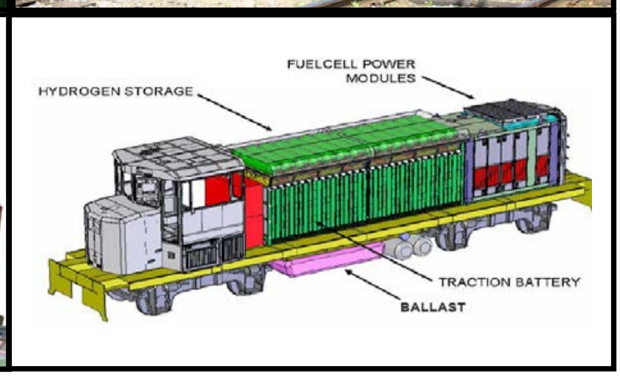
California Environmental Protection Agency

AIR RESOURCES BOARD

TECHNOLOGY ASSESSMENT:

FREIGHT LOCOMOTIVES



November 2016

TECHNOLOGY ASSESSMENT: FREIGHT LOCOMOTIVES

Air Resources Board
Transportation and Toxics Division
November 2016

Electronic copies from this document are available for download from the Air Resources Board's Internet site at: http://www.arb.ca.gov/msprog/tech/report.htm.
In addition, written copies may be obtained from the Public Information Office, Air Resources Board, 1001 I Street, 1st Floor, Visitors and Environmental Services Center, Sacramento, California 95814, (916) 322-2990.

This page left intentionally blank

Table of Contents

Table of Contents – Continued

List of Figures

List of Figures – Continued

List of Tables

List of Tables – Continued

This page left intentionally blank

EXECUTIVE SUMMARY

The California Air Resources Board's (ARB, or CARB) objective is to transition on-road and off-road mobile sources to zero tailpipe emissions everywhere possible, and near-zero emissions with clean, low carbon renewable fuels everywhere else, to meet air quality and climate goals. The purpose of this freight rail technology assessment is to help inform and support ARB planning, regulatory, and voluntary incentive efforts, including:

- California Sustainable Freight Action Plan;
- State Implementation Plan (SIP) development;
- Funding Plans;
- Governor's Zero-Emission Vehicle Action Plan; and
- California's coordinated goals to reduce greenhouse gases (GHG) and petroleum use by 2030 and 2050.

Scope This ARB freight rail technology assessment considers potential advanced locomotive technologies that could operate on the existing rail network with emissions well below the current national Tier 4 emission levels. This assessment is not focused on passenger rail, but many of the same technologies, especially full electrification, would be feasible on that service. ARB staff will separately examine zero-emission cargo conveyance systems that may be potential alternatives to rail and truck transport.

Contents The assessment includes the following elements:

- This Executive Summary introduces locomotives and the rail system, then highlights the findings of this assessment regarding the most promising next generation of cleaner technologies, zero-emission track-mile technologies, and zero-emission technologies.
- Chapter I examines North American and California railroad operations.
- Chapter II provides a summary of the current federal and California programs to reduce locomotive emissions.
- Chapter III looks at the current Tier 2, Tier 3, and Tier 4 locomotive technologies, including establishing Tier 4 as the baseline to compare with advanced locomotive technologies (i.e., those technologies that go beyond Tier 4 levels).
- Chapters IV through IX provide technical assessments of advanced locomotive technologies including aftertreatment, fuel cell locomotives, battery power and battery tender powered locomotives, and freight railroad electrification.
- Chapter X includes suggested pathways for research, development, and demonstration of zero-emission track-mile and zero-emission locomotives.

University of Illinois Report In mid-2016, a research report entitled *Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System in California: Operational and Economic Considerations (U of I Report)* was commissioned by the ARB and developed by the Rail Transportation and Engineering Center at the University of Illinois (U of I). The objective of the U of I Report was to identify and examine the operational changes and economic challenges and opportunities associated with a transition from conventional diesel-electric to zero or near-zero emission line-haul freight rail operations. The executive summary of this report is attached as Appendix B to the freight rail technology assessment. The full report can be found at http://www.arb.ca.gov/railyard/railyard.htm.

