |
| | | Routine and post-incident/accident inspection and maintenance of tender cars and CNG/LNG tanks | | | | | |
| **6** | **Standards** | | | | | | |

| # | Category | Ideas | Priority | Lead Inst. | Feasibility/ Business Case | Barriers | Possible Actions to Overcome Barriers |
|---|---|---|---|---|---|---|---|
| | | Auto Engine Start-Stop | | Locomotive manu-facturers | | | |
| | | FRA locomotive standard that references existing CNG tank standards with special requirements for rail; tanks built to U.S. Department of Transportation/UN standard; Qualified to NGV2, NFPA 52 | | | CNG not for mainline use. Not a priority for investment | | |

## Appendix A—Workshop Logistics

Workshop registrants totaled 55, with actual attendance exceeding 95 percent. To ensure productive discussions and cogent recommendations, invitees were carefully chosen from the RR industry, research labs, locomotive manufacturers, and safety-enforcing agencies and then personally invited to attend the workshop. The workshop enjoyed vigorous participation from both industry and research laboratories. Approximately 73 percent of the participants represented the RR industry and supporting OEM companies. Researchers from universities and Federal laboratories constituted 25 percent of the registrants. Fifteen invited speakers presented on various topics related to NG applications for transportation.

A session titled “Preliminary Listing of R&D Topics” opened the floor for participants to identify key categories for discussion. The six categories identified were OEM concerns, Safety, Performance and Emissions, Fuel, Systems Engineering, and Standards. Periodic teleconference calls enabled participants to act as team leads for the various categories. The team leads, in turn, provided the necessary input to determine and formulate a road map.

## Appendix B—Workshop Agenda

**October 2, 2012 (APS Conference Center, Room 1100)**

| | | |
|---|---|---|
| 11:00 am–12:00 pm | Registration | |
| 12:00–12:10 pm | Announcements | Raj Sekar, ANL |
| 12:15–12:45 pm | GREET Analysis Tool (box lunches provided) | Dr. Michael Wang, ANL |
| 1:00–1:15 pm | Welcome to Argonne | Dr. Larry Johnson, Director, Transportation Technologies, ANL |
| 1:15–1:30 pm | Objectives of the Workshop | Kevin Kesler, Chief, Rolling Stock Research R&D, FRA |
| 1:30–2:00 pm | NG as Transportation Fuel | Glenn Keller, ANL |
| 2:00–2:20 pm | Hazardous Material Transportation and Locomotive Fuel Tank Safety Regulation Review | Francisco Gonzales, Program Manager, FRA Office of R&D |
| 2:20–2:40 pm | Hazardous Material Transportation and Locomotive Fuel Tank Safety Regulation Review | Stephane Garneau, Transport Canada |
| 2:40–3:00 pm | Research on Emissions Associated with Natural Gas in Diesel Engines | Mridul Gautam, Associate Vice President for Research, West Virginia University |
| 3:00–3:30 pm | Break | |
| 3:30–4:00 pm | Burlington Northern Railroad Natural Gas Locomotive Initiative | Les E. Olson, Associate Research Scientist, Texas A&M Transportation Institute (formerly of Burlington Northern RR) |
| 4:00–4:30 pm | Passenger Rail Service Provider Priorities (Future Plan) | Johnson Bridgwater, Federal Programs Manager, Rail Programs Division, Oklahoma Dept. of Transportation |
| 4:30–5:00 pm | CN Natural Gas Locomotive Initiatives | William Blevins, Chief, Mechanical and Electrical Engineering, Canadian National |
| 5:00–5:30 pm | NG Injection Technology Status | Paul Blomerus, Westport Innovations |
| 5:30–6:00 pm | Preview of second day's agenda | Melissa Shurland, FRA |
| 6:30 pm | Dinner (optional, no-host) at Argonne Guest House | |

**October 3, 2012 (Building 240 Conference Center, Room 1416)**

| | | |
|---|---|---|
| 7:30–8:15 am | Continental Breakfast in Building 240 | |
| 8:15–8:35 am | Freight Railroad Priorities (Lessons Learned and Path Forward) | Michael Iden, General Director, Car and Locomotive Engineering, Union Pacific RR |
| 8:35–8:55 am | Locomotive Manufacturers' Priorities | Edward Cryer, EMD |
| 8:55–9:15 am | Locomotive Manufacturers' Priorities | Taral Shah, Product Manager, Global Engine Platforms, GE Transportation |
| 9:15– 9:35 am | Locomotive Manufactures' Priorities | Garrett Riley, MotivePower, Inc. |
| 9:35–9:55 am | Natural Gas Conversion Kit Technology | Dave Cook, Energy Conversion Inc. |
| 9:55–10:15 am | Preliminary Listing of R&D Issues | Munidhar Biruduganti, ANL |
| 10:15–10:45 am | Break | |
| 10:45–11:45 am | Discussion and Summary of R&D | Melissa Shurland, FRA |
| 11:45 am–12:00 pm | Group photo | |
| 12:00–12:45 pm | Future Directions of R&D (box lunches provided) | Melissa Shurland, FRA |
| 1:00–2:30 pm | Tour of ANL Transportation Facilities | Steve McConnell, ANL |

## Appendix C—Workshop Attendee List

| | Last, First Name | Company | Email Address | Phone | Address |
|---|---|---|---|---|---|
| 1 | Acevedo, Francisco | U.S. Environmental Protection Agency - Region 5 | acevedo.francisco@epa.gov | 312-886-6061 | 77 W. Jackson Blvd.<br>Chicago, IL 60604 |
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