



## An Evaluation of Natural Gas-fueled Locomotives

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**Report prepared by:**

BNSF Railway Company  
Union Pacific Railroad Company  
The Association of American Railroads  
California Environmental Associates

## Contributors

The following individuals developed this paper.

Larry Caretto	Former Dean of Engineering and Computer Science and Professor of Mechanical Engineering California State University, Northridge
Steve Fritz	Manager, Medium-Speed Diesel Engines Southwest Research Institute
John Hedrick	Senior Research Engineer Southwest Research Institute
Mike Iden	General Director Car & Locomotive Engineering Union Pacific Railroad
Lanny Schmid	Director of Environmental Field Operations Union Pacific Railroad
Mark Stehly	Assistant Vice President for Environment and Research & Development BNSF Railway
Andrew Trump	Consultant to California Environmental Associates and the Association of American Railroads
Darcy Wheelles	Senior Associate California Environmental Associates
Sarah Weldon	Research Associate California Environmental Associates

Questions about this report may be directed to:

Sarah Weldon  
Research Associate  
California Environmental Associates  
423 Washington Street, 3<sup>rd</sup> Floor  
San Francisco, CA 94111  
[Sarah@ceaconsulting.com](mailto:Sarah@ceaconsulting.com)  
415-421-4213, ext 34

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## Abbreviations and Selected Terms

AAR	Association of American Railroads, the trade association representing the Class I freight railroads and Amtrak
ASME	American Society of Mechanical Engineers
BAAQMD	Bay Area Air Quality Management District
BN	Burlington Northern Railroad
BNSF	BNSF Railway Company
Brake horsepower (bhp)	Power developed by the combustion engine on a locomotive. This is used to provide tractive power to the electric motors that drive the locomotive and to provide auxiliary power.
Btu	British Thermal Unit (a measure of energy content)
CAPTS	Clean Air Partners Transportation System, Inc.
CARB	California Air Resources Board
CEA	California Environmental Associates
CNG	Compressed natural gas
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
CSHVC	City suburban heavy vehicle cycle
DCGM	Dallas Garland and Northeastern Railway – a Texas shortline
Duty Cycle	Average percent of time a locomotive operates in notch settings performing typical duties
ECI	Energy Conversions Inc.
EF&EE	Engine, Fuels & Emissions Engineering
EMD	Electro-Motive Diesel, Inc. (formerly the Electro-Motive Division of General Motors)
EPA	U.S. Environmental Protection Agency
FTP	Federal test procedure
FWWE	Fort Worth and Western Railroad – a Texas shortline
g/hp-hr	Grams per horsepower-hour
GE	General Electric
GWP	Global warming potential
HC	Hydrocarbon
hp	Horsepower
LaCHIP	Late Cycle High Injection Pressure
LEI	Low emission idle
LNG	Liquefied natural gas – a gas consisting primarily of methane
LPG	Liquid petroleum gas (a gas consisting primarily of propane, propylene, butane, and butylene in various mixtures)

MK Rail	A company now known as MotivePower, Inc., a division of Wabtec Corporation.
MMBtu	Millions of BTUs (a measure of energy content, often used to describe the energy content of natural gas).
MOU	Memorandum of Understanding
NMHC	Non-methane hydrocarbon
NPRM	Notice of Proposed Rule Making (an EPA regulatory support document designation)
NO <sub>x</sub>	Oxides of nitrogen
NRE	National Railway Equipment Company
PHL	Pacific Harbor Lines – A California shortline railroad
PM	Particulate matter (typically 10 microns or smaller)
psi	Pounds per square inch (a measure of pressure)
Railpower	Railpower Technologies Corporation
RLM	Refrigerated Liquid Methane (a high-purity form of LNG that is a branded product of Air Products & Chemicals, Inc.)
SCAQMD	South Coast Air Quality Management District
SwRI	Southwest Research Institute
TERP	Texas Emissions Reduction Program
THC	Total hydrocarbons
Tractive power	Power available at the locomotive wheels. Locomotive ratings are based on tractive power; brake horsepower is used in locomotive emission standards.
ULEL	Ultra-Low Emission Locomotive (a CARB designation)
UPRR or UP	Union Pacific Railroad Company

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# 1. Executive Summary

The BNSF Railway Company (BNSF), the Union Pacific Railroad Company (UPRR), and the Association of American Railroads (AAR) (collectively referred to as “the Railroads”) have prepared this report to provide perspective and background information to regulatory agencies and other interested parties on the possible use of natural gas as a fuel for locomotives.<sup>1</sup> Additionally, this document partially satisfies one of the requirements of the rail yard Memorandum of Understanding (MOU)<sup>2</sup>. BNSF and UPRR entered into this MOU in 2005 with the California Air Resources Board (CARB) to reduce particulate emissions from California rail yards. One element of the rail yard MOU requires an ongoing evaluation of possible locomotive emission control technologies.

This document provides information on past, current, and potential future efforts to develop and use natural gas-fueled locomotives to meet engine reliability, operational efficiency, and air quality goals. Some of these efforts were, and continue to be, directed at the retrofitting of line-haul freight locomotives with a natural gas conversion system. Other efforts were focused on developing a new high-horsepower natural gas-fueled locomotive and evaluating fueling infrastructure and fueling system operating requirements associated with the use of this fuel. This document looks at these developments in the context of the U.S. Environmental Protection Agency’s (EPA) locomotive emission standards and exhaust measurement test protocols.

The Railroads have a unique partnership with California and have exhibited a willingness to enter into voluntary yet enforceable agreements with CARB to accelerate emission reductions from rail operations that will help California achieve air quality goals.<sup>3</sup> Additionally, the Railroads and the locomotive builders are driving significant product innovation that, in turn, is leading to the commercialization of lower emitting line-haul and switch locomotive products. This innovation is exciting, noteworthy, and predominately diesel engine-based.

The Railroads have prepared this assessment to help inform discussions among all stakeholders. In 2006, the draft report was sent to several stakeholders to solicit feedback. The stakeholders included several California air districts and CARB. The Railroads received reply comments from the South Coast Air Quality Management District (SCAQMD) and the Bay Area Air Quality Management District (BAAQMD). These are included in this report as Appendices 6 and 7, along with the Railroads’ responses. The Railroads look forward to

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<sup>1</sup> The Railroads initially released a draft of this report in January 2006 and solicited feedback from air quality agencies and other interested parties. This document will be updated periodically as new developments present themselves.

<sup>2</sup> For the 2005 rail yard MOU and supporting information, see <http://www.arb.ca.gov/railyard/ryagreement/ryagreement.htm>. Section 8(c) of the MOU, Agreement to Evaluate Other, Medium-Term and Longer-Term Alternatives, ensures that the evaluation and implementation of feasible air pollution mitigation measures occurs expeditiously. Section 8(c) of the CARB rail yard agreement is presented in Appendix 1. The railroads have also agreed to continue to meet and confer with CARB and other stakeholders to evaluate the feasibility of additional measures in designated rail yards.

<sup>3</sup> Activities include, but are not limited to, EPA certification standards and test procedures for new and rebuilt locomotives, the 1998 South Coast NOx locomotive fleet average MOU, the CARB diesel fuel requirements for intrastate locomotives, the 2005 CARB rail yard MOU, and voluntary programs to investigate new technologies (e.g., diesel particulate filters, an emissions “hood”, and remote sensing).

continuing a fact-based, technical discussion regarding what role, if any, natural gas as a locomotive fuel should play in further reducing emissions from locomotives.

## ***Findings and Conclusions***

### **A history of innovation and inquiry**

The Class I Railroads<sup>4</sup> have a long history of partnering with the locomotive builders to evaluate innovations in locomotive and engine design, including those that involve the use of alternative fuels like natural gas. Section 8 of this report reviews several examples of substantive, railroad-led and funded research and demonstration efforts. These efforts were typically aimed at understanding the use of alternative fuels and locomotive engine technologies to achieve overall operating efficiencies. While not primarily focused on emissions performance, these efforts were focused on efficiency and benefited emissions broadly.

### **Essential locomotive requirements**

In 1994, the Railroads explained to CARB that a key underlying trend must be paramount in any effort to commercialize new locomotive technologies:

Continuous improvements in locomotive design have played a critical role in keeping the railroad industry competitive and viable by improving the cost structure of the industry. These improvements included increased locomotive reliability, greater horsepower, greater horsepower to weight ratios, improved traction motors, and better engine fuel economy. All of these improvements reduce the operating and capital costs and enhance the efficiency of the business.<sup>5</sup>

New locomotives must meet a wide range of railroad company, customer, and community requirements, including:

- safety
- exhaust emissions performance
- extensive range
- high horsepower
- high tractive effort
- fuel economy
- reliability

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<sup>4</sup> Railroads with operating revenues in excess of \$277.7 million per year. There are seven Class I U.S. railroads: BNSF Railway Co., CSX Transportation, Kansas City Southern Railway Co., Norfolk Southern, Soo Line Railroad Co., Grand Trunk Corporation, and Union Pacific Railroad Co. Grand Trunk and Soo Line are owned by the Canadian National Railway.

<sup>5</sup> Amtrak and the Class I Freight Railroads Operating in California, comments in response to the Engine, Fuel and Emissions Engineering Inc Draft Report (EF&EE Report), April 1994. The draft of this report was issued October 13, 1993. The final report was issued March 1995: Christopher S. Weaver and Douglas B. McGregor, "Controlling Locomotive Emissions in California. Technology, Cost-Effectiveness, and Regulatory Strategy," Engine, Fuel and Emissions Engineering Inc., Final Report prepared for CARB under contracts A032-169 and 92-817, March 1995.

The principal line-haul locomotive builders, General Electric (GE) and Electro-Motive Diesel, Inc. (EMD), continue to meet these requirements through clean diesel engine enhancements, not through the commercialization of natural gas-fueled locomotives.

In 1998, EPA adopted uniformly applied federal standards Tier 0, 1, and 2 for locomotive emissions. The current EPA Tier 2 standards will be superseded by their new Tier 3 and Tier 4 standards which are in the final stages of development and are expected to be finalized around the start of 2008. EPA's standards, in concert with the Railroads' ongoing need for more efficient and reliable locomotives, will continue to guide the railroads' efforts to evaluate all options to ensure that locomotives are operating safely, reliably, efficiently, and in an environmentally superior manner compared to other transportation modes.

### **A period of significant innovation**

The past several years have yielded significant innovation in both switch and line-haul locomotive product development. Today the Railroads are deploying the newest diesel line-haul locomotives from GE and EMD which meet EPA's stringent Tier 2 locomotive emission requirements. These 4,300 – 4,400 hp<sup>6</sup> locomotives reduce locomotive emissions significantly (approximately 60% cleaner for NOx) compared to locomotives manufactured before the implementation of EPA's emission standards. They also simultaneously meet the Railroads' needs for interoperability, high horsepower performance, fuel efficiency, and reliability. The Railroads also worked with several companies to commercialize two new diesel-based switch locomotive technologies: a battery-hybrid switch locomotive ("Green Goat") and a multi-engine generator set switch locomotive ("gen set" switcher).<sup>7</sup> The UPY2005 NRE was the prototype of the first gen set switcher and was funded entirely by UP. These locomotives use low-emitting diesel engines meeting U.S. EPA's nonroad Tier 3 standards. The Railroads have placed initial orders for at least 250<sup>8</sup> of these low-emission switch locomotives systemwide. California will be served by 77 of these locomotives by end of 2007.

### ***The Railroads' position on natural gas***

Some members of the regulatory, engine supply, and fuel supply communities believe the railroads have an opportunity to use natural gas as a locomotive fuel to help meet emissions and performance goals. Except for some potential niche applications, the Railroads disagree. Decades of research and development activities and over-the-rail locomotive prototype demonstrations have given the Railroads a great deal of information about the practicality of

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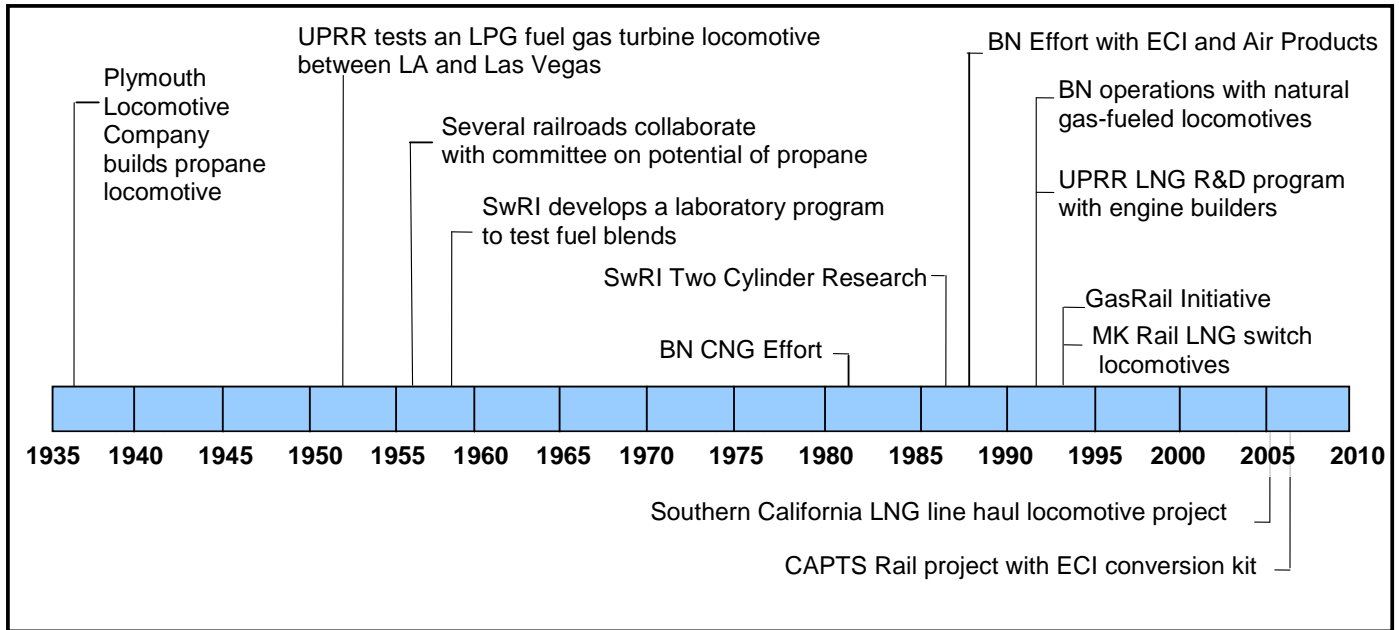
<sup>6</sup> Locomotives use a diesel-electric drive system where the output from a combustion engine is used to generate electric power. That electric power is then used to drive an electric motor to provide the high torque required for the locomotive. Locomotives are rated based on tractive horsepower available to drive the wheels of the locomotive. The emission standards are based on the brake horsepower developed by the combustion engine on the locomotive. Unless stated otherwise, all references in this report to horsepower refer to the tractive horsepower of the locomotive.

<sup>7</sup> A "gen-set" is a self-contained modular package of power generating equipment consisting of a diesel or gas engine coupled to an electrical generator.

<sup>8</sup> Green Goats for both Railroads have been returned to the manufacturer for modification to resolve an equipment malfunction that causes engine fires. One Green Goat for UP is already back in limited service, and the remaining UP Green Goats should be back by the end of the year. BNSF's Green Goats are still with the manufacturer. Some railroads may retrofit Green Goats as gen sets before returning them to operation.

using natural gas-fueled locomotives. Figure 1 below highlights the main Western Class I Railroad research efforts since 1935. While natural gas locomotive technology does not compare favorably with the current Tier 2 standards, it will look even less promising when compared with the forthcoming Tier 3 and Tier 4 standards. EPA has proposed the following standards requiring reductions from the Tier 2 baseline: Tier 3 standards specifying a 50% reduction in particulate matter (PM) effective in 2012; Tier 4 standards requiring an 85% reduction in PM effective 2015 and a 76% reduction in NOx in 2017.

**Figure 1: Timeline of Railroad Research Activities**



### Basis of Comparison

The basis for evaluating the performance of any locomotive technology—including natural gas-fueled locomotives—should be the most stringent applicable EPA locomotive emission standards. These are currently Tier 2 and test protocols, not pre-regulation emission levels. Until EPA adopts the Tier 3 and Tier 4 emissions standards, as expected in the beginning of 2008, the proposed standards are subject to change. This report therefore maintains Tier 2 as the benchmark for emissions comparison.<sup>9</sup> This basis provides the only objective means to compare diesel, natural gas-fueled or any other locomotive technology.<sup>10</sup> Any comparison of effectiveness and long term integrity of a locomotive technology should consider the change in the overall emissions inventory (i.e., consider broader emissions criteria than PM and NOx). This is essential considering there are often trade-offs involved in reducing specific emissions such as increased fuel use to run filters and catalysts that scrub out NOx and PM, resulting in increased GHG emissions. Additionally, cost effectiveness is central to any analysis and must consider the infrastructure and interoperability costs of any shift in technology.

<sup>9</sup> When the Tier 3 and Tier 4 standards are adopted, the Railroads expect this will make LNG alternatives less favorable in comparison to new clean diesel locomotives, not more.

<sup>10</sup> See 40 CFR §§ 92.7 and 92.8. See also Appendix 5.

Also, to ensure an “apples-to-apples” emissions comparison, locomotive emissions performance should be evaluated using EPA certification test protocols (the federal test procedure (FTP)). The FTP uses a steady-state cycle with weighting factors. Current EPA duty-cycle weighting factors are applied to emissions measurements taken from locomotives manufactured before the EPA cycle was created so that they can be compared to emissions measurements taken from newer locomotives. This ensures that previously collected emissions data can be compared.

## Emissions Performance

The Railroads currently know of one commercially available, proven and tested natural gas-fueled line-haul locomotive product available for the North American locomotive market. It is available only as a retrofit or conversion product. It would convert an approximately 25-year-old, EMD645-E3 3,000 hp diesel locomotive to run on natural gas. Comparing the exhaust emissions of this converted locomotive with those of EPA certified Tier 2 compliant diesel locomotives shows that the new diesel locomotives outperform the natural gas-fueled locomotive on emissions (see Table 1). ECI may be able to repeat the application of this conversion kit on to a more advanced EMD710 engine with similar success in emissions reductions.

**Table 1– Comparing Natural Gas-fueled Line-haul Locomotive Conversion and Certified Tier 2 Diesel Line-haul Locomotives (g/bhp-hr)<sup>11</sup>**

Mode	THC	NMHC	CO	NO <sub>x</sub>	PM
<b>ECI Natural Gas Conversion</b>	7.55	1.17	10.0	5.2	0.38
<b>Diesel Tier 2 compliant EMD</b>	0.22	0.22	1.0	5.1	0.07
<b>Diesel Tier 2 compliant GE</b>	0.16	0.16	0.4	5.3	0.10

There is no NO<sub>x</sub> benefit from using this natural gas-fueled locomotive, and all other criteria pollutant emissions are higher—including particulates, which are four to five times greater. Compared to the operation of the same locomotive on diesel fuel, natural gas is less energy efficient<sup>12</sup> and produces more greenhouse gas emissions (CO<sub>2</sub> equivalent). Also, a locomotive using this natural gas conversion kit will likely have higher emissions of some toxic air containments, especially formaldehyde.

## Niche opportunities may exist

There may be niche opportunities to use natural gas in certain locomotive applications, such as the liquefied natural gas (LNG) rail yard switch locomotives in service in Los Angeles for

<sup>11</sup> EF&EE Report, Table 11, April 1994.

<sup>12</sup> For more on energy content of natural gas see Section 8

the BNSF. Another possible use is the multi engine “gen set” switch locomotive outfitted with natural gas-fueled engines. However, because of the relatively small amount of fuel consumed by yard switchers and the possible use of diesel particulate filters on gen sets, there may be little improvement in emissions by using natural gas as a fuel in these engines, and it begs the question as to what advantage there would be in using natural gas given the requisite infrastructure costs that accompany it.

### **Cost Savings Claims**

Claims that natural gas-fueled locomotives will be less expensive to operate than diesel equipment are unfounded. In recent years, prices in the North American natural gas market have been high and unstable. Moreover, support of natural gas-fueled locomotives will require significant investments in new fueling infrastructure that are duplicative to established diesel based infrastructure. These infrastructure investments and their associated operating costs must be accounted for in any evaluation of cost effectiveness.

### **Looking to the Future**

EPA has announced its intention to issue final regulations for Tier 3 and Tier 4 locomotive standards by the end of 2007 which will further reduce emissions from new and rebuilt locomotives. Locomotive manufacturers are pursuing further improvements to diesel locomotive and locomotive engine technology to meet these requirements. Given the small size of the locomotive market (approximately one locomotive is sold for every 211 Class 8 trucks)<sup>13</sup> and given manufacturers’ personnel and financial constraints, it is highly doubtful the builders can simultaneously pursue further improvements in diesel locomotive technology and natural gas-fueled locomotive development. Because of these constraints, it is important for the regulatory agencies to set overall emission performance requirements and give the builders the flexibility to determine the most cost-effective and commercially reasonable way to achieve these goals.

The western Class I freight railroads<sup>14</sup> have and will continue to assess the potential use of natural gas-fueled locomotives. While some air quality regulators argue that natural gas-fueled locomotives are preferable to advanced diesel-based engines for achieving significant emission reductions (particularly for NO<sub>x</sub> and PM), the Railroads disagree. As long as cleaner diesel locomotives continue to be the most cost effective strategy for reducing emissions from rail operations, the Railroads will prioritize investments in diesel technology over natural gas. To put the technologies in perspective, during the last three years the western Class I railroads have made investments and purchase commitments exceeding \$3 billion to build and bring new clean line-haul and switch duty diesel locomotives to California and elsewhere. These locomotives meet and exceed the current EPA locomotive emission standards. From the perspective of dollars per ton of emissions reduced, infrastructure and other operational expenses associated with expanding the use of natural gas as a locomotive fuel keep it from being cost competitive with diesel technology as a means of reducing emissions.

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<sup>13</sup> For information on the size of the 2004 truck market, see <<http://www.nada.org>>.

<sup>14</sup> The BNSF Railway Co. and the Union Pacific Railroad Co.

## 2. Evaluating Natural Gas-fueled Locomotives

The following factors should be considered when evaluating natural gas-fueled locomotives.

### ***Locomotive Type***

There are significant differences between switch and line-haul locomotives. The differences include: the size and horsepower of the engine that powers the locomotive, the amount of tractive effort the locomotive produces, the duty cycle<sup>15</sup> of the locomotive, the fueling infrastructure requirements, and the range of operations. Switch locomotives spend their time in one location (such as a rail yard), whereas line-haul locomotives crisscross North America and often operate interchangeably on different rail company lines. Due to its greater power rating and higher load factor, a line-haul locomotive will burn up to ten times the fuel compared to a switch locomotive.

These differences must be taken into account during product development aimed at improving emissions performance. What is sensible for one locomotive type may not be for another. For example, spark ignited LNG-fueled locomotives are inhibited by low fuel storage capacity, range, and power density, thus making them impractical for line-haul use, but they could be potentially practical for switch duty if the locomotive can stay close to a fueling source and if high power output is less important.

### ***Locomotive Utilization***

High locomotive utilization is critical to ensure that the locomotive asset provides an adequate economic return.<sup>16</sup> To achieve this requirement, high horsepower line-haul locomotives must be interchangeable with other railroad fleets (other railroads must be able to fuel, maintain, and operate these locomotives); be highly reliable so as to minimize maintenance requirements and avoid breakdown events; and have the ability to operate over a long range to minimize refueling events. With the possible exception of switch locomotives, creating captive fleets of unique locomotives serving small geographic regions works against these requirements and will decrease locomotive asset utilization and greatly impair the economic competitiveness of the rail industry. This in turn would alter the

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<sup>15</sup> The duty cycle of the locomotive refers to the percentage of time it is operated at different power settings. Locomotives have eight power settings called “notches”. There are also settings for idling and dynamic breaking.