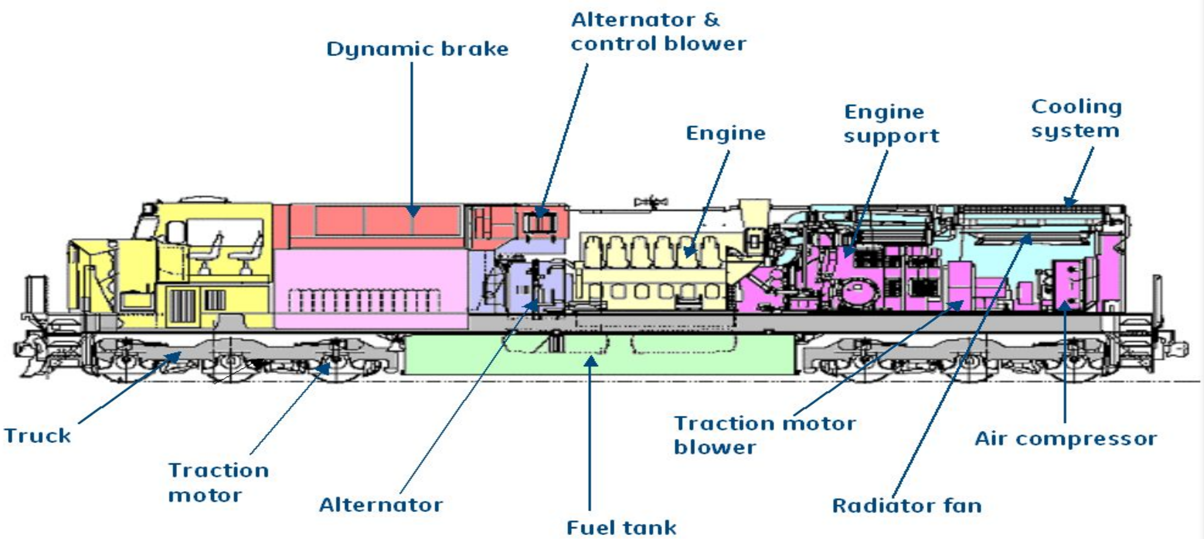
1. What is a locomotive?

A locomotive is a self-propelled vehicle used to push or pull trains. The combination of locomotive(s) pulling freight or passenger railcars forms a train.

A typical freight and passenger locomotive in the United States is powered by a diesel engine that drives an electrical generator or alternator. The generator provides electricity to the traction motors, which in turn drive the locomotive wheels. This is referred to as a "diesel-electric" locomotive. See Figure ES-1 (below) for a diagram of a freight diesel-electric interstate line haul locomotive.

The United States Environmental Protection Agency (U.S. EPA) definition for a locomotive is:

> *Locomotive means a self-propelled piece of on-track equipment designed for moving or propelling cars that are designed to carry freight, passengers or other equipment, but which itself is not designed or intended to carry freight, passengers (other than those operating the locomotive) or other equipment.* (Title 40 Code of Federal Regulations (CFR) Part 1033.901)



Key Specifications: Built with a large medium speed engine (about 1000 revolutions per minute, or rpm), rated at about 4,400 horsepower (hp), typically with 12 or 16 cylinders. Built with a 5,000 gallon fuel tank, this large fuel tank allows a typical freight interstate line haul locomotive to operate, on average, up to 1,000 miles between refuelings.

Figure ES-1:
Diagram of a U.S. Freight Diesel-Electric Interstate Line Haul Locomotive

2. What types of locomotives operate in California?

U.S. EPA specifically defines the smaller switch (yard) locomotive, also called a switcher, to be between 1,006 and 2,300 horsepower (hp). U.S. EPA also defines higher horsepower locomotives as line haul locomotives (i.e., >2,300 hp). (40 CFR Part 1033.901)

ARB staff categorizes U.S. diesel-electric freight and passenger locomotives into three major groups, primarily based on horsepower and types of operations:

- Interstate line haul – (>4,000 hp);
- Medium horsepower (MHP) – (2,301 to 3,999 hp); and
- Switch (yard) – (1,006 to 2,300 hp).

ARB staff further refined the U.S. EPA definition of a freight line haul locomotive. ARB recognizes the significant differences between interstate and MHP line haul locomotives based on: 1) age, 2) horsepower, 3) pulling power or tractive effort, 4) activity and annual fuel consumption levels, and 5) the type of work performed.

3. How do typical U.S. freight and passenger locomotive engines operate?

U.S. diesel-electric freight and passenger locomotives are typically powered by medium speed diesel engines that operate at about 1,000 revolutions per minute (rpm), as compared to a high speed truck engine rated at about 1,800 rpm. An interstate line haul locomotive typically has a 12 or 16 cylinder engine with a gross rating of about 4,500 hp, which is about ten times more horsepower than an average heavy-duty diesel truck.