<sup>16</sup> As with other industries, the rail industry requires a competitive economic return on invested capital. Failing to meet this requirement will cause investment capital to exit the rail industry, resulting in the industry shrinking. Accordingly, the railroads ensure that the assets it deploys, locomotives, rights-of-way, and facilities, are utilized efficiently and productively. The challenge is compounded as the rail industry is extremely capital intensive, more so than other businesses in North America. As a rail company executive speaking to Congress explained: “American’s railroads, like all elements of our national transportation infrastructure, require massive investments for maintenance and capacity expansion. In fact, calling railroading capital intensive is an understatement. The U.S. Census Bureau calculated that railroad capital expenditures in 1999 consumed a whopping 21.7% of revenues, compared with an average of just 3.9% for all manufacturers. Railroads require invested capital of about \$2.50 to generate a dollar of revenue, compared with just 50 cents of invested capital per revenue dollar for truckers.” Matthew Ross, President and Chief Executive Officer of the BNSF, statement before the United States Senate’s Subcommittee on Surface Transportation and Merchant Marine, Washington DC, 2001.

competitive landscape within the goods movement system, drive additional cargo to heavy-duty trucks, and worsen air quality.<sup>17</sup>

The growing practice of run through trains where locomotives interchange from one company's system to another increases locomotive asset utilization.<sup>18</sup> UPRR, for example, reports that up to 12% of the locomotives operating on its system at any given time are locomotives owned by other railroad companies. This level and frequency of interchange and degree of interoperability keeps the nation's railroads operating efficiently. New engine and locomotive technology that cannot integrate into this operations paradigm will drive up costs, create emissions inefficiencies, and impair goods movement on rail.<sup>19</sup> This fact increases the importance of uniformly applied federal emission standards. The devolution of locomotive emissions standards into separate regional or state programs would most certainly lead to higher costs and program inefficiencies to the extent that they presume static and increasingly outdated assumptions about locomotive asset ownership and operational patterns.

### ***Basis and Means of Comparison***

As discussed in Section 7, current EPA locomotive exhaust emission standards and test protocols must be the reference point for evaluating the feasibility of any new or retrofit locomotive technologies, especially those using alternative fuels like natural gas. New or retrofit technologies that promise exhaust emission reductions must be compared against these diesel-based engine standards and the resulting fleet average emissions, not uncontrolled (pre-regulation) baseline or historical emissions. These are currently Tier 2 and test protocols. Until EPA adopts the Tier 3 and Tier 4 emissions standards, as expected in the beginning of 2008, the proposed standards are subject to change. This report therefore maintains Tier 2 as the benchmark for emissions comparison.<sup>20</sup> From the perspective of dollars per ton of emissions reduced, the infrastructure and other operational expenses associated with expanding the use of natural gas as a locomotive fuel are central to any cost competitive evaluation of natural gas to diesel technology as a strategy for reducing emissions. Also, EPA has promulgated test procedures for locomotive manufactures and remanufactures. To ensure an apples-to-apples comparison, all parties—the railroads, other locomotive operators or owners, and regulatory agencies—should evaluate the exhaust emissions performance of locomotives with these test procedures to validate emissions performance.

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<sup>17</sup> On a revenue ton-mile basis (the movement of one ton of goods one mile) the rail system is much more efficient than over the highway trucks from both a fuel economy and an emissions perspective.

<sup>18</sup> A run through train is a train that travels from one company's track to another without changing locomotives.

<sup>19</sup> One partial analogy is that of data traffic across the public internet computer network. On the internet communications data is broken into packets and is transmitted across the network without foreknowledge of its pathway. But because each packet adheres to a common communications protocol (i.e., it is structured with a specific sequence of 0's and 1's that can be interpreted by the network servers that push the traffic along to its destination), each packet arrives at its destination and is reassembled into a complete message. Without this common communication protocol the network would most likely be vastly less efficient. Similarly, locomotives must be interoperable across the North American rail system network, without foreknowledge of a particular destination.

<sup>20</sup> When the Tier 3 and Tier 4 standards are adopted, the railroads expect this will make LNG locomotive technologies less favorable to new clean diesel locomotives, not more.



### ***Reductions from Fuel Shift v. Mode Shift***

Care must also be taken in reviewing emission benefits for specific projects using natural gas locomotives where the benefits do not come from the fuel change, but come from switching freight to rail. For example, railroads have consistently noted the environmental benefits of replacing truck freight by rail freight. Here the appropriate comparison is the difference between two scenarios: 1) the emissions from truck freight, and 2) the emissions from carrying the same amount of freight by rail. Statements from a California consortium evaluating the use of natural gas-fueled locomotives to replace diesel-fueled trucks provides an example where this type of scenario comparison is both useful and, at the same time, potentially misleading. The consortium's website indicates that the planned conversion of four EMD SD40-2 locomotive engines to natural gas using the ECI 1SDT dual-fuel, low pressure injection conversion package result in emission reductions of 68.7 tons of NO<sub>x</sub> and 3,434 pounds of PM annually.<sup>21</sup> According to materials on file with the SCAQMD, the cause of this reduction appears to be *both* the replacement of truck freight by rail freight *and* the potential use of natural gas-fueled locomotives. A similar reduction in NO<sub>x</sub> (e.g. 68.7 tons) and greater reductions in all other criteria pollutants could be obtained by replacing the diesel trucks by Tier 2 locomotives using CARB diesel fuel. This project is discussed in further detail in Section 11.

### ***Potential Future EPA Requirements and Engine Builder Strategies***

EPA standards have established stringent emission limits for diesel engines used in highway trucks and a wide range of nonroad equipment. The latest rules for highway trucks phase in between 2007 and 2010. The latest rules for nonroad diesel engines phase in between 2008 and 2014. As part of the next step in this series of rules, EPA is developing more stringent locomotive emission standards<sup>21</sup> (Tier 3 and Tier 4) as announced in the April 2007 notice of proposed rulemaking (NPRM<sup>22</sup>). EPA has proposed Tier 3 standards effective in 2012 and Tier 4 standards effective in 2015 for PM and in 2017 for NO<sub>x</sub>. Any discussion of natural gas fueled locomotives must recognize that future diesel locomotives will have emissions lower than the present Tier 2 locomotives. EPA anticipates the Tier 4 standards will be met with diesel particulate filters and NO<sub>x</sub> selective catalytic reduction systems.

Also, given the small size of the locomotive market (approximately one diesel locomotive is sold for every 211 diesel Class 8 trucks) and given manufacturer personnel and financial constraints, it is not economical for the builders to pursue further improvements in diesel locomotive technology *and* work on natural gas-fueled locomotive development simultaneously. As shown in Figure 2, the locomotive builders sell a total of around 1,000 new locomotives to the North American market per year.<sup>23</sup>

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<sup>21</sup> Tier 2 locomotives are currently being sold. Tier 2 refers to the portion of the EPA locomotive emission standards applicable to new locomotives starting January 1, 2005. See Section 7 for a discussion of EPA standards.

<sup>22</sup> Environmental Protection Agency, "Control of Emissions of Air Pollution from New Locomotive Engines and New Marine Compression-Ignited Engines Less than 30 Liters per Cylinder," Federal Register vol. 72, number 163 (April 3, 2007)

<sup>23</sup> Average for the period 1996 through 2007 of all types.

Figure 2: North American New Locomotive Sales Volume: 1972- 2007 (est)<sup>24</sup>

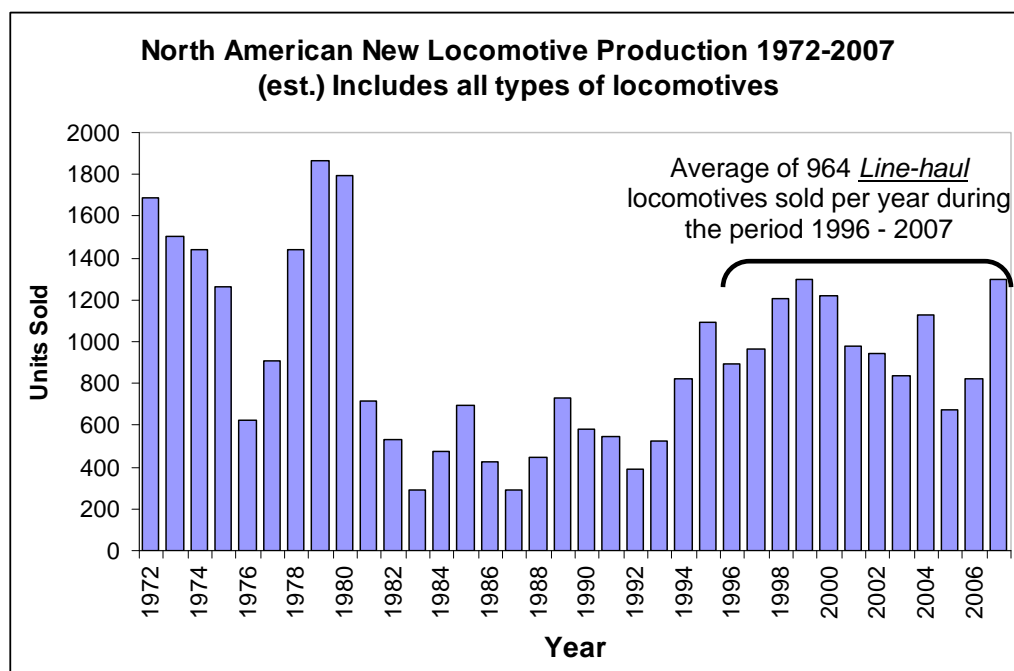


Table 2: New Locomotive Purchases by the Class I Railroads Operating in California (BNSF & UP)

	Tier 0	Tier 0/ Tier	Tier 1			Tier 2		
Year	2000	2001	2002	2003	2004	2005	2006	2007(est)
Total purchased by Class 1 Railroads in California	863	891	722	591	1121	604	562	(500)

Because of these constraints, it is important for the regulatory agencies to set overall emission performance requirements and allow the builders the flexibility to determine the most cost-effective and commercially viable way to achieve these goals.

### Other Considerations

There are numerous criteria that need to be part of any discussion about the costs, benefits, and potential feasibility of natural gas as a fuel for locomotive engines. Some of these include:

#### Emissions performance

<sup>24</sup> Data compiled from various industry reports and purchase orders.

- How does the locomotive using natural gas perform from an emissions perspective for all criteria pollutants, greenhouse gas emissions, and toxic air contaminants?
- What forms of exhaust after-treatment are required to meet emission requirements? Are these technologies available, cost-effective, durable, and “packagable”? How do they differ from exhaust after-treatment requirements for diesel engines, if applicable?

#### Cost effectiveness

- What are the cumulative life-cycle costs of the natural gas fueled locomotive (e.g. on board fuel storage, tenders, fueling facilities, energy to keep fuel liquid at lower pressures)?
- Does the cost of using natural gas take into account commodity price, processing, refining, delivery, storage, and fueling? What quality of gas is required? How does this compare to the cost of diesel fuel? What is the expected price and price volatility over the long term?
- How does risk factor in, whether financial, technical, or operational?
- If costs to deploy and use natural gas fueled locomotives are significantly higher than costs of meeting emission requirements with diesel, will these additional costs lead to modal shift?

#### Power and interoperability concerns

- Can the natural gas engine technology be packaged into the space constraints of a modern locomotive? (See Figure 3)
- Can the natural gas engine technology “scale” to meet broad operational requirements?<sup>25</sup>
- Can a locomotive with the natural gas engine match the power delivery requirements of newer diesel engine locomotives?
- Is the natural gas-fueled locomotive sufficiently reliable and durable?
- What is the fuel economy? How is this measured? How does this fuel economy compare to diesel?
- Are there fuel supply reliability considerations?

#### Applications

- Is the natural gas engine technology applicable to new locomotives, existing locomotives, or both?
- What is the expected use (e.g., switch, local service, passenger, or freight line-haul) and how does the application-specific duty cycle affect emissions?
- Are there safety-related issues associated with the natural gas engine locomotives, the fueling stations and infrastructure, or with the fuel delivery process?
- Should it demonstrate promise, what incentives and disincentives exist to maximize the potential use of natural gas?

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<sup>25</sup> Scale relates to how the technology is deployed in practice versus how it performs in limited test or demonstration modes. An example is the current method of fueling the LNG switch locomotives operating in the Los Angeles area. These locomotives are fueled by tanker trucks dispatched from an Arizona processing facility. This fueling method would not reasonably scale to meet broad operational requirements because the volume of fuel required would be too great. There could be similar issues around track and facility space requirements where scaling to meet broad operational requirements is impossible.

**Figure 3: Locomotive Size Constraints for Bridges and Tunnels Require Uniformity**



These types of considerations are key to the locomotive builders' product development strategy. Answers to these questions are necessary in order to assess whether burning natural gas in a locomotive engine is feasible and cost-effective and will yield emission benefits. Unexamined questions, incorrect answers, or incomplete information could contribute to erroneous conclusions that could place the rail industry at risk and work against creating and maintaining an efficient (from both an emissions and cost perspective) goods movement system in North America.

### 3. Initial Efforts in Evaluating Alternative Fuels by California Air Resources Board (CARB)

In 1993, CARB issued a draft contractor-developed technical report describing a range of potential locomotive emission control technologies (EF&EE Report).<sup>26</sup> Their report contains a now-dated description of the potential of natural gas to reduce emissions beyond what could be expected from applying new technology and knowledge to the conventional diesel engine. In 1994, AAR published comments responding to the initial draft of this report; much of what the AAR wrote then continues to apply today:

Any evaluation of the feasibility of LNG [liquefied natural gas] must address the Railroads' needs for high horsepower performance, fuel efficiency, and reliability.

Improved diesel technology will play a central role in meeting future locomotive emission reduction requirements. ... The Railroads believe improved diesel technology is the way to achieve large emission reductions in a short time period with a high probability of success and low cost per ton of emissions reduced.

The existence of natural gas engines in a variety of stationary and on-road applications identified [by the report authors] does not, however, mean that LNG technology: (a) can be transferred to a variety of locomotive classes operating in all types of service conditions, (b) can meet NOx and other criteria pollutant emission reduction requirements and (c) can meet the railroads' operating requirements for high horsepower, reliability, and overall fuel efficiency.

The main financial risk that the railroads must consider in the economic evaluation of LNG fuel is the future projections of the cost differential between LNG and diesel fuel. It is difficult to predict the future prices of either fuel.

Finally, many other issues need to be considered – including the full range of environmental impacts, employee and public acceptance, and operational and maintenance impacts – which are not addressed [by the report authors].<sup>27</sup>

At the time, both Atchison Topeka & Santa Fe Railway (“Santa Fe” prior to its merger with the Burlington Northern Railroad) and the UPRR were testing the Morrison-Knudsen (now MotivePower) switch locomotives employing LNG-fueled Caterpillar 3516G series spark-

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<sup>26</sup> The draft of this report was issued October 13, 1993. The final report was issued March 1995: Christopher S. Weaver and Douglas B. McGregor, “Controlling Locomotive Emissions in California. Technology, Cost-Effectiveness, and Regulatory Strategy,” Engine, Fuel and Emissions Engineering Inc. (EF&EE), Final Report prepared for CARB under contracts A032-169 and 92-817, March 1995.

<sup>27</sup> AAR, comments to CARB, 18 April 1994, pp. 4, 5, 7, 13.

ignited engines. Four of these 1,200 hp locomotives were slated for a two-year demonstration effort in Los Angeles to determine the emissions reduction potential, operational impacts, and true costs of operation and maintenance.<sup>28</sup> Equally noteworthy, the Burlington Northern was conducting field demonstrations of the Energy Conversions, Inc. (ECI) prototype locomotive conversion package for two 3,000 hp EMD SD40-2 line-haul locomotives. The AAR commented in 1994 that: “[The ECI conversion package] will take extensive field demonstrations to determine the feasibility of this NO<sub>x</sub> control technology.”<sup>29</sup>

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<sup>28</sup> Two of these locomotives have been in service for over ten years. The other two were used by the UPRR, returned to the owner in Boise for several years, and were recently returned to service as BNSF locomotives.

<sup>29</sup> AAR, comments to CARB, 18 April 1994, 7.

## 4. Methods for Using Natural Gas as a Locomotive Fuel

This section explains the basic approach to using natural gas as a locomotive fuel. The 1995 EF&EE Report correctly pointed out that there are three methods of burning natural gas in large-bore, heavy-duty engines: spark-ignited, low pressure, and high-pressure injection with diesel pilot ignition (where the fuel is ignited by compression ignition of a small quantity of diesel fuel introduced into the cylinder). The railroad programs mentioned below (see Section 5 and 8) have added a great deal of knowledge about the first two approaches. Additional and subsequent efforts by the locomotive builders, Southwest Research Institute (SwRI), and the Railroads themselves have added a good deal of knowledge about the third.

Natural gas can be either added to the intake air stream or directly injected into the combustion chamber. The spark-ignited engine generally pre-mixes the air and fuel outside the combustion chamber<sup>30</sup> resulting in a well mixed, homogeneous fuel/air mixture that is then drawn or carbureted into the cylinder and ignited with a spark plug. When the diesel engine is converted to a spark ignition engine there is a loss of rated power and thermal efficiency. Despite the high octane, a number of natural gas, spark-ignited engines require a lower compression ratio of the engine (to avoid pre-ignition of fuel) compared to compression-ignited diesel engines, and this in turn contributes to the lower efficiency. In addition, the use of a throttle to control load results in a decrease in efficiency, especially at lower loads, typical of switch engine operation. Consequently, converting a locomotive diesel engine to spark ignition only makes practical sense where: 1) the emissions benefit outweighs these detrimental efficiency and power effects and 2) these efficiency and power effects are not a significant detriment to safe, reliable, and economic routine operation (e.g. switch duty versus line-haul duty).

The other two methods of using natural gas in a diesel engine maintain diesel cycle operation using either low-pressure or high pressure (direct in cylinder) injection of the natural gas. Both methods use a pilot injection of diesel fuel to obtain compression ignition. Low pressure injection has been successfully demonstrated in in-use locomotives, but there is a loss in efficiency partly due to a need to reduce the compression ratio to prevent engine knock. High-pressure injection has been shown to enable operation with no loss of power or efficiency in laboratory engines, but has not been shown to be feasible in on-the-road locomotive demonstrations. Since it is the only system believed capable of using natural gas with no significant deterioration in power or efficiency, the high pressure injection system has been the goal of recent Railroad and other stakeholder development efforts. In fact, this approach was pursued both by GE and EMD during a UPRR-funded research effort in the mid-1990s as well as the GasRail Program, a research and development activity in the late 1990s (These efforts are described in Section 8).

There are significant differences between the low pressure and high pressure gas injection systems. The high pressure ensures good fuel-air mixing. Low pressure injection introduces the natural gas when the piston in the chamber is near the bottom of its stroke, and

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<sup>30</sup> This method is not practical for high hp, medium speed locomotive engines due to valve overlap that causes the fuel to short-circuit the combustion chamber; increasing HC emissions and leading to poor fuel consumption.

pressures are relatively low. High pressure injection entails injecting the natural gas into the compressed air when the piston is near the top of its stroke. Diesel pilot fuel is introduced in both cases near the top of the piston stroke. For either type of gas injection, the diesel fuel system can typically be used to run the locomotive; this provides a useful emergency back-up. See the ECI Dual Fuel Sourcebook for a discussion on the differences between low and high pressure injection.<sup>31</sup> The following table summarizes the primary differences between these three approaches to using natural gas as a fuel for locomotives.

**Table 3: Comparison of Methods for Using Natural Gas as a Locomotive Fuel**

Method	Convert to spark-ignition engine	Low pressure gas injection	High pressure gas injection
<b>Ignition method</b>	Gas is premixed with air and ignited by spark plug as in gasoline engines	Gas is injected at low pressure and diesel pilot fuel is used to ignite gas	Gas is injected at high pressure and diesel pilot fuel is used to ignite gas
<b>Status</b>	In use in four BNSF yard engines in Los Angeles	Method used in ECI conversion kits, demonstrated in over the road locomotives	Experimental promise, but no current over the road demonstrations
<b>Emissions</b>	Large reductions in NOx and PM, increases total HC and CO; should meet Tier 2 locomotive standards	Reduces NOx to Tier 2 levels with increases in other pollutants; does not meet Tier 2 locomotive standards	Experimental notch-8 demonstration of NOx reductions from 14.1 to 7.3 g/bhp-hr with no loss in power or efficiency. Another study reduced NOx from 12 g/bhp-hr to 3 g/bhp-hr with an 8% loss in efficiency.
<b>Problems</b>	Significant loss of rated power and efficiency	Eight percent loss in efficiency from 1991 data computed on EPA duty cycle	Experimental work limited to laboratory assessment; not capable of being demonstrated in revenue service operation

<sup>31</sup> "ECI Dual Fuel Sourcebook," Energy Conversions Inc., 2002  
<<http://www.energyconversions.com/Sourcebook.pdf>>



## 5. Railroad Interest in Alternative Fuels

As early as the 1930's, the railroad industry took an interest in gaseous fuels as a possible alternative to diesel. An example of an early effort is a locomotive on display at the Museum of Transport in Kirkwood, MO (see Figure 4). The locomotive was built in 1936 by the Plymouth Locomotive Company for the Joplin-Pittsburg Railroad in Missouri and later worked for the Kansas City Public Service Company local freight railroad in the Kansas City area. The locomotive was retired around 1980. The fuel was propane stored under the car body in three cylinders.<sup>32</sup> The power plant inside the car body is a spark ignited engine. The horsepower rating of this locomotive was nominally 450 hp.

**Figure 4: Early 1930's Experimental Propane-fueled Locomotive**



During the late 1950's and early 1960's, interest in propane amongst several railroads was considerable. Working with Southwest Research Institute (SwRI) of San Antonio, technical representatives of the Southern Pacific formed a study committee to evaluate the potential of propane for locomotive use. The study team interviewed the locomotive manufacturers to learn more about their experiences with the fuel. Furthermore, SwRI developed a laboratory program using the Institute's two-cylinder version of the EMD 567C engine. SwRI investigated fuel blends (using pilot injection) and physical modifications to the cylinder heads and fuel injection system. SwRI performed extensive evaluations using this test engine with a variety of instrumentation to monitor the engine performance. SwRI

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<sup>32</sup> Propane is also known commonly as LPG in North America. It is typically a mixture containing at least 90 percent propane, 2.5 percent butane and higher hydrocarbons, and a balance of ethane and propylene. Propane is a by-product of natural gas processing and petroleum refining. Liquid propane is stored in special tanks that keep it under pressure which varies with the temperature of the fuel. Propane is returned to a gaseous form before being burned in the engine.

concluded this effort by developing a comprehensive scope of work for follow-on development and test work.<sup>33</sup>

Another early example of alternative fuel locomotive development is the 1953 Richfield Petroleum Corporation and UPRR effort. For 9 months UPRR tested between Los Angeles and Las Vegas a GE built 4,500 hp gas-turbine-electric locomotive using liquid propane gas (LPG) fuel (see Figure 5). The test included the use of a special LPG tender car. While no significant technical hurdles were encountered during the UPRR gas-turbine test, the poor fuel economy ultimately resulted in the gas-turbine power plants being retired in favor of more-fuel efficient diesel engines.<sup>34</sup>

**Figure 5: Gas Turbine Electric (GTEL) Propane UP57 with Tender 1954**



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<sup>33</sup> On December 8, 1961 SwRI hosted a “Conference on Combustion of Propane in Railroad Diesels.” The proceedings to this conference provide useful background regarding these test and development efforts. Many of the same technical and economic considerations of importance then remain valid today.

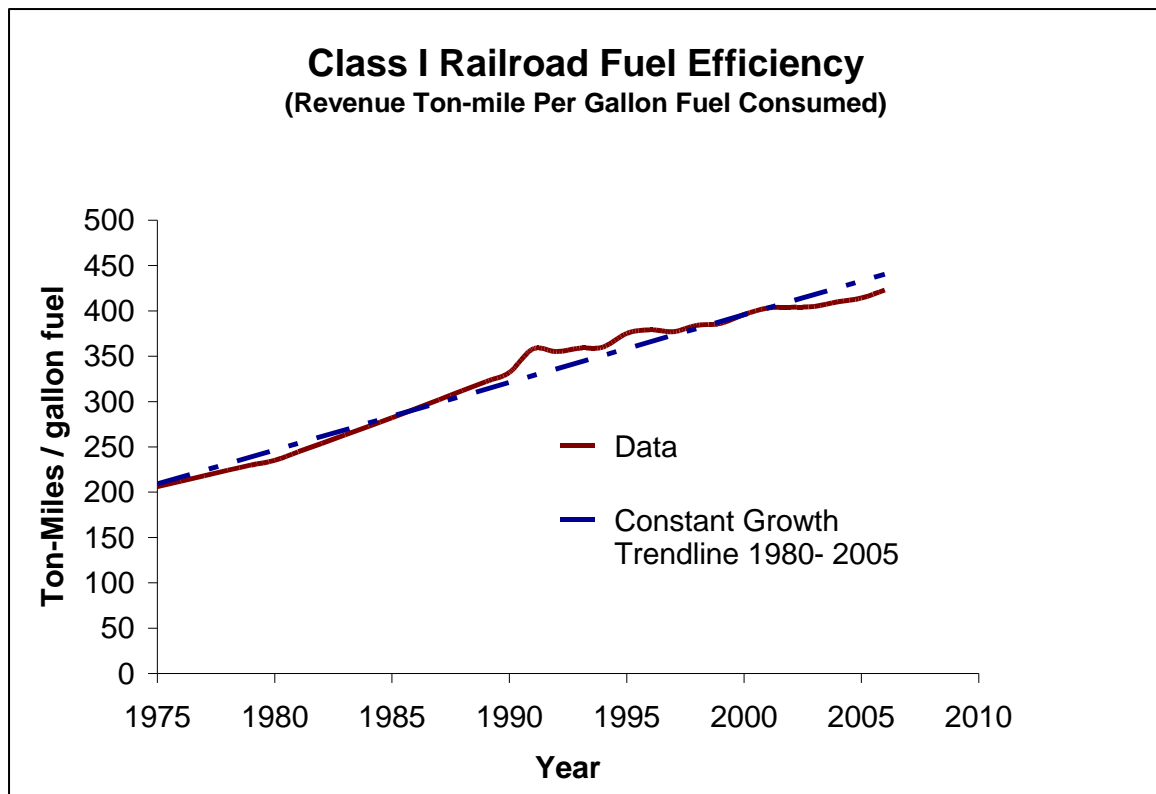
<sup>34</sup> This project tested heavy fuel oil, diesel fuel, and liquefied gases. Regardless of the fuel, this gas-turbine-electric locomotive had poor fuel efficiency compared to diesel locomotive engines.

## 6. Railroad Efficiency Improvements

While not focused on emissions performance, these early locomotive development efforts highlight the railroads' long history of partnering with the locomotive builder community in evaluating innovations in locomotive and engine design. Of particular note is the work of both the UPRR and the BNSF over the past 20 years (these efforts are discussed in Section 8). This interest is not surprising; fuel costs have been and continue to represent the second largest operating expense for the Class I railroads. In 2004, the 22,013 diesel locomotives in the combined Class I fleet consumed 4.1 billion gallons of diesel fuel at a cost of \$4.4 billion.<sup>35</sup> Based on 2002-04 fuel cost data, the Railroads estimate fuel costs exceeded \$5 billion in 2005.

The Railroads, therefore, have considerable economic incentives to reduce fuel costs; these incentives help reduce fuel use which in turn lowers air emissions from railroad operations. Similarly, these economic incentives push the rail industry towards a constant evaluation of alternatives like natural gas. Alternative fuels that can lower costs, increase efficiencies, and help achieve emission requirements are always of considerable interest.

**Figure 6: Class 1 Railroad Freight Efficiency Improvement<sup>36</sup>**



<sup>35</sup> Association of American Railroads, Railroad Facts 2005 (Washington: Association of American Railroads, 2005) 61.

<sup>36</sup> See Railroad Facts 2005. A least squares estimation technique was used for the constant growth rate shown in the figure.

As with other highly competitive industries, the Railroads constantly strive to innovate to drive fuel costs down by pursuing a wide range of efficiency and productivity improvements. There are two primary methods for improving fuel efficiency of a train. The first is to reduce the brake specific fuel consumption of the engine (e.g., get more engine power per unit of fuel) and the second is reducing train resistance (e.g., get more train movement per unit of engine power). Reducing the train resistance decreases the amount of work the engines must produce to move the train. Both components contribute to reducing overall emissions by decreasing the amount of fuel burned to move the load.

Between the passage of the Staggers Act in 1980, which deregulated certain aspects of the rail industry, and 2004, the Class I railroads have increased rail fuel efficiency by over 74%, or around 2.1% to 2.3% per year.<sup>37</sup> Figure 6 shows the energy intensity of Class I railroad freight activity as measured on the amount of goods moved (revenue ton-miles) per gallon of fuel consumed. The overall 2.1% to 2.3% yearly gains since 1980 have been impressive, but recent data show a decrease in the annual percentage of improvement. For the period 2001 to 2004, the overall improvement is 1.7% or about 0.56% per year.<sup>38</sup> Even these smaller, more recent improvements in efficiency, however, are important given the amount of fuel used and the compounded impact of yearly improvements.

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<sup>37</sup> For a comparison of revenue ton-mile per gallon fuel consumed figures for 1980 vs. 2004, see Railroad Facts 2005. The average annual growth depends on the calculation method. Using only the data for 1980 and 2004 gives the 2.3% annual improvement. Using a least squares fit to a constant percent growth rate line (as shown in Figure 4) gives the 2.1% annual growth rate.

<sup>38</sup> See Railroad Facts 2005. The 2001 and 2004 data points only show a growth rate of 0.58% per year; using all data points and a least squares analysis for a constant growth rate gives an annual growth rate of 0.54% per year. 0.56% is used above as a midpoint of these two values.

## 7. EPA Emission Standards and Certification Test Standards for Locomotive Engines

Starting in January 1998, EPA established progressively more-stringent emissions requirements for newly-manufactured and remanufactured locomotives. There are standards for four criteria pollutants: HC, CO, NO<sub>x</sub>, and PM<sup>39</sup> by duty cycle (line-haul or switch) and by “tiers.”<sup>40</sup> Effective in 2002, Tier 0 applies to locomotives with model years between 1973 and 2001 each time that their diesel engines are rebuilt. Tier 1 standards apply to locomotives newly manufactured from 2002 to 2004, and Tier 2 applies to locomotives manufactured in 2005 and beyond. Under the current proposal, when the Tier 3 and Tier 4 standards are adopted at the start of 2008, Tier 3 is scheduled to take effect in 2012 and Tier 4 PM requirements in 2015 with NO<sub>x</sub> requirements following in 2017.

Tables 4 and 6 show EPA’s locomotive engine standards for NO<sub>x</sub>, PM, CO, and HC for each duty-cycle category.<sup>41</sup> Tables 5 and 7 show EPA’s expected in-use levels (“Emission Factor”) which are lower than the standards because manufactures typically develop products that have a compliance safety margin, thus ensuring that their products will meet emission standards over the expected life of the locomotive. Finally, the pre-regulation emissions level is also shown; this is EPA’s baseline emissions level.

**Table 4: Exhaust Emission Standards for Locomotive Engines – Line-haul Duty-Cycle<sup>42</sup>**

Line-haul Duty Cycle	Emission Standard (g/bhp-hr)			
Tier	HC	CO	NO <sub>x</sub>	PM
Pre-regulation (typical)	None	None	None	None
0	1.00	5.0	9.5	0.60
1	0.55	2.2	7.4	0.45
2	0.30	1.5	5.5	0.20

<sup>39</sup> EPA regulations for diesel fuel used in nonroad engines and locomotives will begin on June 1, 2007. EPA is requiring nonroad engine and locomotive diesel fuel to contain less than 500 ppm sulfur, and to have an aromatic content of less than 35 percent. Additionally, EPA will require 15ppm sulfur diesel fuel starting in 2012.

<sup>40</sup> Smoke opacity is also regulated.

<sup>41</sup> The duty cycle for a locomotive refers to the percentage of time the locomotive is operated at different power settings. Locomotive engines have eight power settings called “notches”. There are also settings for idle and dynamic braking.

<sup>42</sup> For emission standards, see Federal Register vol. 63, number 73 (April 16, 1998) 18978, Table IV-2. For emission factors, see Environmental Protection Agency, “Locomotive Emission Standards, Regulatory Support Document” (April 1998) Table 6-1. Some HC and CO emission factors have been rounded to two significant figures.

**Table 5: Exhaust Emission Factors for Locomotive Engines – Line-haul Duty-Cycle**

Line-haul Duty Cycle	Emission Factor (g/bhp-hr)			
Tier	HC	CO	NO <sub>x</sub>	PM
Pre-regulation (typical)	0.48	1.3	13.0	0.32
0	0.48	1.3	8.6	0.32
1	0.47	1.3	6.7	0.32
2	0.26	1.3	5.0	0.16

**Table 6: Exhaust Emission Standards for Locomotive Engines – Switch Duty-Cycle<sup>43</sup>**

Switch Duty Cycle	Emission Standard (g/bhp-hr)			
Tier	HC	CO	NO <sub>x</sub>	PM
Pre-regulation (typical)	None	None	None	None
0	2.10	8.0	14.0	0.72
1	1.20	2.5	11.0	0.54
2	0.60	2.4	8.1	0.24

**Table 7: Exhaust Emission Factors for Locomotive Engines – Switch Duty-Cycle**

Switch Duty Cycle	Emission Factor (g/bhp-hr)			
Tier	HC	CO	NO <sub>x</sub>	PM
Pre-regulation (typical)	1.0	1.8	17.4	0.44
0	1.0	1.8	12.6	0.44
1	1.0	1.8	9.9	0.43
2	0.51	1.8	7.3	0.19

EPA also promulgated an alternate and optional set of CO and PM standards for locomotives which operate on alternative fuels such as natural gas.<sup>44</sup> Due to the characteristics of natural gas, EPA's alternative standards allow for a higher CO limit and a lower PM limit than the primary standards shown in Tables 4 and 6 and are intended to accommodate the challenges that natural gas-fueled locomotives will most likely have meeting CO and HC emission levels. While mainly provided to address these tradeoffs associated with alternative fuel use, manufacturers can certify any locomotive to comply with these alternative standards.<sup>45</sup> These alternative emission standards are shown in Tables 8

<sup>43</sup> See Environmental Protection Agency, "Locomotive Emission Standards, Regulatory Support Document," (April 1998) Table 6-1.

<sup>44</sup> Both sets of EPA's 1998 locomotive emission standards are fuel neutral; a diesel locomotive could theoretically be certified to the alternative standards.

<sup>45</sup> Natural gas locomotives have to meet a non-methane hydrocarbon (NMHC) standard instead of the total hydrocarbon standard met by diesel locomotives. The numerical value of all NMHC standards for natural gas locomotives are the same as the HC standards for diesel locomotives. There is another set of alternative standards, not listed here, for engines that would be fueled with methanol.

and 9. Predicted in-use levels are not included because EPA did not provide any estimates of in-use levels for alternative fuels.

**Table 8: Alternative CO and PM Exhaust Emission Standards for Locomotive Engines – Switch Duty-Cycle**<sup>46</sup>

Switch Duty Cycle (g/bhp-hr)	CO	PM
Tier 0	12.0	0.36
Tier 1	12.0	0.27
Tier 2	12.0	0.12

**Table 9: Alternative CO and PM Exhaust Emission Standards for Locomotive Engines – Line-haul Duty-Cycle**<sup>47</sup>

Line-haul Duty Cycle (g/bhp-hr)	CO	PM
Tier 0	10.0	0.30
Tier 1	10.0	0.22
Tier 2	10.0	0.10

### ***Proper Evaluation Methodology***

Only by using EPA’s test procedures, can true “apples-to-apples” comparisons be made.<sup>48</sup> EPA locomotive exhaust emission standards and test protocols should be the reference point for evaluating the feasibility of new or retrofit locomotive technologies using alternative fuels like natural gas. New or retrofit technologies that promise exhaust emission reductions should be compared against current EPA standards and the resulting fleet average emissions, not uncontrolled baseline or historical emissions.

The EPA test procedures measure fuel consumption, power, exhaust emissions, and opacity. Exhaust emissions are measured on a brake-specific mass emissions basis for HC, NO<sub>x</sub>, CO, CO<sub>2</sub>, and PM. The emissions measurements are aggregated to represent typical operations of switch and line-haul locomotives.<sup>49</sup>

<sup>46</sup> For alternate emission standards, see Federal Register vol. 63, number 73 (April 16, 1998) 18978, Table A8-5.

<sup>47</sup> See Federal Register vol. 63, number 73 (April 16, 1998) 18978, Table A8-5.

<sup>48</sup> The SCAQMD’s guidelines for the Carl Moyer program element involving locomotives supports this position: “Locomotive engine emissions must be determined following the most current and approved U.S. EPA emission testing procedures for locomotives... Model year 1973 and later locomotive projects must meet Federal Tier 1 or Tier 2 locomotive NO<sub>x</sub> standards *based on emission testing*. [Emphasis added].” See SCAMQD Carl Moyer program guidelines, Appendix 4, <<http://www.aqmd.gov/rfp/pdf/moyer-app4-locomotives.pdf>>

<sup>49</sup> See 40 CFR § 92.506. Opacity is measured by measuring the maximum opacity over a period of time.

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## 8. Later Rail Industry Research, Test, and Demonstration Efforts using Alternative Fuels

A great deal has been learned over the past 20 years about the opportunities and challenges of using natural gas to fuel large bore, highly loaded, medium speed diesel engines— the kind of engines that power large locomotives. There has also been work on the fueling system support requirements (e.g., stations and tender cars) necessary to support natural gas-fueled locomotive operations. The advances made by the locomotive builders on reducing emissions from diesel engines in response to the Tier 0, 1, 2, and (prospective) 3 and 4 engine certification standards are equally important.

Much of what the Railroads published in comments to CARB in 1994 continues to be on the mark: “Before LNG can be determined to be a feasible control option, significant technical hurdles tied to the Railroads’ need for high horsepower performance, fuel efficiency, and reliability must be addressed.”<sup>50</sup>

The following sections discuss the most notable examples of efforts to evaluate the potential use of natural gas in locomotives. Each case contributed to today’s body of knowledge about the promise and pitfalls of natural gas as a locomotive engine fuel.<sup>51</sup> They are presented in rough chronological order and include information pertinent to both switch and line-haul locomotive applications.

### ***Burlington Northern CNG Effort (1983-1987)***

In 1983, the Burlington Northern Railroad tested a modified EMD GP-9 locomotive (a 1954-era 1,750 hp switch-sized locomotive with a two-stroke, 16-cylinder 567C model engine) to run the locomotive diesel engine on CNG in a spark-ignited mode. The CNG fuel was stored in compressed gas cylinders mounted on an over-the-road truck trailer placed on a flat car coupled to the experimental GP9 locomotive. The Burlington Northern performed on-the-rail tests for two years in the upper Midwest. It concluded that the low energy density of the CNG made it impractical for wide scale railroad use because of its low range between fueling events.<sup>52</sup> No emissions data exists from this program.

This effort showed that the energy content of CNG vs. LNG vs. diesel is an important consideration in the evaluation of each fuel. Because of the differences in energy content for each fuel, locomotives utilizing these fuels will have different ranges for a given volume of fuel storage. Figure 7 compares the energy densities of each fuel and shows that for a given fuel volume the LNG-fueled locomotive will have 2.4 times the range of a CNG-fueled locomotive. Furthermore, assuming equal engine efficiencies, the diesel-fueled locomotive will have 4.3 times the range as a CNG-fueled locomotive and 1.75 times the range of the LNG-fueled locomotive for equivalent volumes of fuel storage.

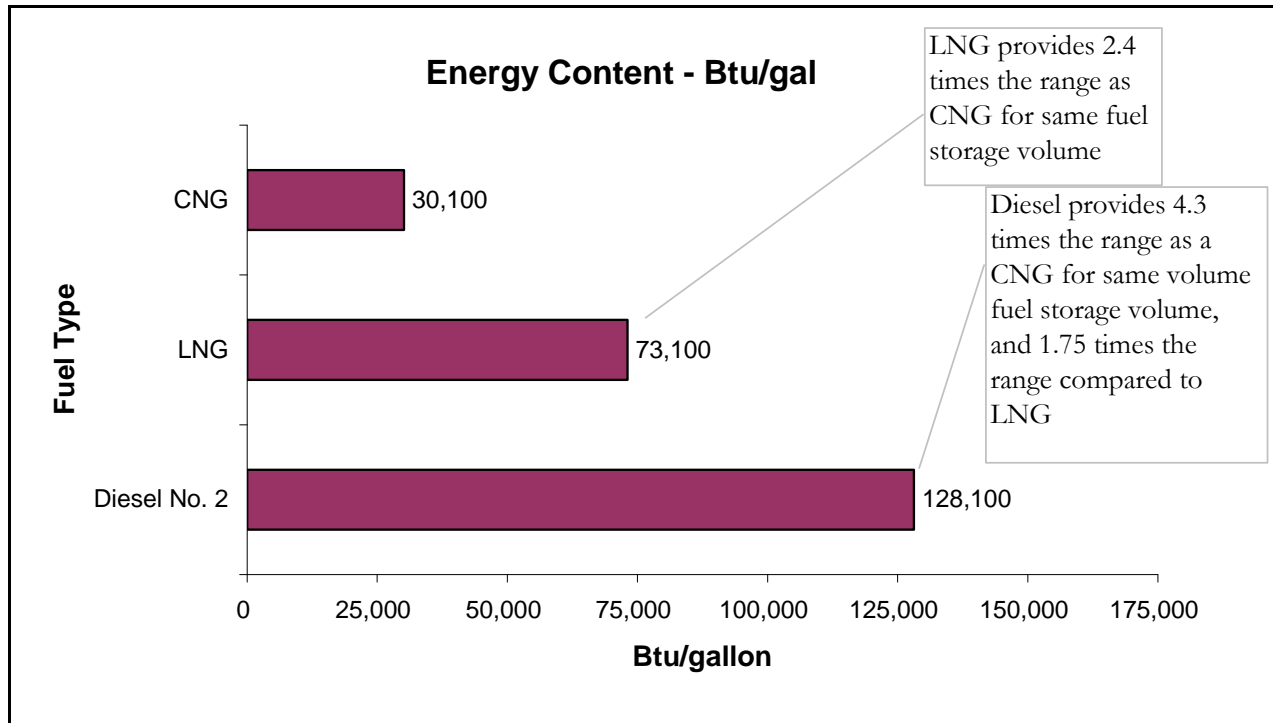
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<sup>50</sup> AAR, comments to CARB, 18 April 1994, 1.

<sup>51</sup> For a review of these efforts, see Steve Fritz, “The Potential for LNG as a Railroad Fuel in the U.S,” *ASME Journal of Gas Turbines and Power*, 122 (January 2000): 130-134. See also “Review of Natural Gas Fuelled Locomotive Technology,” *Transport Canada*, August 1999, Engine Systems Development Center, 17 January 2006 3-12, <<http://www.tc.gc.ca/tdc/publication/pdf/13400/13470e.pdf>>

<sup>52</sup> See “Burlington Northern Railroad’s Natural Gas Locomotive Project”, a paper presented at Texas’ 3<sup>rd</sup> Annual Alternative Vehicle Fuels Market Fair and Symposium, Austin, 13 April 1992.

**Figure 7: Fuel Energy Densities**<sup>53</sup>



In addition to the requirement for a new fueling infrastructure, the lower CNG or LNG energy densities would require new fueling infrastructure and operational strategies for locomotives. This includes the use of fuel tender cars and the creation of captive locomotive fleets whose operational ranges are restricted to specific geographic regions. The use of tender cars reduces the number of revenue freight cars and increases the train weight, thus increasing the cost of moving freight. Also, fuel tenders and the locomotives they supply must be kept coupled together increasing equipment asset utilization and difficulties. An LNG locomotive consist (i.e. several locomotives coupled and controlled as a unit) would require one to two LNG tenders at approximately \$1 million each.

### **SwRI Two Cylinder Research Engine Test (1986)**

In a 1986 project for the U.S. Department of Energy, SwRI modified a two cylinder EMD test engine to operate in a dual fuel mode using LNG as the primary fuel (99%) and diesel fuel for pilot ignition (1%). SwRI's approach utilized a high pressure, late cycle gas injection system where the gaseous fuel was injected into the cylinder along with the pilot ignition diesel fuel near the top of the piston stroke when the chamber air is compressed and highly heated.<sup>54</sup> SwRI performed exhaust emissions tests and concluded that further development was needed for several reasons. Operation of the engine in dual-fuel mode was limited to notch three and above due to limitations in the fueling system. Also, the exhaust emissions

<sup>53</sup> Energy densities are taken from Christopher S. Weaver and Douglas B. McGregor, *op. cit.*, Page 106, Table 32.

<sup>54</sup> There are significant differences between the low pressure and high pressure gas injection systems. The high pressure ensures good fuel-air mixing. See Section 4.

tests showed excessive smoke, PM, and CO emissions, all of which indicated over-fueling and incomplete combustion. The test engine was not installed in a locomotive.

According to SwRI, the program demonstrated that the direct injection high pressure LNG approach could match performance levels of unmodified low power roots-blown (i.e., non-turbocharged) EMD diesel locomotive engines with a slight loss of efficiency. Exhaust emissions tests, however, showed that fuel delivery systems needed further development.<sup>55</sup>

### ***Burlington Northern Effort with ECI and Air Products (1987 - 1992)***

In 1987, the Burlington Northern Railroad began a two pronged effort to develop natural gas fueling infrastructure and line-haul locomotives capable of running on natural gas. For the fueling infrastructure, the Burlington Northern worked with Air Products and Chemicals to develop fueling locations and cryogenic tank tender rail cars to support the use of Refrigerated Liquid Methane (RLM), a high purity form of liquefied natural gas, as a locomotive fuel.<sup>56</sup> A fueling station was constructed in Staples, MN. A cryogenic tank was designed, parts of it extensively tested, and two 25,000 gallon RLM tender cars were manufactured.

For the locomotives, the Burlington Northern Railroad and Air Products and Chemicals worked with ECI to convert two 3,000 hp EMD SD40-2 locomotives (engine model 16-645E3B) to run in a dual fuel mode.<sup>57</sup> This engine conversion kit utilized a low pressure gas injection system which provided compression ignition of the fuel using diesel fuel as the pilot ignition source. For some engine conditions – start, idle, and low notch settings – the locomotive operated exclusively on diesel fuel. The locomotive could also operate in a 100% diesel mode in all notches if required. For natural gas fuel delivery, the RLM passed through a vaporizer on the tender car and was piped to the locomotive and injected into the cylinder as gaseous methane under relatively low pressures (85-125 psi).

In 1987, the EMD SD-40 locomotive was the most common line-haul locomotive in operation. The Burlington Northern eventually converted two EMD SD40-2 locomotives with the ECI conversion retrofit package. In 1991, the Burlington Northern contracted with SwRI to perform an exhaust emissions test on one of the locomotives.<sup>58</sup> These emission results are discussed in Section 11 where they are compared to emissions from current Tier 2 line-haul locomotives.

This ECI EMD 16-645E3B engine and locomotive conversion kit is commercially available today and in 2004 was proposed for line-haul locomotive demonstration by a small trucking company in southern California. The kit is similar to the one used by the Burlington Northern to convert the two SD40-2 locomotives in 1990-91 and consists of five

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<sup>55</sup> Wakenell, *et al.*, “High Pressure Late Cycle Direct Injection of Natural Gas in a Rail Medium Speed Diesel Engine,” SAE Paper #872041, 1987.

<sup>56</sup> RLM is a trademark of Air Products and is a high purity form of natural gas that strips out many of the constituents of natural gas like butane, propane, and nitrogen leaving mostly methane.

<sup>57</sup> ECI is a small, reputable, privately held company that develops retrofit kits to modify diesel engines to run in a dual fuel mode. Its kits can be applied to stationary applications like power generation, drilling platforms, as well as mobile applications like marine vessels.

<sup>58</sup> See Steve Fritz, “Exhaust Emissions from a Dual-fuel Locomotive,” Southwest Research Institute, Report 4602, March 1992.

components: modified pistons and cylinder heads, diesel pilot fuel control system, natural gas inlet valves and an engine electronic control unit. An ECI representative indicates that the kit has been upgraded from the version used in 1991. No EPA emissions test data are available for a locomotive using this upgraded kit and it is unclear how the upgrade will affect fuel economy and emissions.<sup>59</sup>

### ***Burlington Northern Operations with Natural Gas-fueled Locomotives (1992-1995)***

In 1992 the Burlington Northern placed the two ECI-converted SD40-2 dual fuel locomotives in revenue service on a coal train operating in the Midwest. The two locomotives operated as a pair and were fueled using a specially-designed-and-manufactured LNG tender car that supplied the liquefied methane to each locomotive placed on either side of the tender car. These locomotives operated between Montana coal fields and an electric power plant in Superior, Wisconsin, a roundtrip of 1,700 miles. A single RLM fueling facility was constructed in Staples, Minnesota.<sup>60</sup> The Burlington Northern ran the program until 1995 when the Burlington Northern and the Santa Fe railroad companies merged to become BNSF Railway Company. The Burlington Northern gained a good deal of experience on the fueling infrastructure and safety issues associated with using natural gas, but after approximately three years of operation the Burlington Northern concluded that there was little more to be learned by continuing to run the locomotives. The program was discontinued in 1995. The locomotives were converted back to standard diesel configuration and were returned to general revenue service.

**Figure 8: BN7890—EMD SD-40-2 Converted to Dual Fuel Using the ECI Conversion Kit**



<sup>59</sup> Paul Jensen (ECI), personal communication with Andrew Trump, October 2005.

<sup>60</sup> The locomotives were in effect “tethered” to a geographic scope of operations in proximity to the fueling facility.

### ***MK Rail LNG Switch Locomotives (1993 - present)***

In 1993, MK Rail Corporation (now known as MotivePower Industries, a Wabtec Company) introduced a 1,200 hp (tractive) LNG fueled switch locomotive that utilizes a Caterpillar 3516G spark ignited natural gas engine. The engine used in this locomotive is found in many stationary power generation applications. The fuel tank for the LNG is incorporated underneath the locomotive, alleviating the need for a separate fuel tender car. The BNSF and the UPRR each operated two of these locomotives. The UPRR ended its participation in the program in 1998 due in part to the high costs incurred by the fuel supplier and poor locomotive reliability. The two UPRR-leased locomotives were returned to the owner (the leasing company), while the BNSF continued to operate their two locomotives in daily revenue service. Today, the BNSF leases and operates all four of the LNG switch locomotives in the Los Angeles area – their two original locomotives and the two former UPRR locomotives. The high purity LNG (very high methane content) is delivered to the BNSF from a fuel supplier in Arizona by truck and the locomotives are fueled directly from a truck beside the locomotive.

MK Rail used steady state emissions data from this engine to estimate notch results for the LNG locomotive. These estimates were used to compute the brake-specific emissions, shown in the table below, for the EPA switch duty cycle.<sup>61</sup>

**Table 10: Emission Results for MK LNG Switch Locomotive (g/bhp-hr)**

HC	CO	NO <sub>x</sub>	PM
3.3 <sup>62</sup>	2.2	1.4	0.09

The CO, NO<sub>x</sub>, and PM emissions data meet or exceed the alternative locomotive emission standards for Tier 2 locomotives. Although it is not clear if the HC data are THC or NMHC, the data are thought to be THC and the NMHC figure is likely to be less than the EPA Tier 2 standard of 0.60 g/bhp-hr.

The conversion of the Caterpillar 3516 engine from a diesel engine to a spark-ignited LNG engine reduces the maximum brake power from 2,000 hp to 1,350 hp, a 33% reduction.<sup>63</sup> The derating is done to prevent pre-ignition detonation, or “knocking”, of the gaseous fuel. The thermal efficiency of the Caterpillar 3516 LNG engine on the EPA yard duty cycle is 22.3%. A typical diesel switch locomotive using the EMD 645E engine, for example, has a thermal efficiency of 29.5%.<sup>64</sup> Thus, the LNG locomotive requires almost 1/3 more fuel energy than a typical diesel switch locomotive to produce the same amount of useful work.

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<sup>61</sup> Data obtained from Mark Stehly of BNSF. At the time these locomotives were put into service the EPA emissions test protocol did not exist.

<sup>62</sup> There is some confusion in that this number is reported in one sources as HC and in another as NMHC, however, it is most likely HC.

<sup>63</sup> The locomotive is rated at 1,200 tractive hp on natural gas.

<sup>64</sup> Computed from data supporting the Regulatory Support Document for the EPA locomotive rule, assuming a lower heating value of 18,250 Btu/lb. See Environmental Protection Agency, “Locomotive Emission Standards, Regulatory Support Document,” (April 1998). The data for the 645E engine are not in the RSD itself, but come from a Lotus spreadsheet available on the EPA web site as <http://www.epa.gov/otaq/regs/nonroad/locomotv/frm/locorsd.wk3>.

These locomotives will have to meet EPA Tier 0 requirements when they are remanufactured, but the available emissions data indicates that the locomotives already meet Tier 0, 1, and 2 levels except for HC emissions, for which the data are uncertain. If the HC data of 3.33 g/bhp-hr represent THC as expected, the NMHC emissions are likely to be about 0.5 g/bhp-hr. This would meet the Tier 2 NMHC standard of 0.60 g/bhp-hr for natural gas locomotives. The expected value of NMHC emissions for this locomotive will almost certainly be below the Tier 0 requirement of 2.60 g/bhp-hr for natural gas fuel. Also, while MotivePower Industries has not sold any more of these LNG locomotives it has indicated a willingness to do so if an order is placed. Any new locomotives would fall under EPA's Tier 2 exhaust emission requirements.

**Figure 9: MK Rail LNG Switch Locomotive Operated by BNSF in the LA Area**



### ***UPRR R&D Program with Engine Builders (1992-1995)***

In 1992 the UPRR began separate research and development programs with EMD and GE Transportation Systems (GE) to investigate the use of natural gas in line-haul, high-horsepower locomotive engines. This was a significant, multi-year effort. By the time these programs ended in 1995, the UPRR had expended \$15 million (and the locomotive builders had incurred their own undisclosed expenses) exploring basic engine and fueling technology issues. The UPRR-funded EMD effort was aimed at modifying two new EMD SD60M locomotives (3,800 hp rating) to run in a dual fuel or a diesel only mode. The UPRR-funded GE program was aimed at modifying two new Dash-8 locomotives (4,100 hp rating) similarly in dual-fuel or diesel-only mode. In both programs a late cycle high pressure (> 3,000 psi) natural gas injection, dual-fuel, compression ignition approach was pursued.

While the aim of each program was to deliver demonstration locomotives that would enable on-the-rail evaluations, neither effort succeeded past basic engine and locomotive fuel system development. Experimental locomotives operated at the EMD facility at LaGrange,



IL and the GE facility at Erie, PA, but due to technical limitations, these locomotives were incapable of revenue operation outside of the builder's facilities. In fact, GE was only able to demonstrate approximately five continuous hours of operation in the LNG mode while stationary at the factory. Figure 10 shows the GE test locomotive.

**Figure 10: UP9555 LNG C41-8W & tender at GE-Erie 1994**



The technical difficulties in both programs included failure of gas injectors, cryogenic LNG pumps for handling the cryogenic fuel between the tender tanks and the locomotives, the engine control system software, the gas transition control system software, and fuel system joint leaks. All four locomotives were converted back to diesel-only operation and ultimately delivered to UPRR for general revenue service in 1995.

In 1994, GE published a technical paper on the test engine it developed for this project, which it called the “H-process” engine.<sup>65</sup> The paper presented data only for full power (Notch 8) operation. The table below shows results from the paper; the units have been converted so that comparisons can be made.

**Table 11: Performance of GE “H-Process” LNG Test Engine**

Fuel	Power (hp)	Efficiency	NO <sub>x</sub> (g/hp-hr)	HC <sup>66</sup> (g/hp-hr)
LNG	4,141	42.15%	7.3	1.16
Diesel	4,112	42.65%	14.1	0.34

<sup>65</sup> B. D. Hsu, G. L. Confer, and R. E. McDowell, “The H-Process Dual-Fuel Diesel Engine,” Natural Gas and Alternative Fuels for Diesel Engines, ASME ICE-24, 25-30, 1994.

<sup>66</sup> HC stands for total hydrocarbon. Caution is needed to avoid comparing NMHC and HC values.

Operating on LNG (with 4.6% of the total fuel coming from the diesel pilot fuel) the experimental locomotive engine had a slightly higher power output and a slightly lower efficiency than an unmodified diesel locomotive engine. In the conclusions to the paper the authors stated the efficiencies of the two fuels were “basically the same.”

This paper further indicated (erroneously) that GE was successful in developing a dual fuel natural gas diesel engine and:

Two units of this engine are currently used on GE locomotives in a field test at a major U.S. railroad. These locomotives use liquefied natural gas. These locomotives can be changed to run from pure diesel to mostly natural gas even while the engine is in operation.<sup>67</sup>

Such operation never occurred; the 1994 GE paper contained an incorrect statement that the engines were undergoing a field test. In fact, prior to publication of GE’s 1994 paper, UPRR requested that GE issue a memo to UPRR to ensure that a proper record was established regarding the outcome of this important UPRR-funded effort. This error was eventually explicitly acknowledged in a 2003 email from GE to UPRR which is attached to this report as Appendix 2. This 2003 email memo notes that the dual-fuel engine had “several significant component durability issues that would make over the road testing impractical if not impossible.” In fact, there were durability problems with the high pressure gas injector and the engine could be only continuously run using LNG for a maximum of five hours. The 2003 email memo also noted that “durability issues were not known and significant time and resources would have to be invested to attempt to find solutions.” Because of these problems “GE and UP mutually agreed to suspend testing.”<sup>68</sup>

### ***GasRail Initiative (1993-1998)***

In 1993 a multi-year, multi-party research effort was started known as GasRail USA. Participants in this program include the US Department of Energy, SwRI, the SCAQMD (South Coast Air Quality Management District), the Southern California Regional Rail Authority, the Southern California Gas Company, the Gas Research Institute, Amoco Petroleum Products, CARB, EMD, and UPRR. The focus of the GasRail initiative was the development of a gas fueled EMD locomotive suitable for commuter rail service. The program participants designed, tested, and evaluated six different LNG engine combustion systems and selected the “LaCHIP” design (Late Cycle High Injection Pressure). This project took advantage of the knowledge gained by the UPRR research and development effort with EMD and GE described earlier. In fact, SwRI ultimately recommended a high pressure fuel injection system very similar in concept to that selected by UPRR as part of its earlier efforts, SwRI considered the “LaCHIP” design to have the highest chance of meeting both NO<sub>x</sub> reduction and engine efficiency goals without derating engine power. The goal was to equip a Metrolink F59PH locomotive with this natural gas system. The LNG equipment and fuel storage tank was planned to be installed in a baggage car semi-permanently coupled to the locomotive.

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<sup>67</sup> See “The H-Process Dual-Fuel Diesel Engine.”

<sup>68</sup> Dave Ducharme (GE), “Clarification on results of UP/GE Dual Fuel Diesel Engine Project,” memo to Mike Iden (UPRR), 19 November, 2003. See Appendix 2.



Development testing at SwRI started on a single-cylinder EMD 1-710 research engine, then progressed to an EMD 16-710G3 test cell engine normally rated at 4,000 hp using diesel fuel. The ultimate objective was to install this system in a 3,000 hp EMD F59-PHI passenger locomotive by converting its 12 cylinder 710G3 engine, along with the required fuel storage and handling systems.

The program ended in 1998 in part due to the lack of support from EMD, the principal locomotive builder participating in the program.<sup>69</sup> At that time the SwRI engineers were working on “integration engineering phase of the prototype”<sup>70</sup> engine, with numerous tasks required before installation into the locomotive car body. The installation of this experimental engine was not completed nor was the engine operated in an actual over-the-road locomotive. According to a SwRI representative, however, some of the participating parties, including the SCAQMD, believe there remains promise with this locomotive engine design and want to gather additional funding in order to continue the development effort.<sup>71</sup>

SwRI reports that the EMD 16-710G3 test engine that was developed for the GasRail project was able to produce 3 g/bhp-hr NO<sub>x</sub> when evaluated over the EPA line-haul duty cycle, compared to a 12 g/bhp-hr NO<sub>x</sub> level for the same engine operating on diesel fuel. Furthermore, SwRI reports that this NO<sub>x</sub> level was demonstrated in the test engine without any changes to the after coolers, turbocharger or piston but there was an 8% reduction in efficiency.<sup>72</sup> SwRI believes that the GasRail program demonstrated that natural gas has the potential to be used in line-haul applications, but also notes that infrastructure, durability, and life cycle costs are all unknown.<sup>73</sup>

### ***Southern California LNG Line-haul Locomotive Project (2004)***

A group of companies worked together starting in 2004 to convert a 1970-era in-use EMD locomotive with the LNG retrofit "kit" from ECI discussed above with the goal of sponsoring the operation of an intermodal train between the Port of Los Angeles and a proposed intermodal terminal in Lancaster, CA. The venture is known as Clean Air Partners Transportation Systems, Inc. (CAPTS). At the center of this initiative is Hunter & Hunter Trucking, Inc., a Riverside County based trucking company with experience using LNG-fueled heavy duty trucks. ECI would provide the locomotive conversion equipment. While MotivePower was described as the company to perform the locomotive conversions in the 2004 Moyer application, they subsequently opted out of this portion of the project,<sup>74</sup> and a replacement company to perform the shop work to convert the locomotives has not been identified.<sup>75</sup>

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<sup>69</sup> John Hendrick (SwRI), personal communication with Andrew Trump, September 2005.

<sup>70</sup> Steve Fritz, “The Potential for LNG as a Railroad Fuel in the U.S,” *ASME Journal of Gas Turbines and Power*, 122 (January 2000): 130-134.

<sup>71</sup> EMD owns the hardware right to the gas injectors developed during the GasRail Program, therefore, EMD’s would have to support of any continuation of this project.

<sup>72</sup> John Hendrick, email to Andy Trump, 10 January 2006.

<sup>73</sup> John Hendrick and Steve Fritz (SwRI), written comments to Railroads, September 2005.

<sup>74</sup> Carl Moyer Memorial Air Quality Standards Attainment Program, Response to Request for Proposal, CAPTS, October 2004.

<sup>75</sup> Paul Jensen (ECI), personal communication with Andrew Trump, 24 October 2005.

CAPTS received public funding from CARB's Carl Moyer program in 2004. The funding would have enabled the retrofitting of one EMD SD40-2 locomotive equipped with the EMD 645E3B engine to dual fuel operation using the ECI conversion kit at a cost of approximately \$1,719,265.

The model SD40-2 locomotive planned for this program was a six axle locomotive with an EMD 16-645E3 engine rated at 3,600 hp produced during the 1968-74 era. The CAPTS program required four SD40-2 locomotive engine conversions to support the planned operation.<sup>76</sup> CAPTS planed for the locomotives to make one round trip per day from the Port of Los Angeles to Lancaster, California operating over (presumably) UPRR and Metrolink track and (presumably) utilizing UPRR train crews, fueling at an LNG fueling station to be located in Lancaster. The fueling infrastructure – one location in Lancaster would have restricted the potential operating range of these locomotives.

In addition to initial Carl Moyer funding, \$100,000 in grant money was provided by EPA's Pacific Southwest Office. Carl Moyer program materials indicate \$400,000 was required to purchase the used locomotive, \$275,000 for the ECI conversion kit, \$1.0 million for the conversion labor, \$300,000 for the dual fuel tank system installation, and \$160,000 for sales tax on the locomotive and the parts.<sup>77</sup> The project required an additional \$430,700.<sup>78</sup> Unfortunately, CAPTS lost momentum and interest due to the remaining funding gap. The public funding has since been returned to the appropriate entities, and the project is on hold.<sup>79</sup>

BNSF and UPRR believe the commercialization and availability of the ECI engine technology has added a good deal of knowledge about the potential benefits and feasibility of using natural gas to fuel locomotives. Also, the Railroads believe that to the extent this program could have demonstrated reduced truck trips it may also have demonstrated associated air quality benefits.

Other important questions that should be considered for this and other similar projects in the future include:

- How reliable are the locomotives? For example, should the locomotives experience an in-route break down, diesel locomotives will have to be dispatched to help complete the train movement and bring the non-functioning locomotive to a repair shop. This would impact emissions.
- Where will the locomotives be maintained and by whom?<sup>80</sup>

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<sup>76</sup> See CAPTS <<http://www.captsrail.com/lng.html>>.

<sup>77</sup> Carl Moyer Memorial Air Quality Standards Attainment Program, Response to Request for Proposal, CAPTS, October 2004.

<sup>78</sup> For July and September 2005 meeting notes describing the CAPTS program, see West Coast Collaborative, 30 November 2005 <<http://westcoastcollaborative.org/about.htm>>.

<sup>79</sup> Personal Communication between Henry Hogo and Peter Okurowski October 2007.

<sup>80</sup> Section F of the Carl Moyer application materials provide a brief, one paragraph description of maintenance plans. "Basic maintenance on the locomotives will be performed by Hunter & Hunter mechanics. Hunter & Hunter will, however, contract with Motive Power for the routine maintenance of the four LNG locomotives. If necessary, Power System Associates (located approx. ½ mile from Hunter & Hunter) can assist in the emergency maintenance of these units if and when a Motive Power crew is not immediately available."

- Where will the locomotives be inspected for Federal Railroad Administration safety inspections?
- What company will provide the train crews?
- Over whose tracks will the locomotives operate?
- Will these locomotives and the revenue service contribute towards the upkeep of the rail infrastructure?
- How will safety issues be addressed in the event of a derailment?

Answers to these questions and others go to the heart of understanding the Railroads' arguments about the critical importance of maintaining locomotive interoperability throughout the North American rail network system. While a technology may be effective in a pilot program or small scale, it must be able to be "scaled up" to operate seamlessly within the existing national rail system to maintain operating efficiencies. The Class I railroad companies cannot be competitive operating small fleets of locomotives that are captive to specific regions.

The CAPTS web site indicates that the program would have reduced NOx and PM by 68.7 and 1.72 tons per year, respectively. Other sources state different emissions benefits.<sup>81</sup> To evaluate these claims, the exhaust measurement data developed by SwRI for the BN conversion is presented in this report in Sections 10 and 11 and is compared to new Tier 2 diesel locomotives that meet EPA's current exhaust emission standards for locomotives. Once ready for operations, the locomotives should be tested for exhaust emissions using the EPA locomotive certification test protocol and the results should be documented for Carl Moyer program evaluation. Only by using this approved test protocol can the results from this demonstration program be compared to the documented emissions performance of other locomotive propulsion systems. Also, any documented emissions benefits should be segregated to indicate the portion of the reductions attributable to removing trucks from the highways.

### ***ECI Conversion Kit for the EMD 645 Engine (2006)***

ECI markets a locomotive conversion retrofit kit for the EMD 645 two-stroke diesel engine to run on LNG and diesel fuel, using a low pressure (85-125 psi), pilot compression ignition approach. With the ECI system, the LNG fuel is vaporized and injected as a gaseous fuel; the fuel and air mix during compression. A small portion of diesel "pilot" fuel is then injected into the cylinder at the top of the stroke to facilitate combustion. The locomotive engine can also operate in a 100% diesel mode, if needed.

The ECI locomotives conversion kit includes ECI's patented electronically controlled gas injectors, specially designed pistons and cylinder heads, electronic engine control and monitoring system, supplementary diesel control hardware, Low Emission Idle (ECI's patented bank idling system), and supplementary after cooling hardware. This kit was used by the Burlington Northern in its 1992-95 demonstration program; an ECI representative, however, emphasizes that the product used at that time was not optimized for emissions and

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<sup>81</sup> For August 2005 project description material, see West Coast Collaborative, <<http://westcoastcollaborative.org/about.htm>>. "Use of the LNG locomotive will significantly reduce emissions compared to the use of a conventional diesel locomotive. Specifically, the project will result in reductions of: 17.2 tons of nitrogen oxides (NOx) per year; and 0.43 tons of particulate matter (PM) per year".

today's product has been modified from its earlier version in ways that will improve exhaust emissions performance.<sup>82</sup>

Exhaust measurement data was collected by SwRI in 1991 on one of the two BN (Burlington Northern Railroad) SD40-2 conversions utilizing the ECI kit. The 1991 emission measurements are presented in Sections 10 and 11 and are compared with results from EPA certification test results for Tier 2 locomotives. This analysis shows that the new diesel locomotives outperform the 1991 version of the ECI natural-gas-fueled locomotive from an emissions perspective.<sup>83</sup> EPA's Tier 3 standards will expand the advantage of new diesel locomotives.<sup>84</sup> In fairness, ECI does not claim that its retrofit product will outperform the newest diesel locomotives. Its web site states: "ECI systems in both 100% diesel and dual-fuel options are proven to provide the necessary emissions to meet or beat EPA Tier 0 locomotive emissions standards."<sup>85</sup>

### ***Other Efforts Using ECI Products***

The Napa Valley Railroad in northern California contracted with ECI to convert a retired passenger locomotive with the EMD ECI gas conversion kit. This locomotive was converted in 2002 in part with Carl Moyer program funds. The original 1950s-era ALCO diesel engine has been replaced with a 1970s-era EMD diesel non-turbo charged engine converted to use CNG fuel using a pre-mixed air charge, a pre-chamber, and spark ignition. It runs on 100% natural gas. This CNG-fueled locomotive makes several low speed 56-mile round trips per week hauling a dinner train consisting of several passenger cars. Exhaust measurement tests have not been performed on the locomotive and therefore the exhaust emissions performance of the locomotive is unknown.<sup>86</sup>

ECI also reports that it has completed a GE diesel CNG engine conversion project for a mountain railroad in Peru owned and operated by Ferrocarril Central Andino and US-based Railroad Development Corporation. This project converted GE 7FDL 16 cylinder, 4 stroke, 6 axle locomotives (each with dedicated CNG tender cars). With the ECI conversion, the locomotives can operate in a compression ignition mode on both diesel and dual-fuel mode

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<sup>82</sup> Paul Jensen (ECI), personal communication with Andrew Trump, 24 October 2005. Jensen indicates that cylinder liners, lube oil rings and the engine management control system are improved from the 1991-92 vintage product supplied to the BN. Jensen also indicates that a different lube oil specification would be recommended. See also Energy Conversions Inc. <<http://www.energyconversions.com/loco2.htm>>. The website states: "Emission numbers were derived from tests conducted by SwRI in 1990-91. ECI has since optimized certain components (i.e., gas injectors, etc.) to enhance system performance. Recent test data from our facilities confirm further performance and emissions improvements, but have yet to be verified by a certified standards laboratory and thus is not publishable at this time."

<sup>83</sup> The Railroads explain this claim in Sections 10 and 11 in detail. This claim is based on superior (lower) emissions on PM, CO, and HC, and rough parity on NOx.

<sup>84</sup> Another challenge is the potential for the natural gas-fueled retrofit locomotive to reduce particulate in the EMD two stroke engines. Much of the particulate that is emitted from the 2-stroke EMD engine is due to the incomplete combustion of lubricating oil in the cylinder. Converting the engine to use natural gas may not affect significantly this engine characteristic.

<sup>85</sup> ECI website on LNG locomotives, Retrieved May 1, 2007 from <http://www.energyconversions.com/locoemis.htm>

<sup>86</sup> Paul Jensen (ECI), personal communication with Andrew Trump, 24 October 2005. The railroads believe that if Carl Moyer program funds were used for this program emissions benefit estimations should have been developed to support and justify funding. At the time of this writing, however, the Railroads did not have access to this information.

with natural gas, depending upon power requirements. ECI reports that even at high elevations, in this case up to 16,000 feet, the converted locomotives can deliver full power by running exclusively on diesel fuel. The railroad has 37 diesel locomotives, 34 GE and 3 EMD, and has plans to convert additional locomotives according to an ECI representative. Given the high comparative cost of diesel fuel in Peru, the payback of the conversion is estimated at one year.<sup>87</sup> An ECI representative reports that this program is mostly focused on fuel savings and the technical conversion is mostly suited to switch and short haul operations.<sup>88</sup> The Railroads do not know any information about the exhaust emissions data for this conversion.

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<sup>87</sup> Paul Jensen (ECI), personal communication with Andrew Trump, 24 October 2005. The Railroads believe that the payback in this instance is not illustrative of the payback in North America because the price differentials between the fuels is much different in Peru than in North America. Peru is a net exporter of natural gas and an importer of diesel fuel.

<sup>88</sup> For a description of the presentation of Scott Jenkins (ECI), see “Locomotives and Rail Workgroup: July 19, 2005 Teleconference Meeting Summary,” West Coast Collaborative, July 19, 2005  
<<http://westcoastcollaborative.org/wkgrp-loco-archive.htm>>

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## 9. Recent Innovations & Investment

The recent significant locomotive product innovation in the North American market will fundamentally change the “hurdle” for commercial feasibility of natural gas-fueled locomotives in either switch or line-haul duty. The most important examples are discussed in this section.

### ***EPA Certified Tier 2 Line-haul Locomotives***

Starting in 2005, both EMD and GE began offering EPA-certified line-haul locomotives meeting EPA’s Tier 2 exhaust emissions requirements. These locomotives are electronically fuel injected and equipped with idle reduction technology. Certification test exhaust measurement results are presented in Section 11. In 2005, the Class I freight railroads took delivery of 115 EMD model SD70ACe locomotives (shown in Figure 11 below), 201 GE model C45ACCTE, 93 GE ES44AC, and 195 GE 44DC locomotives. All of which are rated at 4,400 hp except for the EMD SD70ACe which is rated at 4,300 hp. In 2006, the Railroads took delivery of an additional 562 Tier 2 locomotives. For 2007 the Railroads plan to order around 500 Tier 2 locomotives.

**Figure 11: EMD SD70ACe Tier 2 Line-haul Locomotive**



### ***GE Diesel-battery Road Hybrid Locomotive***

GE is developing a prototype diesel-battery road hybrid locomotive. In 2003, GE developed and tested an early engineering prototype of a line-haul battery-hybrid. It used a large capacity battery which captures regenerative energy as the locomotive descends mountain grades in dynamic braking. The locomotive delivers 4,400 hp from the diesel engine and can store up to the equivalent of 2,000 hp for 30 minutes in the batteries. The hybrid road locomotive is designed to capture electrical energy produced during dynamic braking, energy which is otherwise dissipated to the atmosphere as waste heat. Currently, this locomotive is under internal evaluation by GE to reconfigure the locomotive and determine its commercial

potential. While the 2003 trial demonstrated this technology works in concept, the configuration of the experimental locomotive was not practical as the batteries filled one entire side of the locomotive making half of the diesel engine inaccessible for maintenance. Several railroads, including BNSF and UPRR, regularly review GE's efforts.<sup>89</sup>

GE has assembled an experimental proof of concept road hybrid test locomotive, using a highly modified ES44AC locomotive equipped with regenerative batteries and related equipment. Preliminary testing at GE's Erie Pennsylvania facility occurred in April and May 2007.

### ***Railpower Technologies Corporation "Green Goat" Diesel-battery Hybrid***

Railpower Technologies Corporation of Vancouver, British Columbia has commercialized a diesel-battery hybrid switch locomotive which it has trademarked the Green Goat<sup>TM</sup>. This hybrid (shown in Figure 12 below) uses a 290 horsepower EPA Tier 2 nonroad diesel generator engine to recharge electric batteries. As such, it is similar to the Toyota Prius hybrid automobile in that propulsion power comes directly from large storage batteries. As the battery charge is depleted, a diesel-generator set recharges them. In early 2005, UPRR received Carl Moyer Program funds to place one Green Goat hybrid in service in Fresno, California. In August of 2005, the UPRR announced plans to purchase (without Moyer funding) another ten Green Goat locomotives for operations in Southern California.<sup>90</sup> As of spring 2007 UPRR was operating 11 Green Goats in California. All Green Goats are currently back with the manufacturer for modification to resolve an equipment malfunction that causes engine fires. One Green Goat for UPRR is already back in limited service, and UPRR intends to put remaining back by the end of 2008. Some railroad companies are considering replacing the Green Goats with gen sets given these technical and safety challenges.

Railpower's Green Goat hybrid locomotive meets EPA's Tier 2 locomotive and CARB's Ultra-Low Emission Locomotive (ULEL) standards (not exceeding 4.0 g/bhp-hr). To achieve CARB's ULEL rating, a locomotive must achieve a NO<sub>x</sub> output which is about 28% lower than the Tier 2 rating. To achieve these results, Railpower uses a nonroad engine in the Green Goat which meets EPA certification requirements for either Tier 2 or Tier 3 *nonroad* engines. Based on Tier 2 *nonroad* certification levels, Railpower has computed emission values for the EPA *locomotive* duty cycle which show that the Green Goat meets and exceeds the EPA Tier 2 *locomotive* certification standards.<sup>91</sup> However, no formal certification has been granted by EPA for the Green Goat because this locomotive is formally exempt from such requirements due to the horsepower rating of its engine. In March 2006, CARB granted provisional ULEL status through December 2006 for two of the Green Goat engine models: Cat C-9 (1.51 g/bhp-hr) and the Deutz 1015 (2.16 g/bhp-hr). Railpower expects to

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<sup>89</sup> Mike Iden (UPRR), personal communication with Andrew Trump, January 2005.

<sup>90</sup> See UPRR, "Union Pacific Orders 10 'Green Goat' Hybrid Locomotives for Southern California Rail Yard Operations," 15 August 2005  
<[http://www.uprr.com/newsinfo/releases/environment/2005/0815\\_ggoat.shtml](http://www.uprr.com/newsinfo/releases/environment/2005/0815_ggoat.shtml)>.

<sup>91</sup> Nonroad engines used in a wide variety of applications such as tractors and construction equipment have emissions standards that are based on a steady-state cycle. Although this cycle is different from the steady-state cycle used for locomotive emission standards, results from the nonroad cycle can be used to estimate results for the locomotive emissions cycle.



complete the additional analysis needed to finalize these emission levels and is working toward receiving ULEL certifications for Green Goats with other engine models.

**Figure 12: UPRR's Railpower Green Goat "Hybrid" Switch Locomotive.**



### ***National Railway Equipment "Gen Set Switcher"***

National Railway Equipment Company (NRE), located in Mt. Vernon, Illinois, has produced the first working prototype "gen set switch" locomotive. UPRR specified and funded its development and took delivery of the prototype in November 2005 (see Figure 13). The prototype NRE "gen set switch" locomotive uses two 700 hp Tier 3 nonroad gen sets. UP purchased 60 production locomotives for delivery by year end 2007 for use in its Los Angeles Basin rail yards, with the first locomotives arriving in August 2006. Forty-two gen sets will be built for BNSF for system wide use in 2007 and they have ordered another 33 for 2008. These locomotives will use three Tier 2 nonroad 700 hp gen set engines.<sup>92</sup> Other railroads have also been investing in the NRE gen set switchers, including 8 delivered for short rail lines Dallas Garland and Northeastern Railway (DGNO), Fort Worth and Western Railroad (FWWR), in Texas and Pacific Harbor Lines (PHL) in California.

### ***Railpower Technologies "Gen Set Switcher"***

Railpower is also developing its heavy duty "RP Series road switchers" (like the NRE locomotive these are sometimes informally referred to as "gen set switch" locomotives). Railpower is developing two models: the RP20BH model utilizes two 627 hp nonroad diesel generator engines and a large battery pack. The RP20BD model utilizes three 627 hp nonroad diesel generator engines and no battery pack. Railpower's locomotives will use Tier 3 compliant *nonroad* engines. In 2005, the UPRR ordered 98 RP20BD locomotives for service in Texas. UPRR took delivery of the first locomotives in fall of 2006. The 98 UPY2602-2699 Railpower gensets for Texas were co-funded by the Texas Emissions

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<sup>92</sup> See UPRR, "Union Pacific Acquiring 60 New Generation Environmentally Friendly Locomotives for Los Angeles Basin Rail Yards", 9 February 2006.

Reduction Plan (TERP), a set of incentive programs to improve air quality in Texas, provided \$81 million towards the purchase of these locomotives.

**Figure 13: UPRR-funded National Railway Equipment Prototype “Gen Set Switcher” Locomotive**



Both the UPRR and the BNSF are optimistic about NRE’s and Railpower’s “gen set switcher” product development efforts resulting in commercially viable, ultra clean switch locomotives running on diesel fuel. The UPRR’s purchase commitments reflect this optimism and they have recently ordered an additional four switchers for their Roseville California yard co-funded by the Carl Moyer program. Norfolk Southern has also taken delivery of two switchers and has four more on order. The UPRR and BNSF gen set purchases, when combined with previously announced purchases, will ensure that 50% of the switch and low horsepower locomotive fleets of both Railroads in Southern California will meet or exceed the most stringent EPA Tier 2 locomotive emissions requirements. The BNSF shares UPRR’s optimism but notes that the engines used in the “gen set switcher” locomotives could utilize natural gas as well.<sup>93</sup> Manufacturers like Cummins offer generator engine products of comparable size configured to run on natural gas at a reduced power level. However, given the low emissions levels that the Railroads expect from the diesel EPA Tier 3 nonroad “gen set switchers,” it is doubtful that any significant air quality benefits of using natural gas would arise, especially when the additional costs of locomotive development, duplicative fueling infrastructure, construction, operation (lower efficiency of natural gas engines), and maintenance are considered. In any event, both Railroads agree that innovation is driving the market and providing choices that will further improve goods movement emissions performance.

### ***Clean Engine Technology Investments***

The UPRR and BNSF are purchasing and taking delivery of new line-haul locomotives to reduce the overall emissions of their fleets. This includes buying new locomotives that meet

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<sup>93</sup> A gen set locomotive operating on LNG fuel would require comparable, but spark ignited, engines. See Section 2 for a discussion of natural gas engines. Sections 10 and 11 discusses the emissions of natural gas locomotives.

EPA's Tier 2 standards, as well as their many investments since 2000 in Tier 0 and Tier 1 locomotives and retrofitting idling control devices. While each Railroad negotiates its own proprietary purchase contract, the price of either the GE or the EMD Tier 2 locomotive is approximately \$2.0 million. By the mid 2007, the BNSF and UPRR took delivery of or made a purchase commitment for over 1500 Tier 2 line-haul locomotives, representing an investment of approximately \$3 billion. Each Railroad plans to continue to update its locomotive fleet by acquiring more Tier 2 locomotives in the future. This investment, in addition to UPRR's and BNSF's ULEL switch locomotive purchase commitments is summarized below in Table 12.

**Table 12: BNSF Railway and UPRR Investments in Air Quality Improvements**

<b>Locomotive Technologies</b>	<b>First Year Available</b>	<b># of Locomotives</b>	<b>Percent of CA Fleet</b>	<b>NOx Reduction from baseline<sup>94</sup> (per unit)</b>	<b>Incremental Air Quality Investment to date</b>
<b>Mandatory Re-Build – Tier 0</b>	2000	4938		30%	
<b>Buy New Units – Tier 1</b>	2002	1856		45%	
<b>Buy New Units – Tier 2</b>	2005	1559		60%	
<b>Future Additional Line-haul Units to be purchased by 2010</b>	2005	80			\$160 million
<b>Ultra Low-Emitting California Switchers in service (as of 7/07)</b>	2005	67	12%	80%	
<b>Total ULEL California Switchers (By 12/07)</b>	2005	91	60%	80%	\$136.5 million
<b>ULELs purchased for other states</b>	2005	144			\$288 million
<b>Automatic Shutdown Devices</b>					
<b>Line-haul units nationally (44%Complete)</b>	2001	6113			\$32 million
<b>California units (Completed)</b>		383	85%		
<b>California units (Future by 6/08)</b>		67	15%		\$9 million
<b>Total Air Quality Investment</b>					\$625 million

<sup>94</sup> Baseline emissions are pre regulation locomotives.

## 10. Comparison of Exhaust Measurements from Different Locomotives

This section provides tables summarizing and comparing the exhaust emissions performance of switch and line-haul locomotives. The tables provide information for locomotives that are either in service today and/or are commercially available; they avoid speculation about performance of locomotives that may be developed in the future. They also provide “benchmarks” to typical in-use locomotives that were placed in service prior to the adoption of the EPA emission standards in 1998, but have since been remanufactured to meet the applicable Tier 0 standards.

Emissions data are presented in the standard brake specific units of g/bhp-hr used for EPA certification, as well as in units of grams per gallon. The tables also present results of mass emission computations that assume the EPA-published duty cycle and typical yearly average diesel fuel consumption of 400,000 gallons per year for line-haul locomotives and 40,000 gallons per year for switch locomotives. Calculations for these numbers are provided in Appendix 5.

**Table 13: Comparison of Switch Locomotives and their Emissions Performance**

Vendor and locomotive type	EMD Diesel GP38-2 (typical)	MK Rail LNG	National Railway Equipment, "Gen Set" Switcher	Railpower "Green Goat" Battery Hybrid
<b>Background Information</b>				
Fuel Type	Diesel	LNG	Diesel	Diesel
Status of Commercial Development - test cell, prototype, demonstration, commercial	Typical diesel locomotive in service today	Four locomotives in operation (two for over 10 yrs); Motive Power can build new locomotives if ordered	Ending prototype phase. 98 have been ordered for TX; 60 have been ordered in CA for delivery in 2006 and 2007.	Commercial stage; UPRR has ordered ten locomotives for delivery in 2006.
EPA Locomotive Exhaust Measurement Certification Requirement, if any	Requires locomotive Tier 0 at time of remanufacturing	Requires locomotive Tier 0 at time of remanufacturing. Any new locos must meet Tier 2 certification standards (40 CFR 92). <b>See note a</b>	Meets EPA locomotive Tier 2 standards (40 CFR 92) and CARB certification as Ultra-Low Emitting (ULEL) << 4.0 g/bhp-hr.	Meets EPA locomotive Tier 2 standards (40 CFR 92) and CARB certification as Ultra-Low Emitting (ULEL) << 4.0 g/bhp-hr. <b>See note b</b>
Reference for exhaust emissions performance	<b>See note c</b>	<b>See note d</b>	<b>See note e</b>	<b>See note f</b>
Approximate Locomotive Cost	\$350,000	Unknown – locomotives leased	\$1,300,000	\$1,000,000
Tractive	2,000	1,200	2,000	2,000

Vendor and locomotive type	EMD Diesel GP38-2 (typical)	MK Rail LNG	National Railway Equipment, "Gen Set" Switcher	Railpower "Green Goat" Battery Hybrid
Horsepower (HP)				
Idle Reduction Technology Equipped?	Yes. Retrofit kit available	Yes. See note g	Yes	Yes
<b>Comparative Emissions Information</b>				
Duty Cycle Assumption	EPA Switch	EPA Switch	EPA Switch	EPA Switch
Yearly Fuel Use Assumption Used for Emissions Computations (gals)	40,000	66,667 of LNG (energy equivalent of 40,000 of diesel)	40,000	40,000
<b>Brake Specific Emissions Data, g/bhp-hr</b>				
NOx	17.4	1.4	3.4	1.51 or 2.16 depending on engine used
PM	0.44	0.09	0.048	Not currently available
CO	1.83	2.2	1.51	Not currently available
HC (NMHC for LNG)	1.01	3.3 See note 1	0.036	Not currently available
<b>Fuel Specific Emissions Data, g/gallon of diesel or diesel equivalent</b>				
NOx	257	20.3	Not currently available	Not currently available
PM	6.52	1.35	Not currently available	Not currently available
CO	27.0	32.0	Not currently available	Not currently available
HC (NMHC for LNG)	15.0	48.7	Not currently available	Not currently available
<b>Mass Emissions, lbs/day for annual fuel use on switch duty cycle (365 days / year operation)</b>				
NOx	62.2	5.02	12	Not currently available
PM	1.57	0.334	0.17	Not currently available
CO	6.52	7.92	5.37	Not currently available
HC (NMHC for LNG)	3.61	11.8	0.13	Not currently available



**Table 14: Comparison of Line-haul Locomotives and their Emissions Performance**

Vendor and locomotive type	Remanufactured EMD SD60	High pressure gas injection	Low pressure gas injection	GE Tier 2 - ES44AC or ES44DC	EMD Tier 2 - SD70DCE or SD70ACE
<b>Background Information</b>					
Fuel Type	Diesel	dual fuel engine (LNG and diesel)	dual fuel engine (LNG and diesel)	Diesel	Diesel
Status of Commercial Development - test cell, prototype, demonstration, commercial	Typical in-use diesel locomotive (assumes re-manufactured after 2001)	R&D development test stand program ended in 1995	Commercially available retrofit conversion kit for 3,000 hp EMD locomotive	Commercially Available; 720 locomotives purchased by UP and BNSF in 2005	
EPA Exhaust Measurement Certification Requirement, if any	EPA Tier 0	Prospectively, Tier 0, 1, 2 or 3	Tier 0, 1 or 2 depending on age of converted locomotive. No EPA certified locomotive operational.	EPA Tier 2 certified	
Reference for exhaust emissions performance	<b>See note h</b>	Only limited test data publicly available. <b>See note i</b>	1992 SwRI emissions test on BN locomotives <b>See note j</b>	Exhaust measurements using EPA certification test protocol. <b>See note k</b>	
Approximate Locomotive Cost	\$400,000	n/a	unknown	\$2,000,000	\$2,000,000
Operating Range, miles	500 to 1,500 depending on train route, weight, speed, etc.	n/a	Unknown. Determined by tender car capacity	500 to 1,500 depending on train route, weight, speed, etc.	
Tractive Brake Horsepower (HP)	3,800	n/a	3,000	4,400	4,300
Idle Reduction Technology Equipped?	Yes (ZTR retrofit kit)	n/a	Unknown	Yes	Yes
<b>Comparative Emissions Information</b>					
Duty Cycle Assumption	EPA line-haul	n/a	EPA line-haul	EPA line-haul	EPA line-haul
Yearly Fuel Use Assumption Used for Emissions Computations (gals)	400,000	n/a	400,000 gallons diesel <i>equivalent</i>	400,000	400,000
<b>Brake Specific Emissions Data, g/bhp-hr</b>					
NOx	8.7	n/a	5.2	5.3	5.1

Vendor and locomotive type	Remanufactured EMD SD60	High pressure gas injection	Low pressure gas injection	GE Tier 2 - ES44AC or ES44DC	EMD Tier 2 - SD70DCE or SD70ACE
PM	0.36	n/a	0.38	0.10	0.07
CO	2.2	n/a	10.0	0.4	1.0
HC (NMHC for LNG)	0.71	n/a	1.17	0.16	0.22
<b>Fuel Specific Emissions Data, g/gallon of diesel or diesel equivalent</b>					
NO <sub>x</sub>	174	n/a	103	106	102
PM	7.2	n/a	7.7	2.0	1.4
CO	44.0	n/a	199	8.0	20.0
HC (NMHC for LNG)	14.2	n/a	23.3	3.2	4.4
<b>Mass Emissions, lbs/day for annual fuel use on line-haul duty cycle (365 days / year operation)</b>					
NO <sub>x</sub>	420	n/a	249	256	246
PM	17.4	n/a	18.5	4.83	3.38
CO	106	n/a	481	19.3	48.3
HC (NMHC for LNG)	34.3	n/a	56.4	7.73	10.6

#### Notes for the Tables 13 and 14 on Yard Switcher and Line-haul Locomotives

- The existing MK Rail LNG (now MotivePower) locomotives are likely to meet Tier 0 standards except for hydrocarbons (HC). Any new Rail LNG locomotives would require Tier 2 certification. The Railroads are unaware of any purchase commitments for new MotivePower LNG locomotives.
- Railpower uses a nonroad engine in the Green Goat hybrid locomotive which meets EPA certification requirements. In addition, CARB has determined provisional NO<sub>x</sub> emission levels for the Green Goat™ locomotive based on operating data supplied by NRE and certification data for the nonroad engines used in the Green Goat™. The provisional emission levels depend on the nonroad engine used. For a Caterpillar model C-9 engine the NO<sub>x</sub> emission level is 1.51 g/bhp-hr on the line-haul duty cycle.<sup>95</sup> For a Deutz model 1015 engine, the NO<sub>x</sub> emission level is 2.16 g/bhp-hr on the line-haul duty cycle.<sup>96</sup> (These certifications were made for the line-haul duty cycle because the results of that cycle are used to determine compliance with the 1998 fleet-average agreement between the Railroads and CARB.) These provisional emission levels are valid through December 31, 2006.
- Data for in-use locomotive (without remanufacture) taken from EPA Regulatory Support Document for 1997 locomotive rule.

<sup>95</sup>Letter from Robert D. Fletcher, California Air Resources Board, to Karen Dzienkowski, RailPower Hybrid Technologies Corporation, March 17, 2006.

<sup>96</sup>Letter from Robert D. Fletcher, California Air Resources Board, to Karen Dzienkowski, RailPower Hybrid Technologies Corporation, March 2, 2006.



- d. Data provided by Mark Stehly, BNSF.
- e. Data provided by James M. Wurtz, Jr., National Railway Equipment.
- f. Information supplied by Karen Dzienkowski, Railpower.
- g. The MK LNG locomotive and the multi engine gen sets and hybrid switch locomotives have engines that contain antifreeze and therefore will be shut down in cold weather.
- h. Emission measurements taken from EPA certification data. SD60 data is average of four engine families: 4getk0710mfC, 4GMXK0710MJ0, 2CSXK0710GB0, and 2CSXK0710GBM.
- i. The ASME paper discussed in Section 8 notes that the experimental GE “H Process” engine reduced NO<sub>x</sub> by 48% in notch 8. Also see Appendix 2.
- j. Data taken from the discussion in Section 11 of this paper and SwRI report referenced there.
- k. Emission measurements taken from EPA certification data. GE Tier 2 data is for engine family 5GETg0958efb. EMD Tier 2 data is for engine family 5GMXG0710ES1.
- l. There is some confusion in that this number is reported in one sources as HC and in another as NMHC, however, it is most likely HC. Although no data are available, the NMHC emissions for this engine are estimated to be about 0.5 g/bhp-hr.

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## 11. Exhaust Emissions Evaluation of the ECI Product versus a New Locomotive Meeting EPA Tier 2 Certification Standards

As discussed earlier, only one natural gas-fueled commercially available locomotive product (the ECI 645E3 engine retrofit) is available for line-haul service. In the early to mid-1990's the ECI conversion product was demonstrated on the Burlington Northern Railroad. As part of this effort, exhaust emission tests commissioned by the Burlington Northern were performed on this locomotive by SwRI in October 1991. This section compares the exhaust emissions performance of the ECI conversion product to a new, high horsepower EMD or GE diesel locomotive that meets EPA's Tier 2 exhaust emissions certification standards by using the SwRI report generated in 1992 as part of this locomotive demonstration effort.<sup>97,98</sup>

### **Results of SwRI's Exhaust Emissions Test**

Although there were no standard EPA test procedures at the time of the test, SwRI has a strong record in emission measurements and the measurements outlined in the report are similar to the ones used in the current EPA procedures. Furthermore, since the locomotive FTP uses a weighted set of steady-state measurements, it is possible to use the notch-by-notch data in the 1992 SwRI report to compute the FTP emissions from this set of measurements. Three sets of results are available: 1) for the unmodified locomotive, 2) for the ECI dual-fuel locomotive using 100% diesel fuel, and 3) for the ECI locomotive operating in natural gas mode.<sup>99</sup> The brake specific emissions and engine efficiencies for these three sets of measurements are compared in the table below.

**Table 15: EPA Line-haul Cycle Test Results for ECI Conversion on BN SD40-2 Locomotive (g/hp-hr)**

	THC	NMHC	CO	NO <sub>x</sub>	PM	CO <sub>2</sub>	Efficiency
<b>Unmodified (pre Tier 0)</b>	0.33	0.33	0.8	11.7	0.28	554.7	36.1%
<b>ECI diesel</b>	0.74	0.74	1.9	9.0	0.55	555.4	35.9%
<b>ECI gas</b>	7.55	1.17	10.0	5.2	0.38	440.1	33.3%
Note: The original test results, for notch-by-notch data, are weighted by the factors in the EPA line-haul duty cycle to obtain the results above.							

These 1992 results, weighted using the EPA line-haul cycle show that the ECI kit applied to this locomotive and using natural gas fuel reduces NO<sub>x</sub> from 11.7 g/bhp-hr to 5.2 g/bhp-hr, when compared to the unmodified locomotive. However, the results for the modified locomotive using 100% diesel fuel show that a significant part of this reduction, from 11.7 g/bhp-hr to 9.0 g/bhp-hr, comes from design changes to the diesel engine alone. These changes included a six (6) pass aftercooler and bank idling.

<sup>97</sup> See Steve Fritz, "Exhaust Emissions from a Dual-fuel Locomotive," Report 4602, Southwest Research Institute, March 1992. The actual tests were done in October 1991. The CO<sub>2</sub> mass emission data in the original report were not correct. According to a December 27, 2005 email from Steve Fritz to Larry Caretto, the other mass emission rates and brake specific values are correct and the CO<sub>2</sub> results can be computed from a carbon balance from the fuel data and the other emission rates. This was done for the CO<sub>2</sub> data in this section.

<sup>98</sup> The Railroads provided an early draft of this section to ECI for comment. ECI's comments are summarized in Appendix TBD.

<sup>99</sup> "ECI locomotive" is used casually here and elsewhere in this report. ECI provides the equipment necessary to convert the EMD 645E3 locomotive engine to burn natural gas. The EMD 645E3 engine is commonly found in the EMD SD40-2 locomotives.

Although the use of LNG reduces NO<sub>x</sub> and CO<sub>2</sub>, PM, HC, and CO are increased. The increase in particulate emissions is due to the problems in operation at low throttle notches where the engine is operating exclusively on diesel fuel. The increase in hydrocarbon emissions (mostly methane) and CO emissions is due to problems in the combustion process. There is also an efficiency loss of 2.8 percentage points when using the gas fuel and this in turn would require 8.5% more energy to be provided for gas operation. The large amount of methane emitted with the natural gas fuel, 6.38 g/bhp-hr (= 7.55 – 1.17), is also a significant emission of a greenhouse gas. One gram of methane has the equivalent effect of 23 grams of CO<sub>2</sub> on global warming; this factor of 23 is called the global warming potential (GWP) for methane.<sup>100,101</sup> When the brake specific methane emissions are multiplied by 23 and added to the CO<sub>2</sub> emissions the total equivalent CO<sub>2</sub> emissions of greenhouse gases increase from 554.7 g/bhp-hr for the unmodified locomotive to 587.0 g/bhp-hr for the LNG locomotive. Therefore, LNG increases green house gases emissions by 5.8% compared to the diesel configuration.

### **Emissions Comparison with Tier 2 Locomotives**

The emissions data for the ECI dual-fuel locomotive presented above was assumed on a version of this conversion technology that is approximately 15 years old. A recent conversation with an ECI representative indicated that the system has been modified to reduce emissions. The Railroads are unaware of any data on the current, commercially available version of this conversion system. Consequently, the only comparison that is available between the ECI dual-fuel locomotive and a clean diesel locomotive meeting the EPA Tier 2 locomotive standards is the 1991 ECI conversion. With this caveat in mind, the comparison between the 1991 ECI locomotive conversion data shown above and the certification data for two Tier 2 locomotives<sup>102</sup> is presented below.

**Table 15: Comparing EPA Line-haul Cycle 1992 ECI Data to Tier 2 Line-haul Locomotives (g/bhp-hr)**

Mode	THC	NMHC	CO	NO <sub>x</sub>	PM
ECI gas	7.55	1.17	10.0	5.2	0.38
EMD	0.22	0.22	1.0	5.1	0.07
GE	0.16	0.16	0.4	5.3	0.10

This chart shows that the NO<sub>x</sub> emissions are essentially the same for the three locomotives while the emissions of the other criteria pollutants and total hydrocarbons are higher with the ECI product. The Tier 2 locomotives are also expected to have even better efficiency than the unmodified SD 40-2; this improved efficiency should produce even lower brake-specific emissions of CO<sub>2</sub> than those of the SD 40-2; thus the difference in global warming

<sup>100</sup> Environmental Protection Agency, "In Brief - The U. S. Greenhouse Gas Inventory," EPA pamphlet 430-F-02-008, 21 December 2005 <<http://yosemite.epa.gov/oar/globalwarming.nsf/content/Emissions.html>>.

The global warming potential value of 23 for methane is taken from the more recent Third Assessment Report of the Intergovernmental Panel on Climate Change. In accordance with the IPCC guidelines, EPA uses the earlier IPCC value of 21 for the GWP of methane in its inventory calculations to provide consistent trend data.

<sup>101</sup> Environmental Protection Agency, "Inventory of U. S. Greenhouse Gas Emissions and Sinks," EPA report 430-R-05-003, 15 April 2005 <<http://yosemite.epa.gov/oar/globalwarming.nsf/content/Emissions.html>>

<sup>102</sup> The certification data was downloaded from <<http://www.epa.gov/otaq/certdata.htm#locomotive>> on 21 December 2005.

emissions noted above would be even greater when the ECI locomotive is compared to the Tier 2 locomotives.

### **Toxic Pollutant Emissions**

The only data on air toxic emissions from locomotive engines of which the Railroads are aware were obtained in a SwRI study sponsored by CARB with in-kind support from BNSF and UPRR.<sup>103</sup> That study compared three diesel fuels in both EMD and GE locomotives. The toxic compounds from these locomotive engines were similar to those from heavy duty truck engines.

Although there are no data on toxic emissions from LNG locomotive engines, there are data on such emissions from truck engines using CNG. These truck engine data should indicate the trends that would be observed for natural gas and diesel fuel use in locomotive engines: gaseous toxic air emissions from CNG truck engines are often higher than those from diesel engines certified to meet the 1998 highway standard of 4.0 g/bhp-hr NO<sub>x</sub> and 0.1 g/bhp-hr of PM.

One such study was performed on school buses using a chassis dynamometer using a driving cycle known as the city suburban heavy vehicle cycle (CSHVC).<sup>104</sup> For this cycle, the results were reported in micrograms per mile (mg/mi) rather than the usual brake specific units. In addition to the 1998 engine and the LNG engine, a low-emission diesel engine that used a catalytic particulate filter (achieving a PM emission level of 0.01 g/bhp-hr) was also included in the comparison. The low-emission diesel engine required a fuel with sulfur content less than 15 ppm.

The emissions comparison for the main mobile source toxics considered by EPA and included in their MOBILE6.2 emissions model are shown in the table below.

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<sup>103</sup> Steven G. Fritz, "Diesel Fuel Effects on Locomotive Exhaust Emissions," SwRI Report 08.02062 prepared for CARB, October 2000.

<sup>104</sup> Terry L. Ullman, *et al.*, "Comparison of Exhaust Emissions, Including Toxic Air Contaminants, from School Buses in Compressed Natural Gas, Low Emitting Diesel, and Conventional Diesel Engine Configurations," Paper 2003-01-1381 presented at SAE World Congress, Detroit, 3-6 March 2003.

**Table 17: Comparison of Toxic Emissions from Truck Engine Study**

Compound	Cycle Average Emissions (mg/mi)		
	1998 Diesel Engine	Low Emission Diesel	CNG Engine
Acetaldehyde	9.5	2.7	24
Acrolein	3.3	0.45	4.9
Benzene	4.7	ND	4.3
1,3-Butadiene	ND	1.3	4.5
Formaldehyde	27	5.2	500
ND indicates that the compound was not detected			

These data show that the natural gas engine has significantly higher emissions of toxic air contaminants than a low emission diesel. For some compounds such as formaldehyde, the CNG engine has emissions that are significantly higher than those from a 1998 diesel engine. Another study by CARB and University of California at Davis compared different diesel and CNG bus engines and concluded that a diesel particulate filter “yields lower emissions of all pollutants measured relative to CNG without catalyst with the exception of [elemental carbon], NO<sub>x</sub>, NO<sub>2</sub>, and CO<sub>2</sub>.”<sup>105</sup> The authors note the problem that diesel particulate matter was classified as a toxic air contaminant by CARB, but particulate emissions from natural gas engines were not.

Although toxic emissions from LNG engines could be reduced by use of an oxidation catalyst, none was used on the Burlington Northern Railroad ECI conversion locomotive tested at SwRI. If no catalyst is used, toxic compound emissions from the engine, converted with the ECI kit can be expected to be higher when it is fueled with natural gas than it would be with diesel fuel.

### **Summary of ECI Test Data**

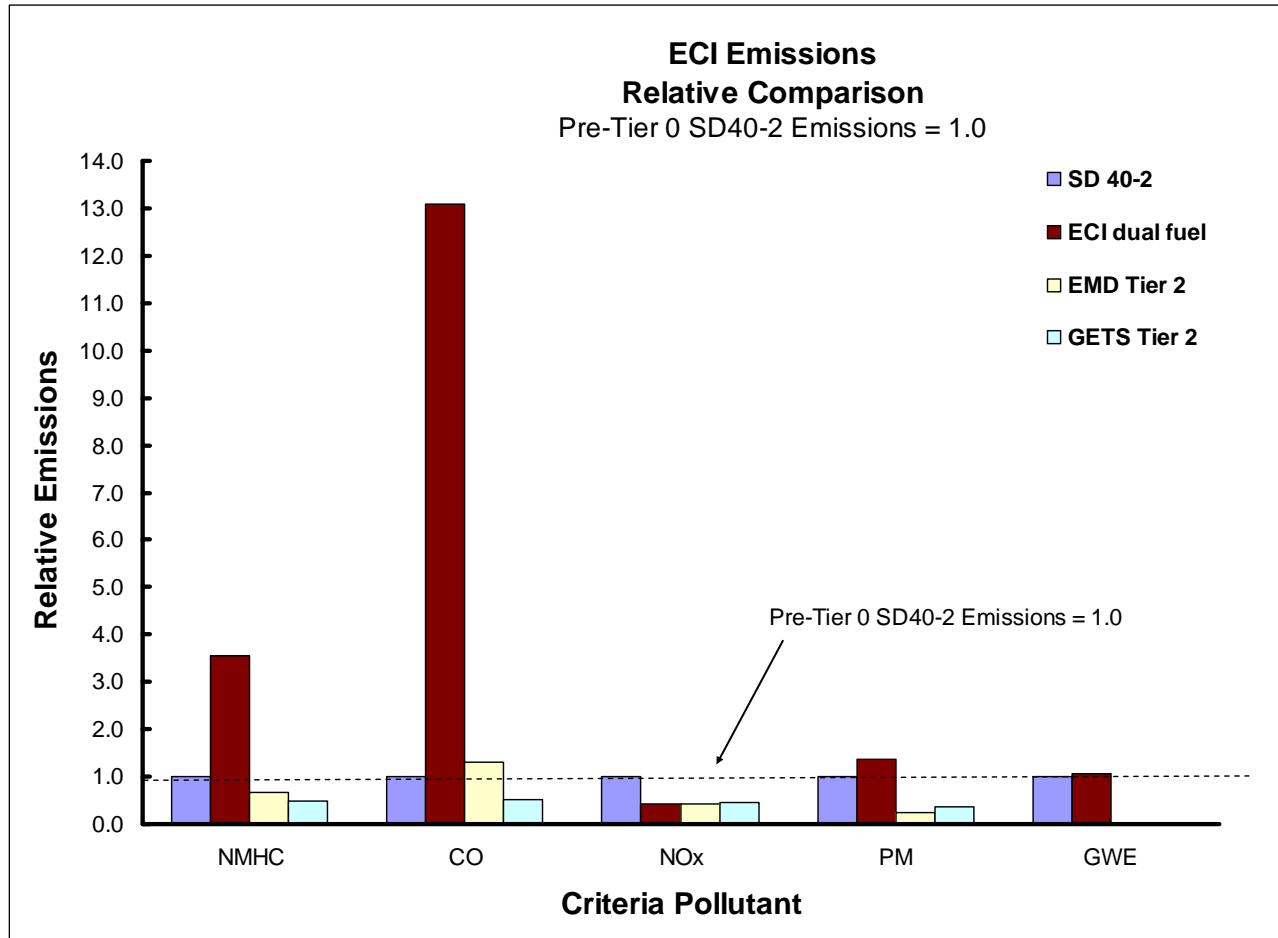
Data from the 1991 tests of a locomotive using the ECI conversion kit show that the natural gas operation on the SD40-2 locomotive reduces NO<sub>x</sub> compared to an unregulated (pre Tier 0) engine. Part of this reduction is due to engine design changes that also reduce NO<sub>x</sub> when the same locomotive is running on 100% diesel fuel. When the same emissions data are compared to emission results from modern locomotive engines certified to EPA Tier 2 locomotive standards, there is no NO<sub>x</sub> benefit from the ECI kit.

All other criteria pollutant emissions are increased including particulate emissions which are four to five times higher (see Figure 14). Furthermore, the large methane emissions with gas fueling cause an increase in greenhouse gases, compared to operation with diesel fuel on the same locomotive. In addition, there is also a decrease in efficiency when the converted locomotive is switched from diesel fuel to natural gas. Although no data are available on toxic air contaminant emissions from a locomotive using the ECI kit, data on bus engines

<sup>105</sup> Alberto Ayala, *et al.*, “CNG and Diesel Transit Bus Emissions in Review,” 9th Diesel Engine Emissions Reduction Conference, Newport, Rhode Island, 24-28 August 2003. For the web version, see <[http://www.eere.energy.gov/vehiclesandfuels/pdfs/deer\\_2003/session5/deer\\_2003\\_ayala.pdf](http://www.eere.energy.gov/vehiclesandfuels/pdfs/deer_2003/session5/deer_2003_ayala.pdf)>.

without exhaust after-treatment indicate that a locomotive using the ECI kit will likely have higher emissions of these species, especially formaldehyde.<sup>106</sup>

**Figure 14: Relative Comparison of ECI Emission**



<sup>106</sup> CARB classifies diesel particulate matter as a toxic air contaminant but not particulate matter from natural gas combustion. However, PM emissions will be higher when using the EPA line-haul cycle weights because 56% of the particulate emissions from the ECI kit with natural gas fuel come from the four notch settings where the dual-fuel operation reverts to 100% diesel fueling. Other notch settings will have some particulate emissions from diesel fuel, but even if these emissions are not counted. The result is that the emission of diesel particulate matter from the ECI kit is at least two times that from the Tier 2 locomotives.

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## 12. Natural Gas vs. Diesel Fuel Economics

The comparative costs of natural gas and diesel fuel play a large role in determining the potential feasibility of deploying natural gas-fueled locomotives and the cost-effectiveness of any resulting air quality emission reductions. All else being equal (i.e. emissions, thermal efficiency, reliability, etc.), the delivered cost of natural gas would have to be much less expensive than diesel fuel to justify a conversion to its use due to the significant investment required in new and/or retrofit locomotives, duplicative fueling infrastructure, and related operational support costs.

It is beyond the scope of this paper to provide an analysis of the economic comparison between the two fuels, as such a comparison depends on many assumptions about the nature of the locomotive fleet being analyzed, its location, and the size and distribution of fueling resources that are not currently at hand. In the 1995 EF&EE Report, CARB explained the factors that influenced LNG cost: “The cost of supplying LNG would depend heavily on the fuel source, purity, quantity demanded (related to plant size), quantity to be stored, and delivery mode.”<sup>107</sup>

Presently the four LNG switch locomotives that the BNSF leases and operates in Southern California are fueled by LNG that is refined and liquefied in Arizona and is delivered to the locomotive along the right-of-way by truck. According to a BNSF representative, the fuel is delivered “every few days” and each locomotive’s 1,300 gallon fuel tanks are topped off during each refueling. While this is practical for these four locomotives, any appreciable sized fleet of locomotives that use LNG would require a nearby, sizeable, and reliable source of LNG.<sup>108</sup> By the end of 2005, California had 40 LNG fueling facilities scattered throughout the state and primarily located near major thoroughfares and serving on-the-road vehicle operators.<sup>109</sup> These facilities are not sized or located to support Railroad operations. Furthermore, how this infrastructure might be expanded is unknown.

### **Recent Price Experience with Natural Gas and Diesel**

In addition to safety, the most important considerations about the feasibility of using natural gas as a locomotive fuel are its price and price volatility compared to the price and price volatility of diesel fuel. There are many reports, statements, and forecasts for future price behavior of each fuel. There are also many variables cited as influencing the price of these fuels. It is difficult to predict the future. In 1995, CARB opined:

Though natural gas prices tend to fluctuate with other energy prices, they have historically been both lower (on a per-BTU basis) and less volatile than prices for diesel fuel...The largest component of the cost of production for LNG would be the cost of the natural gas feedstock. For this calculation, natural gas was priced at \$1.80 per MMBTU plus \$0.20 per MMBTU

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<sup>107</sup> Christopher S. Weaver and Douglas B. McGregor, *op. cit.*, Page 108.

<sup>108</sup> Any building and operating of liquefaction facilities near rail facilities would have to take the pipeline feedstock natural gas and refine and liquefy it for use in locomotives.

<sup>109</sup> See Alternative Fuels & High Efficiency Vehicles. California Energy Commission. 17 January 2006 <[http://www.energy.ca.gov/afvs/vehicle\\_fact\\_sheets/lng.html](http://www.energy.ca.gov/afvs/vehicle_fact_sheets/lng.html)>.

transportation cost. The sum, \$2.00 per MMBTU of pipeline natural gas, is equivalent to \$0.16 per gallon of LNG.<sup>110</sup>

Both natural gas and diesel fuel have experienced significant price increases and price volatility. Natural gas prices, for example, are currently approximately five times higher than the \$2.00/MMBtu figure cited by CARB in 1995.

To compare the fuel costs it is also necessary to normalize energy content. The energy content of natural gas and diesel fuel are different and depend on whether the unit of measure is volumetric or weight. A pound of LNG contains more energy than a pound of diesel fuel, but a gallon of LNG weighs less. When comparing the fuels on a volume and energy content basis, this paper uses the following conversion factors: a gallon of diesel fuel contains 128,100 BTUs and a gallon of LNG contains 73,100 BTUs. On an equal BTU basis, a gallon of diesel is equal to 1.68 gallons of LNG (e.g., 128,100 BTUs each).<sup>111</sup>

Natural gas prices are typically cited in terms of dollars per thousand cubic or per million of BTUs (MMBtu). Using the conversion factors above, it is possible to compare cost differences of the fuels by normalizing for the amount of energy. The natural gas data presented in Figure 15 comes from the Department of Energy's Energy Information Administration. It reports prices for both Commercial and Industrial end use categories.<sup>112</sup> These costs represent the cost of the delivered commodity ready for consumption. They *do not* reflect the additional refining, liquefaction, and transportation costs that would be required for natural gas to be stored liquefied as a locomotive fuel. Both categories are cited because it is speculative as to how large a customer the Railroads would be and what kind of pricing they might expect.

The diesel fuel prices also come from the Department of Energy's Energy Information Administration; the data set is not specific to the Railroad industry but rather reflects average prices paid by large end use customers (such as agriculture, industry, and electric utilities) throughout the United States.

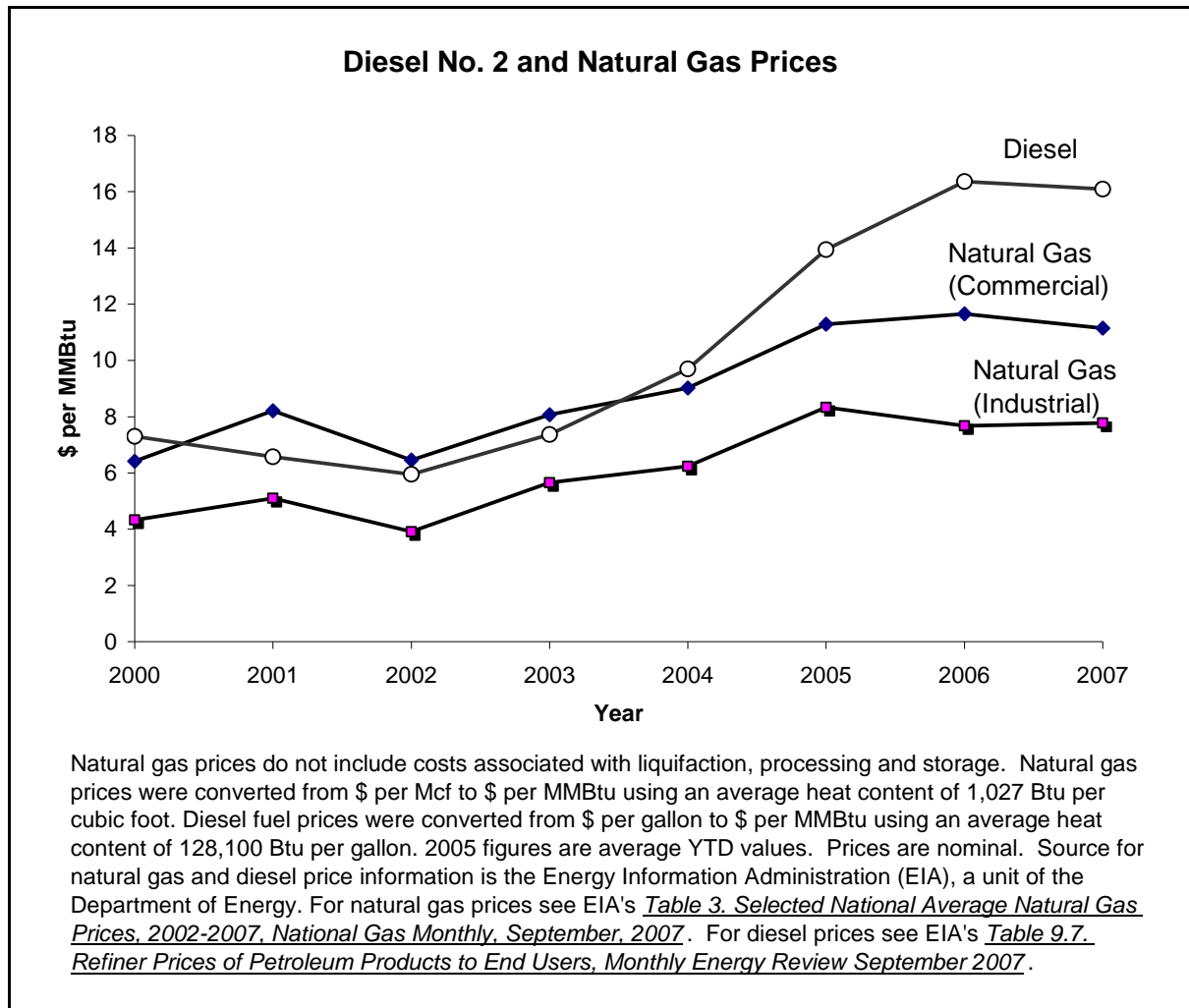
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<sup>110</sup> Christopher S. Weaver and Douglas B. McGregor, *op. cit.*, Page 107.

<sup>111</sup> Christopher S. Weaver and Douglas B. McGregor, *op. cit.*, Page 106.

<sup>112</sup> The Energy Information Administration reports figures by three end use categories – Industrial, Commercial and Residential.

Figure 15: Comparison of Diesel No. 2 and Natural Gas Prices



How natural gas and diesel prices will trend is uncertain. Both markets are changing dramatically and are experiencing tremendous upward price pressure. Until 1980 the United States was self-sufficient in natural gas. However, consumption began to outpace production and imports principally from Canada rose to make up the difference. Net imports as a percentage of total consumption jumped dramatically and are now around 20% of total usage. The industrial sector has always been the heaviest user of natural gas (around half) and this sector's use is intensifying because of the recent increase in gas-fired electricity generation plants throughout North America.

Because of the United States' extensive natural gas use and the consequences of major storms in the Gulf of Mexico in recent years (i.e. the resulting damage done to natural gas drilling and processing facilities), many utilities throughout the U.S. are warning customers to expect substantial increases in residential utility bills. Whether prices will decline is uncertain and this will depend on many factors including, but not limited to: the weather (demand), natural gas well productivity, new well drilling activity, natural gas storage capacity

importation (LNG import facilities along coastal regions), and the type and pace of development of additional electricity generating facilities (one of the largest users of natural gas). Diesel fuel is also experiencing price increases and price volatility.

### 13. Conclusions

The BNSF Railway Company (BNSF), the Union Pacific Railroad Company (UPRR), and the Association of American Railroads (AAR) (collectively referred to as “the Railroads”) have prepared this report to provide perspective and background information to regulatory agencies and other interested parties on the possible use of natural gas as a fuel for locomotives.<sup>113</sup> Additionally, this document partially satisfies one of the requirements of the rail yard Memorandum of Understanding (MOU)<sup>114</sup>. BNSF and UPRR entered into this MOU in 2005 with the California Air Resources Board (CARB) to reduce particulate emissions from California rail yards. One element of the rail yard MOU requires an ongoing evaluation of possible locomotive emission control technologies.

This document provides information on past, current, and potential future efforts to develop and use natural gas-fueled locomotives to meet engine reliability, operational efficiency, and air quality goals. Some of these efforts were, and continue to be, directed at the retrofitting of line-haul freight locomotives with a natural gas conversion system. Other efforts were focused on developing a new high-horsepower natural gas-fueled locomotive and evaluating fueling infrastructure and fueling system operating requirements associated with the use of this fuel. This document looks at these developments in the context of the U.S. Environmental Protection Agency’s (EPA) locomotive emission standards and exhaust measurement test protocols.

The Railroads have a unique partnership with California and have exhibited a willingness to enter into voluntary yet enforceable agreements with CARB to accelerate emission reductions from rail operations that will help California achieve air quality goals.<sup>115</sup> Additionally, the Railroads and the locomotive builders are driving significant product innovation that, in turn, is leading to the commercialization of lower emitting line-haul and switch locomotive products. This innovation is exciting, noteworthy, and predominately diesel engine-based.

The Railroads have prepared this assessment to help inform discussions among all stakeholders. In 2006, the draft report was sent to several stakeholders to solicit feedback. The stakeholders included several California air districts and CARB. The Railroads received reply comments from the South Coast Air Quality Management District (SCAQMD) and the Bay Area Air Quality Management District (BAAQMD). These are included in this report as

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<sup>113</sup> The Railroads initially released a draft of this report in January 2006 and solicited feedback from air quality agencies and other interested parties. This document will be updated periodically as new developments present themselves.

<sup>114</sup> For the 2005 rail yard MOU and supporting information, see <<http://www.arb.ca.gov/railyard/ryagreement/ryagreement.htm>>. Section 8(c) of the MOU, Agreement to Evaluate Other, Medium-Term and Longer-Term Alternatives, ensures that the evaluation and implementation of feasible air pollution mitigation measures occurs expeditiously. Section 8(c) of the CARB rail yard agreement is presented in Appendix 1. The railroads have also agreed to continue to meet and confer with CARB and other stakeholders to evaluate the feasibility of additional measures in designated rail yards.

<sup>115</sup> Activities include, but are not limited to, EPA certification standards and test procedures for new and rebuilt locomotives, the 1998 South Coast NOx locomotive fleet average MOU, the CARB diesel fuel requirements for intrastate locomotives, the 2005 CARB rail yard MOU, and voluntary programs to investigate new technologies (e.g., diesel particulate filters, an emissions “hood”, and remote sensing).

Appendices 6 and 7, along with the Railroads' responses. The Railroads look forward to continuing a fact-based, technical discussion regarding what role, if any, natural gas as a locomotive fuel should play in further reducing emissions from locomotives.

## ***Findings and Conclusions***

### **A history of innovation and inquiry**

The Class I Railroads<sup>116</sup> have a long history of partnering with the locomotive builders to evaluate innovations in locomotive and engine design, including those that involve the use of alternative fuels like natural gas. Section 8 of this report reviews several examples of substantive, railroad-led and funded research and demonstration efforts. These efforts were typically aimed at understanding the use of alternative fuels and locomotive engine technologies to achieve overall operating efficiencies. While not primarily focused on emissions performance, these efforts were focused on efficiency and benefited emissions broadly.

### **Essential locomotive requirements**

In 1994, the Railroads explained to CARB that a key underlying trend must be paramount in any effort to commercialize new locomotive technologies:

Continuous improvements in locomotive design have played a critical role in keeping the railroad industry competitive and viable by improving the cost structure of the industry. These improvements included increased locomotive reliability, greater horsepower, greater horsepower to weight ratios, improved traction motors, and better engine fuel economy. All of these improvements reduce the operating and capital costs and enhance the efficiency of the business.<sup>117</sup>

New locomotives must meet a wide range of railroad company, customer, and community requirements, including:

- safety
- exhaust emissions performance
- extensive range
- high horsepower
- high tractive effort
- fuel economy
- reliability

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<sup>116</sup> Railroads with operating revenues in excess of \$277.7 million per year. There are seven Class I U.S. railroads: BNSF Railway Co., CSX Transportation, Kansas City Southern Railway Co., Norfolk Southern, Soo Line Railroad Co., Grand Trunk Corporation, and Union Pacific Railroad Co. Grand Trunk and Soo Line are owned by the Canadian National Railway.

<sup>117</sup> Amtrak and the Class I Freight Railroads Operating in California, comments in response to the Engine, Fuel and Emissions Engineering Inc. Draft Report (EF&EE Report), April 1994. The draft of this report was issued October 13, 1993. The final report was issued March 1995: Christopher S. Weaver and Douglas B. McGregor, "Controlling Locomotive Emissions in California. Technology, Cost-Effectiveness, and Regulatory Strategy," Engine, Fuel and Emissions Engineering Inc., Final Report prepared for CARB under contracts A032-169 and 92-817, March 1995.

The principal line-haul locomotive builders, General Electric (GE) and Electro-Motive Diesel, Inc. (EMD), continue to meet these requirements through clean diesel engine enhancements, not through the commercialization of natural gas-fueled locomotives.

In 1998, EPA adopted uniformly applied federal standards Tier 0, 1, and 2 for locomotive emissions. The current EPA Tier 2 standards will be superseded by their new Tier 3 and Tier 4 standards which are in the final stages of development and are expected to be finalized around the start of 2008. EPA's standards, in concert with the Railroads' ongoing need for more efficient and reliable locomotives, will continue to guide the railroads' efforts to evaluate all options to ensure that locomotives are operating safely, reliably, efficiently, and in an environmentally superior manner compared to other transportation modes.

### **A period of significant innovation**

The past several years have yielded significant innovation in both switch and line-haul locomotive product development. Today the Railroads are deploying the newest diesel line-haul locomotives from GE and EMD which meet EPA's stringent Tier 2 locomotive emission requirements. These 4,300 – 4,400 hp<sup>118</sup> locomotives reduce locomotive emissions significantly (approximately 60% cleaner for NOx) compared to locomotives manufactured before the implementation of EPA's emission standards. They also simultaneously meet the Railroads' needs for interoperability, high horsepower performance, fuel efficiency, and reliability. The Railroads also worked with several companies to commercialize two new diesel-based switch locomotive technologies: a battery-hybrid switch locomotive ("Green Goat") and a multi-engine generator set switch locomotive ("gen set" switcher).<sup>119</sup> The UPY2005 NRE was the prototype of the first gen set switcher and was funded entirely by UP. These locomotives use low-emitting diesel engines meeting U.S. EPA's nonroad Tier 3 standards. The Railroads have placed initial orders for at least 250<sup>120</sup> of these low-emission switch locomotives systemwide. California will be served by 77 of these locomotives by end of 2007.

### ***The Railroads' position on natural gas***

Some members of the regulatory, engine supply, and fuel supply communities believe the railroads have an opportunity to use natural gas as a locomotive fuel to help meet emissions and performance goals. Except for some potential niche applications, the Railroads disagree. Decades of research and development activities and over-the-rail locomotive prototype

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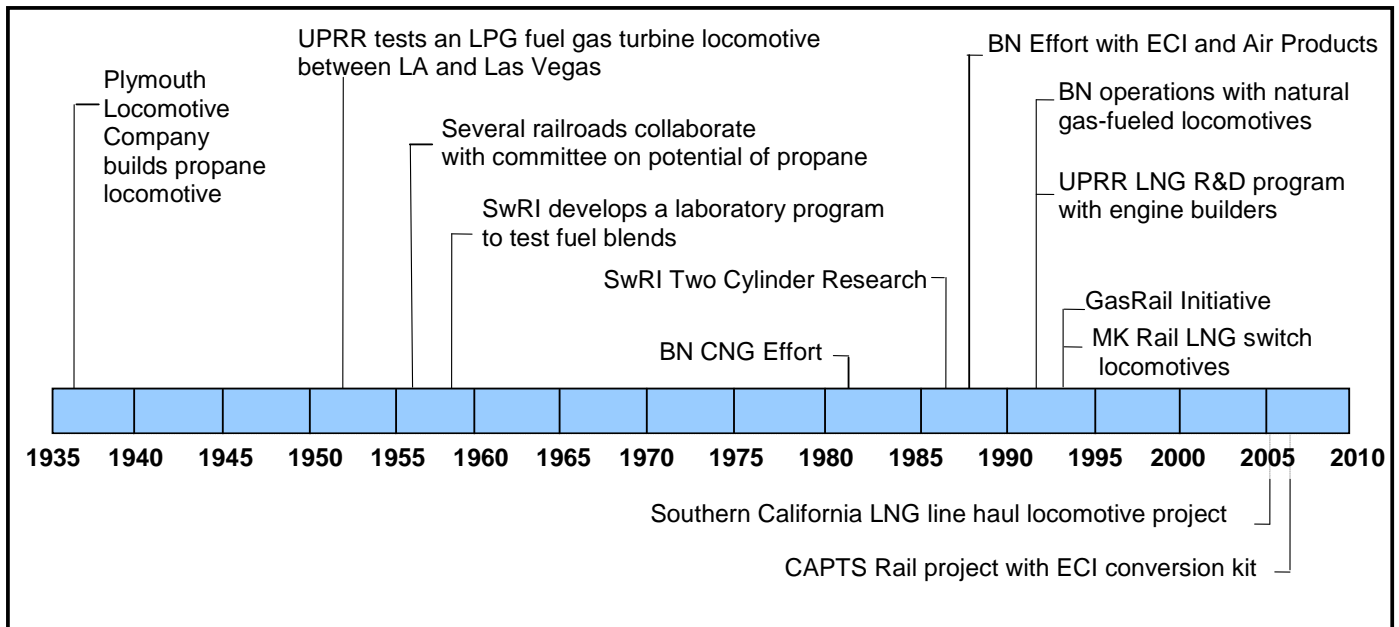
<sup>118</sup> Locomotives use a diesel-electric drive system where the output from a combustion engine is used to generate electric power. That electric power is then used to drive an electric motor to provide the high torque required for the locomotive. Locomotives are rated based on tractive horsepower available to drive the wheels of the locomotive. The emission standards are based on the brake horsepower developed by the combustion engine on the locomotive. Unless stated otherwise, all references in this report to horsepower refer to the tractive horsepower of the locomotive.

<sup>119</sup> A "gen-set" is a self-contained modular package of power generating equipment consisting of a diesel or gas engine coupled to an electrical generator.

<sup>120</sup> Green Goats for both Railroads have been returned to the manufacturer for modification to resolve an equipment malfunction that causes engine fires. One Green Goat for UP is already back in limited service, and the remaining UP Green Goats should be back by the end of the year. BNSF's Green Goats are still with the manufacturer. Some railroads may retrofit Green Goats as gen sets before returning them to operation.

demonstrations have given the Railroads a great deal of information about the practicality of using natural gas-fueled locomotives. Figure 16 below highlights the main Western Class I Railroad research efforts since 1935. While natural gas locomotive technology does not compare favorably with the current Tier 2 standards, it will look even less promising when compared with the forthcoming Tier 3 and Tier 4 standards. EPA has proposed the following standards requiring reductions from the Tier 2 baseline: Tier 3 standards specifying a 50% reduction in particulate matter (PM) effective in 2012; Tier 4 standards requiring an 85% reduction in PM effective 2015 and a 76% reduction in NO<sub>x</sub> in 2017.

**Figure 16: Timeline of Railroad Research Activities**



### Basis of Comparison

The basis for evaluating the performance of any locomotive technology—including natural gas-fueled locomotives—should be the most stringent applicable EPA locomotive emission standards. These are currently Tier 2 and test protocols, not pre-regulation emission levels. Until EPA adopts the Tier 3 and Tier 4 emissions standards, as expected in the beginning of 2008, the proposed standards are subject to change. This report therefore maintains Tier 2 as the benchmark for emissions comparison.<sup>121</sup> This basis provides the only objective means to compare diesel, natural gas-fueled or any other locomotive technology.<sup>122</sup> Any comparison of effectiveness and long term integrity of a locomotive technology should consider the change in the overall emissions inventory (i.e., consider broader emissions criteria than PM and NO<sub>x</sub>). This is essential considering there are often trade-offs involved in reducing specific emissions such as increased fuel use to run filters and catalysts that scrub out NO<sub>x</sub> and PM, resulting in increased GHG emissions. Additionally, cost effectiveness is central to any analysis and must consider the infrastructure and interoperability costs of any shift in technology.

<sup>121</sup> When the Tier 3 and Tier 4 standards are adopted, the Railroads expect this will make LNG alternatives less favorable in comparison to new clean diesel locomotives, not more.

<sup>122</sup> See 40 CFR §§ 92.7 and 92.8. See also Appendix 5.



Also, to ensure an “apples-to-apples” emissions comparison, locomotive emissions performance should be evaluated using EPA certification test protocols (the federal test procedure (FTP)). The FTP uses a steady-state cycle with weighting factors. Current EPA duty-cycle weighting factors are applied to emissions measurements taken from locomotives manufactured before the EPA cycle was created so that they can be compared to emissions measurements taken from newer locomotives. This ensures that previously collected emissions data can be compared.

## Emissions Performance

The Railroads currently know of one commercially available, proven and tested natural gas-fueled line-haul locomotive product available for the North American locomotive market. It is available only as a retrofit or conversion product. It would convert an approximately 25-year-old, EMD645-E3 3,000 hp diesel locomotive to run on natural gas. Comparing the exhaust emissions of this converted locomotive with those of EPA certified Tier 2 compliant diesel locomotives shows that the new diesel locomotives outperform the natural gas-fueled locomotive on emissions (see Table 18). ECI may be able to repeat the application of this conversion kit on to a more advanced EMD710 engine with similar success in emissions reductions.

**Table 18– Comparing Natural Gas-fueled Line-haul Locomotive Conversion and Certified Tier 2 Diesel Line-haul Locomotives (g/bhp-hr)<sup>123</sup>**

Mode	THC	NMHC	CO	NO <sub>x</sub>	PM
<b>ECI Natural Gas Conversion</b>	7.55	1.17	10.0	5.2	0.38
<b>Diesel Tier 2 compliant EMD</b>	0.22	0.22	1.0	5.1	0.07
<b>Diesel Tier 2 compliant GE</b>	0.16	0.16	0.4	5.3	0.10

There is no NO<sub>x</sub> benefit from using this natural gas-fueled locomotive, and all other criteria pollutant emissions are higher—including particulates, which are four to five times greater. Compared to the operation of the same locomotive on diesel fuel, natural gas is less energy efficient<sup>124</sup> and produces more greenhouse gas emissions (CO<sub>2</sub> equivalent). Also, a locomotive using this natural gas conversion kit will likely have higher emissions of some toxic air containments, especially formaldehyde.

## Niche opportunities may exist

There may be niche opportunities to use natural gas in certain locomotive applications, such as the liquefied natural gas (LNG) rail yard switch locomotives in service in Los Angeles for

<sup>123</sup> EF&EE Report, Table 11, April 1994.

<sup>124</sup> For more on energy content of natural gas see Section 8

the BNSF. Another possible use is the multi engine “gen set” switch locomotive outfitted with natural gas-fueled engines. However, because of the relatively small amount of fuel consumed by yard switchers and the possible use of diesel particulate filters on gen sets, there may be little improvement in emissions by using natural gas as a fuel in these engines, and it begs the question as to what advantage there would be in using natural gas given the requisite infrastructure costs that accompany it.

### **Cost Savings Claims**

Claims that natural gas-fueled locomotives will be less expensive to operate than diesel equipment are unfounded. In recent years, prices in the North American natural gas market have been high and unstable. Moreover, support of natural gas-fueled locomotives will require significant investments in new fueling infrastructure that are duplicative to established diesel based infrastructure. These infrastructure investments and their associated operating costs must be accounted for in any evaluation of cost effectiveness.

### **Looking to the Future**

EPA has announced its intention to issue final regulations for Tier 3 and Tier 4 locomotive standards by the end of 2007 which will further reduce emissions from new and rebuilt locomotives. Locomotive manufacturers are pursuing further improvements to diesel locomotive and locomotive engine technology to meet these requirements. Given the small size of the locomotive market (approximately one locomotive is sold for every 211 Class 8 trucks)<sup>125</sup> and given manufacturers’ personnel and financial constraints, it is highly doubtful the builders can simultaneously pursue further improvements in diesel locomotive technology and natural gas-fueled locomotive development. Because of these constraints, it is important for the regulatory agencies to set overall emission performance requirements and give the builders the flexibility to determine the most cost-effective and commercially reasonable way to achieve these goals.

The western Class I freight railroads<sup>126</sup> have and will continue to assess the potential use of natural gas-fueled locomotives. While some air quality regulators argue that natural gas-fueled locomotives are preferable to advanced diesel-based engines for achieving significant emission reductions (particularly for NOx and PM), the Railroads disagree. As long as cleaner diesel locomotives continue to be the most cost effective strategy for reducing emissions from rail operations, the Railroads will prioritize investments in diesel technology over natural gas. To put the technologies in perspective, during the last three years the western Class I railroads have made investments and purchase commitments exceeding \$3 billion to build and bring new clean line-haul and switch duty diesel locomotives to California and elsewhere. These locomotives meet and exceed the current EPA locomotive emission standards. From the perspective of dollars per ton of emissions reduced, infrastructure and other operational expenses associated with expanding the use of natural gas as a locomotive fuel keep it from being cost competitive with diesel technology as a means of reducing emissions.

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<sup>125</sup> For information on the size of the 2004 truck market, see <<http://www.nada.org>>.

<sup>126</sup> The BNSF Railway Co. and the Union Pacific Railroad Co.

## **Appendix 1 – Additional Measures to be Evaluated According to Section 8(c) of the MOU on Rail Yards**

(c) Additional Measures. The parties agree to continue to meet and confer to evaluate additional measures that are feasible at the Designated Rail Yards. The initial list of possible measures includes:

- (i) Accelerated replacement of line haul locomotives operating outside of the South Coast Air Basin with lower emitting locomotives.
- (ii) Retrofit or rebuild of existing line haul locomotives with lower emitting technology.
- (iii) The use of other lower-emitting technologies, such as LNG- or CNG-fueled locomotives, truck engine switch locomotives or battery/electric hybrid switch locomotives in Designated Yards.
- (iv) Retrofit of non-locomotive diesel rail yard equipment with diesel particulate filters or other diesel particulate matter emission reduction devices.

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## Appendix 2 – Internal GE Memo, UPRR R&D Effort

To: Mr. Mike Iden (UPRR)  
From: Dave Ducharme (GETS)  
Date: 19 November 2003  
Subject: Clarification on results of UP/GETS Dual Fuel Diesel Engine Project

Mike, I am providing the following information in response to the concerns you expressed in your e-mail of 19 November 2003 regarding the assertion that the UP funded, GETS developed dual fuel locomotive diesel engines were built and tested over the road on a major US railroad.

The paper entitled “The “H-Process” Dual Fuel Diesel Engine” appearing in ASME ICE-Vol 24, Natural Gas and Alternative Fuels for Engines 1995 and written by Mr. B. D. Hsu et. al., indicated that the dual fuel (i.e. liquefied natural gas and diesel fuel) diesel engine powered locomotives developed by General Electric Transportation Systems business in the 1994-1995 timeframe were operated in a field test on a major US railroad. Available records (primarily GETS internal memos) and interviews with GETS employees who were involved and/or aware of the project indicate that in fact, testing was limited to that done at the GETS factory in Erie Pennsylvania and was suspended before the dual fuel engine locomotives were tested over the road or in railroad service. Available records and these interviews indicate that due to technical difficulties GETS and UP mutually agreed to suspend testing. The locomotives were subsequently delivered to UPRR in a diesel fuel only configuration. The internal memo indicates that even though sufficient laboratory testing had been done to show that lower NOx emissions could be achieved, there were several significant component durability issues that would make over the road testing impractical if not impossible. The component durability issues were specifically related to the liquefied natural gas fuel injectors, the liquefied natural gas fuel pump and gas delivery system, engine control system software, gas transition control software, and fuel system joint leaks. In light of these issues GETS was only able to demonstrate approximately 5 continuous hours of operation in the liquefied natural gas (LNG) mode. GETS internal memo and the interviews indicate that GETS made a recommendation to UP advising against an over the road test unless the durability issues were resolved. It is also indicated in the memo that solutions for the durability issues were not known and significant time and resources would have to be invested to attempt to find solutions.

In summary limited operation in a laboratory environment showed that significant NOx reduction could be achieved by operating a locomotive engine with LNG however the lack of durable and reliable fuel injection, gas delivery, and control system components made an over the road and/or an in railroad service demonstration impractical if not impossible.

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## Appendix 3 – Comments of GE and EMD

The BNSF and UPRR requested comments from GE and EMD concerning each company's current and future research and development directions. At the time this report was completed we received the following email comment from EMD:

At this time EMD has no active engineering research / design projects regarding natural gas technology. We continually update and evaluate our product plan and should any changes occur regarding LNG I will let you know.<sup>127</sup>

The Railroads also received the following email comment from GE:

GE does not have any ongoing projects/studies related to LNG-fuel alternatives. In addition, our Corporation does not have any active LNG-fuel research projects. We are, however, continuing to develop a GE 'diesel vs. LNG' position statement (per your earlier request) in support of the position paper you are jointly creating with BNSF and AAR. Since our current involvement in the area of LNG-fuel alternatives has been minimal, it is taking us some time to thoughtfully develop and finalize our position. I will keep you updated on our progress.<sup>128</sup>

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<sup>127</sup> James Schnabel (EMD), email to Mike Iden (UPRR), 11 January 2006.

<sup>128</sup> Richard J. Kolkman (GE Transportation), email to Mike Iden (UPRR), 19 January 2006.

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## **Appendix 4 – U.S. EPA Document References**

Locomotive exhaust emission standards are published in 40 Code of Federal Regulations (CFR) §§ Parts 92, 94, and 1033 et al. Additionally, please note various subparts of the regulation:

- Subpart B: Equipment specifications; required hardware for testing.
- Subpart C: Measurement instruments.
- Subpart D: Calibration and verifications; for measurement systems.
- Subpart E: Engine selection, preparation, and maintenance.
- Subpart F: Test protocols; step-bystep sequences for laboratory testing and test validation.
- Subpart G: Calculations and required information.
- Subpart H: Fuels, fluids, and analytical gases.
- Subpart I: Oxygenated fuels; special test procedures.
- Subpart J: Field testing and portable emissions measurement systems.
- Subpart K: Definitions, references, and symbols.

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## Appendix 5 – Calculation Details for Exhaust Emissions Data

Data presented in Sections 10 and 11 have been provided three ways: (1) a brake specific basis (g/bhp-hr) that results from emission measurements required for EPA certification, (2) a fuel-specific basis (g/gallon), and (3) annual or daily emissions from typical operation, defined as 400,000 gallons per year for a line-haul locomotive and 40,000 gallons per year for a switch locomotive. The fuel specific emission factors are usually found by multiplying the brake specific emission factors by the duty cycle weighted brake specific fuel consumption. The fuel specific emission factors can then be multiplied by the annual fuel use to determine the annual emissions. Locomotives are assumed to operate 365 days a year for the computation of the daily emissions.

Data on brake specific fuel consumption is often not available. For example, such data are not given in the publicly available EPA certification data.<sup>129</sup> Where these data are not available, the fuel efficiency for line-haul locomotives can be estimated from a recent report by Sierra Research that updated the guidance for emission inventories to account for the new locomotives standards.<sup>130</sup> Although this updated guidance has not yet been formally approved by EPA, the following table, taken from that report, shows the emission and energy performance locomotive models that were manufactured prior to the 1998 adoption of EPA's locomotive standards.

**Table A5-1: Locomotive Emission and Energy Performance Used Here for Fuel Use Data**

Locomotive	Percent of U.S Class I Railroad fleet <sup>131</sup>	Brake-Specific Emissions (g/bhp-hr)				Fuel use bhp-hr/gal
		HC	CO	NO <sub>x</sub>	PM	
SD70MAC	13.4%	0.31	1.5	12.7	0.37	20.3
C40-8	8.6%	0.32	0.88	14.6	0.18	20.4
C44-9W	28.8%	0.31	1.8	11.7	0.17	20.0
SD75MAC	5.1%	0.31	1.5	12.7	0.37	20.6

The weighted average fuel use for the locomotives in this table is 20.2 bhp-hr/gallon of diesel fuel. A rounded value of 20 bhp-hr/gals, was used for three diesel-fueled line-haul locomotives, the SD60 and the two Tier 2 locomotives, shown in Table 13 (e.g. Line-haul locomotive comparison). Multiplying the brake-specific data by the fuel use gives the fuel specific emission factors. Multiplying the latter factors by the annual fuel use of 400,000 gallons per year (and assuming operation 365 days per year) gives the daily emissions.

<sup>129</sup> The certification data was downloaded from <<http://www.epa.gov/otaq/certdata.htm#locomotive>> on 21 December 2005.

<sup>130</sup> Sierra Research, Inc., and Larry Caretto, "Development of Railroad Emission Inventory Methodologies," Report SR2004-06-02, June 2004.

<sup>131</sup> These percentages are based on a 2002-03 survey and do not reflect the current fleet composition. The data represents the pre control fleet; Tier 1 and 2 locomotives have not had a significant change in fuel economy.

For the ECI conversion locomotive, the annual emissions were computed by assuming that it would produce the same annual energy as a line-haul locomotive burning 400,000 gallons per year of diesel fuel and producing 20 bhp-hr/gallon. This gives an annual energy production of 8,000,000 bhp-hr/year. Multiplying the brake specific factors for the ECI conversion by this annual energy use gives the annual tons as shown in the Table below.

**Table A5-2: Emission Results for ECI Conversion Kit**

Description of Result	THC	NMHC	CO	NO <sub>x</sub>	PM
Brake specific (g/bhp-hr)	7.55	1.17	9.96	5.16	0.38
Annual (tons per year)	66.6	10.3	87.8	45.5	3.4
Daily (pounds per day)	365	56	481	249	18.5
Fuel specific (g/gal diesel equivalent)	151	23.3	199	103	7.7
Note: The fuel specific factor is <i>not</i> the emissions per gallon of LNG (or emissions of total gallons of LNG plus diesel fuel) burned in the ECI conversion kit locomotive.					

The final row in this table is a hybrid emission factor representing the emissions of the ECI conversion per gallon of equivalent diesel fuel consumed. Using this basis the fuel specific emissions factors for the ECI conversion can be directly compared to the similar factors for diesel-fueled locomotives. In any event, it would be difficult to obtain a fuel specific emission factor for this locomotive since it burns a combination of natural gas and diesel pilot fuel.

The comparison locomotive for yard locomotives is an EMD GP 38-2. For this locomotive, available data showed a fuel use of 14.76 bhp-hr per gallon.<sup>132</sup> This value was used to compute the fuel specific emission factors and the daily emissions shown in Table 12 (i.e. Switch locomotive comparison). The annual emissions and the fuel-specific emission factors for the MK Rail LNG switch locomotive were found using the same approach used for the ECI conversion kit. The annual energy requirement for the GP 38-2, using 40,000 gallons per year and producing 14.76 bhp-hr/gallon is 590,400 bhp-hr per year. Multiplying the brake specific emission factors for the MK Rail locomotive by this figure gives the annual emissions.

**Table A5-3: Emission Results for MK Rail LNG Locomotive**

Description of Result	HC	CO	NO <sub>x</sub>	PM
Brake specific (g/bhp-hr)	3.3 <sup>133</sup>	2.2	1.4	0.09
Annual (tons per year)	2.17	1.45	0.92	0.06
Daily (pounds per day)	11.9	7.92	5.02	0.33
Fuel specific (g/gal diesel equivalent)	49.2	32.0	20.3	1.35
Note: The fuel specific factor is <i>not</i> the emissions per gallon of LNG				

<sup>132</sup> Environmental Protection Agency, "Locomotive Emission Standards, Regulatory Support Document," (April 1998).

<sup>133</sup> There is some confusion in that this number is reported in one sources as HC and in another as NMHC, however, it is most likely HC.

## Appendix 6 – Railroad Responses to Questions and Issues Raised by the Bay Area Air Quality Management District

This section addresses questions raised by the April 12, 2006 **Bay Area Air Quality Management District (BAAQMD)** letters. The Railroads organized the responses into the following four sections. Text from the BAAQMD comment letter is shown below in italics.

### Comments of BAAQMD

#### 1. What emissions would be possible from newly designed and built LNG locomotives?

*This "new apples to old apples"<sup>134</sup> comparison is necessitated by the lack of new, purpose built LNG locomotives. The comparison however is only useful for highlighting the large strides made in cleaning up diesel locomotive emissions rather than refuting the potential for new LNG locomotives. Newly designed LNG locomotives would most likely be lower in emissions than a converted, older diesel engine. At a minimum, the newer LNG locomotives, if they existed, would meet the EPA Tier II standards.*

**Railroad Response:** Natural gas provides cleaner emissions than diesel in other mobile sources in some niche areas. The Railroads and the locomotive builders, however, do not know if the use of natural gas in locomotives is practical or feasible for a newly designed LNG locomotive that must at least meet existing EPA Tier 2 or, more importantly, the future locomotive emission standards currently under development. Given existing knowledge, improvements to diesel technology have met the existing Tier 2 standards. The Railroads believe using clean diesel technology to meet EPA Tier 3 and Tier 4 locomotive emission standards will be more cost-effective than natural gas, especially when considering the duplicate fueling infrastructure implications.

Regarding the "new apples to old apples" comparison, the Railroads believe it is relevant to establish a foundation of empirically-derived facts and observations about what is known today about the use of natural gas as a locomotive engine fuel. This foundation provides insights into the future direction (and challenges) of locomotive engine development. The report highlights several important development challenges for any future LNG locomotives. For example, industry experts agree that a high-pressure injection system is the engine configuration most likely to provide commercially acceptable power densities for line-haul locomotive applications. However, high-pressure injection has not yet been developed beyond the laboratory engine stage. Significant development and reliability testing would also be required.

Second, the new EPA locomotive emission standards will likely require after-treatment to reduce NMHC, CO, HC, and PM emissions. After-treatment devices to reduce PM and NOx emissions are currently under development for diesel engines and should be able to be adapted to LNG locomotive engines as well (the Railroads are not aware of any efforts to

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<sup>134</sup> pp. 8, 20, & 57 of the report

develop after-treatment for LNG locomotive engines). However, if clean diesel can achieve the forthcoming standards, the reasons for switching to LNG are less compelling given the existing technical hurdles for line-haul units, the lack of fueling infrastructure, and the 20% efficiency reduction from using LNG as a locomotive fuel. Regardless, the EPA Notice of Proposed Rule Making (NPRM) remains fuel neutral—an important regulatory design principle—and would allow for an alternative fuel locomotive to meet these future standards.

The report also discusses the locomotives that are available today using diesel fuel and natural gas. Any short-term decisions about how to reduce locomotive emissions must be based on the available technology discussed in the Railroad report.

## **2. What are the costs and emission results from using LNG in the hybrid and gen-set locomotives discussed in the report?**

*We would, however, like to learn more about the potential for using natural gas instead of diesel engines in both the hybrid and "gen-set" switch designs. This option is dismissed without much discussion on pages 32 - 33. We recommend that a more in-depth examination of the use of natural gas gen-sets be presented in the paper, along with examples of potential engines, costs and emissions characteristics.*

**Railroad Response:** The Railroads recognize this is a meaningful question and one that the draft report does not address. Spark-ignited natural gas engines in horsepower ratings up to ~700 hp are commercially available and since the draft of this report was released in March 2006, BNSF has been researching if these engines can be used in the multi-engine gen set switch locomotives (e.g. assessing the viability of packaging design, variable duty cycle, noise, vibration, temperature variations and other such factors that impact practicality). Other options for gen set switch locomotives include Tier 4 offroad engines (which will have after-treatment), or onroad engines (which have after-treatment) to further reduce emissions from the diesel engines. It is not clear if low-hp LNG engines would be cleaner than these diesel options. After the new EPA standards require both diesel and LNG low-hp engines to use after-treatment, there will be little or no emissions benefit from using an LNG engine in this application.

To address this question in more detail, it is necessary to identify candidate engines and then compare them to their diesel counterparts. If this is of interest, the Railroads propose this item be discussed at a future CARB/Railroad/Stakeholder technology symposium. In the interim, the Railroads will work with CARB, the locomotive builders, and others to learn more so this question can be addressed.

## **3. What is the potential for using LNG in the California intrastate short haul fleet?**

*The paper does not discuss the potential for LNG conversions for the older locomotives used for short haul service within California. We recommend that the paper be expanded to discuss the potential for LNG conversion on the large number of older locomotives that are part of the California intrastate fleet. These locomotives are used for short-haul service and do not generally serve as switch engines. These ex-line-haul locomotives have higher horsepower ratings than switch*

*engines, and current hybrid and "gen-set" locomotives may not represent suitable replacement technologies. The conversion of these locomotives to LNG operation could return significant emission reductions and the paper should provide a comparison of the average California intrastate locomotive to an ECI LNG locomotive.*

*Many of the [short haul] intrastate locomotive, as reported by UP and BNSF, are not currently compliant with EPA's Tier 0 emissions standard; indeed many are old enough to be exempt from any emission standards. A discussion on the potential costs and emissions benefits of upgrading these locomotives to Tier 0 engines would provide a useful contrast to converting these locomotives to LNG operation. This kind of comparative information would be especially useful in considering potential grant funding to reduce air quality impacts from the current intrastate fleet in California.*

**Railroad Response:** A detailed comparison of the costs of the various retrofit options (including LNG) for older locomotives is beyond the scope of this paper since it would involve accounting for the full scope of impacts, including fueling infrastructure costs. However, as a general principle, the Railroads remain open to learning how incentive funding might be useful in retrofitting the small number of older, short haul in-use locomotives.

The typical cost of a Tier 0 upgrade is approximately \$50,000 compared to an ECI retrofit, which is estimated to cost \$1.5 to \$2 million. The Railroads believe that comparing the diesel Tier 0 rebuild with the ECI natural gas engine conversion is academic since the ECI kit has not demonstrated compliance with EPA Tier 0 emission standards.

Faced with a theoretical choice between converting an older short haul locomotive with the ECI retrofit kit or purchasing a new Tier 2 locomotive, the prudent choice would be to purchase a new locomotive. The Railroads' LNG paper shows that this choice would yield lower emissions. Furthermore, information from the Carl Moyer program<sup>135</sup> indicates that the ECI conversion for one locomotive will range from \$1.5 to \$2 million—compared to the approximately \$2 million price of a new Tier 2 locomotive—before considering additional operating and fuelling infrastructure-related costs. Also, the ECI retrofit kit is not EPA Tier 0 certified, nor has it demonstrated its ability to meet EPA's Tier 0 standards due to CO and HC emissions; therefore, it is not clear if a locomotive can be lawfully retrofitted using this kit.

Nonetheless, the Railroads agree that this question might be discussed at a future technology symposium.

#### **4. Minor adjustments of tables would be helpful to the reader.**

*1) Figure 1, page 4 should be extended to show the number of new locomotives already on order and to be delivered in 2006 and 2007. The Figure should also indicate the fraction of purchases completed by UP and BNSF; 2) Tables 4-6 on pages 21-22 would be clearer if only the EPA*

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Carl Moyer Memorial Air Quality Standards Attainment Program, Response to Request for Proposal, CAPTS, October 2004.

*emissions standards are shown. Inclusion of the measured emissions does not add to the discussion in this section of the paper and are covered more extensively and clearly in a later section.*

**Railroad Response:** Regarding Figure 1 (showing all Class 1 North America new locomotive sales from 1972 - 2007 (est.)—including all types of locomotives), the data shown in Figure 1 is from assorted industry records.<sup>136</sup> The UP and the BNSF generally only publish “rolled-up” industry data and do not separate this information by company. However, the following table has been incorporated into the report and presents the information for the two California Class 1 companies. As noted below, the California Railroads purchased approximately 562 Tier 2 locomotives in 2006 and estimate 2007 deliveries to be around 500.

**Table 2: New Locomotive Purchases by the California Class 1 Railroads**

	Tier 0	Tier 0/ Tier	Tier 1			Tier 2		
Year	2000	2001	2002	2003	2004	2005	2006	2007 (est)
Total purchased by CA Class 1 Railroads	863	891	722	591	1121	604	562	(500)

We appreciate the observation about Tables 4 and 6. We have separated the tables per the suggestion.

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<sup>136</sup> Gathered data through industry data from a variety of trade magazines and publicly released purchase orders.



## Appendix 7– Railroad Responses to Questions and Issues Raised by the South Coast Air Quality Management District

This section addresses questions raised by the July 14, 2006 South Coast Air Quality Management District (SCAQMD) letter. The Railroads organized the responses into the following two sections. The text from the SCAQMD comment letter is shown below in italics.

### Comments of the SCAQMD

#### 1. What is the appropriate comparison between diesel and LNG locomotives?

*While it is true that emissions are similar when a comparison of a 1995 model pre-regulated locomotive engine converted to run on natural gas is compared to a new Tier 2 locomotive engine, the draft report should provide a more appropriate comparison of the emissions between the original diesel locomotive engine with the natural gas converted engine. The relative difference in emissions provides the true benefits of the natural gas engine. This is clearly seen in Table 8 (Pg. 23)[Table 10, pg 29 of revised report], which shows that natural gas locomotive engines are capable of about one-half the NO<sub>x</sub> of a diesel engine, an observation omitted in the Executive Summary.*

**Railroad Response:** We assume the SCAQMD comment is referring to the 1985 model locomotive engine. In the report, the Railroads have described in what is known about the current state of LNG engine technology as it relates to use in locomotives. It is true that the ECI retrofit kit reduces NO<sub>x</sub> emissions when applied to a 25+ year-old in-use pre-Tier 0 locomotive (5 grams NO<sub>x</sub> vs. around 9 grams NO<sub>x</sub> post-rebuild to Tier 0). It is also true that the Railroad Report describes what is known about the ECI kit and points out some limitations, such as the source data (pre-EPA test protocols, etc.). Based on this information, it appears the “kit” can reduce NO<sub>x</sub> on an older locomotive, potentially to the same level as the Tier 2 locomotive but at a penalty of other emissions. Furthermore, such a kit is not even Tier 0 compliant.

If the comparison requested is of a ECI kit applied to a Tier 2 locomotive, we could easily dismiss this. First, such a kit does not exist. Second, it would increase emissions of CO, PM, and HC, based on what we know today.

*In addition, emissions from spark-ignited natural gas switchers were nearly four times lower than their diesel counterpart. Should power be an issue, more cylinders can be used with natural gas units and still have substantially lower emissions.*

**Railroad Response:** For the spark-ignited natural gas switchers it is true that the NO<sub>x</sub> levels are significantly lower than the same vintage engine running on diesel fuel. The Railroad report has been revised and points out that:

“The CO, NO<sub>x</sub>, and PM emissions data meet or exceed the alternative locomotive emission standards for Tier 2 locomotives. Although it is not clear

if the HC data are THC or NMHC, the data are thought to be THC and the NMHC figure is likely to be less than the EPA Tier 2 standard of 0.60 g/bhp-hr.” (Revisions underlined)

The Railroads also note that the natural gas engine’s reduced fuel economy and large methane emissions will lead to higher greenhouse gas emissions. The fifth paragraph in this section of the report was also significantly revised;

“These locomotives will have to meet EPA Tier 0 requirements when they are remanufactured, but the available emissions data indicates that the locomotives already meet Tier 0, 1, and 2 levels except for HC emissions, for which the data are uncertain. If the HC data of 3.33 g/bhp-hr represent THC as expected, the NMHC emissions are likely to be about 0.5 g/bhp-hr. This would meet the Tier 2 NMHC standard of 0.60 g/bhp-hr for natural gas locomotives. The expected value of NMHC emissions for this locomotive will almost certainly be below the Tier 0 requirement of 2.60 g/bhp-hr for natural gas fuel. Also, while MotivePower Industries has not sold any more of these LNG locomotives it has indicated a willingness to do so if an order is placed. Any new locomotives would fall under EPA’s Tier 2 exhaust emission requirements.”(Revisions underlined)

For the existing four natural gas-fueled switch locomotives operated by the BNSF in Los Angeles, the conversion reduces the power output of the engine from 2,000 hp on diesel fuel to 1350 hp.<sup>137</sup> Producing the same power would require the engine displacement to be increased by almost 50% ( $2000/1350 = 1.48$ ). For many line-haul locomotives where power is a critical factor it is not possible to replace the diesel engine with a natural gas engine that has 50% more cylinders.

*Regardless, late-cycle, high-injection-pressure, natural-gas locomotive engines have demonstrated lower NOx without any loss of power or efficiency with the same size of engine.*

**Railroad Response:** The Railroads agree late-cycle, high-injection-pressure would be the most promising technology for use of natural-gas on line-haul locomotives. However, even with this technology, efficiency is less with natural gas, than it is with diesel fuel. (See the discussion of the 710 engine in the Gas Rail Program on page 32 in the report: “3 g/bhp-hr NOx when evaluated over the EPA line-haul duty cycle, compared to a 12 g/bhp-hr NOx level for the same engine operating on diesel fuel.” ... “[However,] “there was an 8% reduction in efficiency.”)<sup>138</sup>

*Emissions data prior to locomotive emission standards and test procedures are valid information and the natural gas locomotive engines were tested consistently and appropriately compared with diesel engines. The test data from the prototype natural-gas locomotive engines can be used to*

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<sup>137</sup> These four LNG switchers have never been emission tested and do not have EPA Tier 0 certification.

<sup>138</sup> The paper (page 32) also references notch-8 data for a GE engine using the same technology that shows essentially no decrease in efficiency, however, the NOx reduction is only 48% from a baseline of 14.1 g/bhp-hr.

*compare their relative emission capabilities. Such engines when compared to diesel locomotive engines tested under similar test conditions clearly show lower emissions.*

**Railroad Response:** The Railroads agree that pre-regulation data can be used to compare diesel and LNG engines. In fact, the Railroads interpreted pre-regulation emissions information gathered by SwRI on the ECI-modified BN locomotive to make comparisons to EPA-certified locomotives. However, there are two other issues to be considered. First, now that the EPA has adopted emissions certification test protocols, every effort should be made to test locomotive engines using these protocols to ensure the accuracy of comparisons. Second, when using pre-regulation emissions data, the data must be used to ensure that it is reasonably consistent with notch specific weighting factors now in use as part of the EPA-adopted protocols.

*The draft report also asserts, without supporting analysis, which it would be uneconomic to establish low-emission locomotive pools dedicated to a particular area such as the South Coast Air Basin, and that the resulting economics would result in a shift of goods transport to trucks, with a resulting increase in emissions. This argument is questionable in four ways. First, the analysis in the 1994 CARB report (EFC&EE) shows that a California-only locomotive fleet would result in only a modest cost increase compared to then-prevalent operating pattern. This modest cost increase does not appear to significantly alter the truck/rail split.*

**Railroad Response:** The Railroads rebutted the assertions made in the draft 1994 contractor's report to CARB at the time of publication. That report was never relied upon by any decision-making body to establish the relative opportunities or challenges associated with LNG.

The Railroads did not intend this report to address all of the implications of using natural-gas fueled locomotives (operational and maintenance issues, fueling infrastructure, etc). Such an analysis is well beyond the scope of the Railroad report. The Railroads believe that the costs of establishing separate pools of locomotives is uneconomic and would lead to a variety of severe financial and logistics impacts to the goods-movement industry.

*Second, no such analysis compared the added capital and operating costs of the 1998 MOU (i.e., the added costs of this segregated fleet were acceptable to the Railroads).*

**Railroad Response:** As noted above, a capital and operating cost analysis is well beyond the scope of this report.

However, it is important to note that the 1998 MOU (Fleet Average Agreement) does *not* require a dedicated fleet in the South Coast Air Basin. In fact, this MOU requires each Railroad's fleet, on average, to meet Tier 2 NO<sub>x</sub> requirements. The CARB and EPA-approved Fleet Average Agreement uses a performance-based standard, rather than a prescriptive standard, that guarantees, on average, the Tier 2 NO<sub>x</sub> emission levels will be achieved. This method provides flexibility to the Railroads and allows each company to develop compliance strategies for achieving those standards based on their respective rail systems and operations. Requiring a captive fleet removes flexibility the Railroads need to efficiently conduct freight operations on rail lines within the South Coast Basin and over a

large portion of its entire system due to the rippling effects that service interruptions in one area can have on other parts of the system. The imposition of regional specifications for individual line-haul locomotive units already subject to the 1998 MOU would thwart the Railroads' implementation planning and would threaten the Railroads' ability to conduct efficient rail operations throughout this part of the system. Furthermore, were one to introduce the requirement for a captive fleet that necessitated an entirely new fueling infrastructure to operate, it would drastically compound operating inefficiencies and costs.

*Third, the Port of Los Angeles Portwide Rail Synopsis report recommends the use of dedicated "shuttle" locomotive consists between the Port and an inland location for purely operation reasons--- to reduce rail congestion and delays due to light locomotive moves, locomotive turning, and inter-terminal transfers. Such shuttle locomotives could readily operate on natural gas, or otherwise be retrofitted with emissions after-treatment devices.*

**Railroad Response:** Shuttle trains have been advocated by consultants who do not operate Railroads. The Railroads have always cautioned there are complex and unintended consequences of such a requirement, regardless of the locomotive propulsion method chosen. In any case, such units would be governed by the same shortcomings noted elsewhere in the report, especially when the requirements of the 1998 MOU are considered.

*Fourth, it is by no means clear, as the draft report claims, that a shift from rail to truck would increase emissions. A fleet of advanced, 2010-standard natural gas or "clean" diesel trucks shuttling containers to and from the Ports would likely result in lower NO<sub>x</sub> and PM emissions per container than moving the same containers by rail using Tier 2 locomotives as provided in the 1998 MOU.*

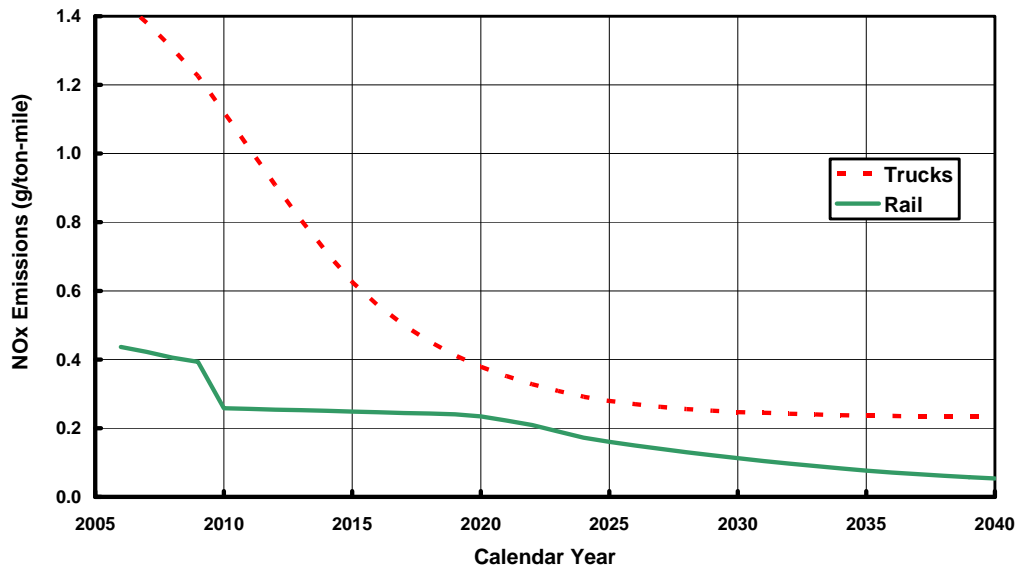
**Railroad Response:** EPA – the only agency with jurisdiction over new and in-use locomotives – is currently developing new locomotive emission standards requiring an additional 50-90% reduction compared to Tier 2 standards when fully phased-in in 2017. Currently, rail remains the most environmentally friendly way to move freight over land; trains are two to three times cleaner (for NO<sub>x</sub> and PM) than trucks. With the adoption of new EPA regulations that require locomotives to be substantially cleaner than existing locomotives, the Railroads will retain their environmental advantage.

According to a review of the EPA's proposed marine and locomotive engine rule Regulatory Impact Analysis,<sup>139</sup> the truck and rail emission forecasts in the South Coast Air Basin show the rail NO<sub>x</sub> emissions drop significantly between 2009 and 2010 due to the fleet average agreement. PM also decreases, but the effect is less pronounced. Both NO<sub>x</sub> and PM rail emissions continue to drop through 2020 at a moderate rate and decrease more rapidly after 2020 when the new EPA standards begin to take effect. Truck emissions decrease rapidly through 2020 and then flatten out through 2040.

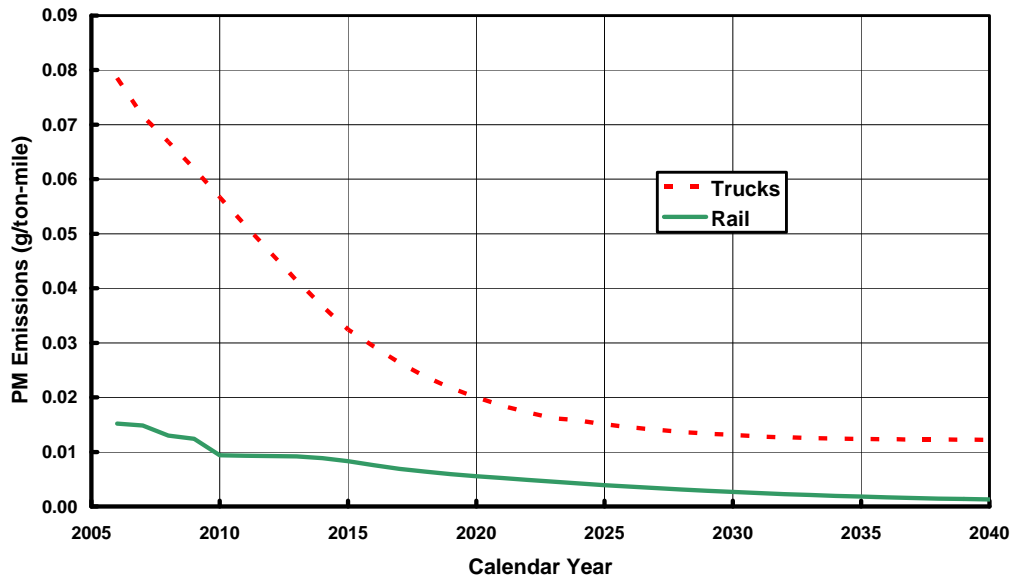
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<sup>139</sup> Larry Caretto, Effect of Proposed Locomotive Rule on the Comparison of Rail and Truck Emissions per Ton Mile of Freight Projections for South Coast Air Basin and Statewide Emissions in California for 2006 – 2040, October 5 2007

**Figure 1 -- NOx Emissions per Ton Mile of Freight  
South Coast Air Basin**



**Figure 2 -- PM Emissions per Ton Mile of Freight  
South Coast Air Basin**



Also, until such a fleet of “advanced, 2010-standard natural gas or ‘clean’ diesel trucks shuttling containers to and from the Ports” as envisioned by the SCAQMD is required by some agency with authority to do so, the hypothetical comparison of comparative fleet emissions rates is purely speculative.

## 2. Should LNG locomotives be considered as an emissions control technology?

*In conclusion, the draft report conclusions regarding natural gas locomotive engines are unsupported by either data or analysis. While the report is correct in stating that “clean diesel” technology can achieve similar levels to the older general natural gas engines, the latest generation natural gas engines are still about 50 percent cleaner than their diesel counterparts. The SCAQMD staff believes that natural-gas locomotives represent a viable low-emission approach that should be considered as a means to achieve air quality goals and minimize health effects in communities surrounding rail yards and Railroad activities.*

**Railroad Response:** It is important to note that recent LNG line-haul or switch locomotives have not been produced for the reasons and constraints outlined in the Railroads’ paper. Nevertheless, the Railroads agree that all low-emissions approaches should be considered. When the Railroads have evaluated feasible options, they come to the conclusion that the cleanest and most practical alternative available today is clean diesel locomotives. The Railroads further agree that all “viable low-emission approach[es] that should be considered as a means to achieve air quality goals and minimize health effects in communities surrounding rail yards and Railroad activities”. To date, in the Railroads opinion, natural gas powered locomotives have not been established as “viable.”