The newer U.S. diesel-electric freight interstate line haul locomotives have considerable pulling power by being able to apply up to 200,000 pounds of force from the wheels to the rail. Engine efficiency is the relationship between the total energy contained in the fuel, and the amount of energy available to perform useful work. The newest diesel-electric freight interstate line haul locomotives can have engine efficiencies of up to 40 to 50 percent.

4. Who are the railroad operators in California?

The federal Surface Transportation Board (STB) defines Class I (major), Class II (regional), and Class III (shortline) freight railroads based on annual operating revenue. In 2013, Class I major railroads were defined as having greater than $467 million in annual operating revenue. (AAR, 2015) Table ES-1 shows the categories of locomotives operated in California, together with the emissions of nitrogen oxides (NOx) from each category.

Table ES-1:
California Locomotives and
Percent of Statewide Locomotive NOx Emissions

Type of Service	Categories of California Locomotives	Percent of Statewide Locomotive NOx Emissions
Freight	Class I interstate line haul locomotives	85%
	Class I intrastate locomotives	8%
	Class III shortline intrastate locomotives	1%
	Military and industrial intrastate locomotives	<0.4%
Passenger	Passenger intrastate MHP locomotives	6%

Class I Freight Railroads

California's two Class I or major railroads, Union Pacific Railroad (UP) and BNSF Railway (BNSF), operate about 10,000 freight *interstate* line haul locomotives annually within the State, and represent about 85 percent of statewide locomotive activity and emissions. (ARB, 1998a) UP and BNSF also operate about 400 to 500 *intrastate* locomotives that represent about an additional eight percent of statewide locomotive activity and emissions. (ARB, 2005)

As a result, this technical assessment focuses primarily on UP and BNSF diesel-electric freight interstate line haul locomotives. However, the assessed technologies will also have applicability to other freight and passenger locomotives.

Shortline Freight Railroads

California has about 26 shortline railroads that operate within the State. These smaller freight rail operations typically feed small numbers of railcars to UP and BNSF, which the Class I railroads in turn transport across the North American freight rail network.

California's shortline railroads operate about a total of 140 switcher and some MHP locomotives statewide. Up to one-third of the shortline railroads' older locomotives have been upgraded to new ultra-low emitting technologies (e.g., genset switch locomotives) through federal and California incentive funding programs. For example, one operator has replaced four older units with four new Tier 4 MHP locomotives.

Military and Industrial Railroads

California also has military and industrial railroads that typically operate smaller, older switchers and MHP locomotives within the boundaries of a granary, plant, or facility. Military and industrial railroads operate about 75 older, smaller MHP and switch locomotives statewide, and generate less than one percent of statewide locomotive diesel fuel consumption and emissions.

Commuter Passenger Railroads

California has seven commuter passenger railroads: Metrolink, Caltrain, Amtrak Pacific Surfliner, Capital and San Joaquin Valley Corridors, Altamont Commuter Express (ACE), and the North Coast Transit District (NCTD).

The State's seven commuter passenger railroads operate about 130 diesel-electric locomotives, typically in the MHP range – 3,000 to 4,000 hp. California's passenger rail operators are beginning to order and receive new Tier 4 diesel-electric passenger locomotives that have higher horsepower (i.e., 4,000 to 5,000 hp) to pull more passenger cars per locomotive.

One of the major differences between diesel-electric passenger locomotives and freight locomotives is that passenger locomotives generally have a main propulsion engine and onboard hotel power (a generator) – the latter rated at about 600 hp or so. This diesel generator provides electricity via cable for the lights, air conditioning, and other material comforts to connected passenger railcars.

5. Who manufactures locomotives?

In the U.S., there are two primary manufacturers of freight interstate line haul locomotives: General Electric (GE) and Caterpillar/Electro-Motive Diesel (CAT/EMD). GE has roughly 70 percent of new diesel-electric freight interstate line haul locomotive sales in the U.S., while CAT/EMD has the remaining 30 percent of the U.S. market.

6. How many freight and passenger locomotives are there in the U.S.?

ARB staff estimates that the number of U.S. freight and passenger diesel-electric locomotives that could be potentially subject to U.S. EPA locomotive regulations is about 31,000. (AAR, 2016; Progressive Railroading, 2014; U.S. DOT, 2015)

Table ES-2 summarizes the U.S. locomotive population. (The Diesel Shop, 2016)

Table ES-2:
Estimated Number of U.S. Freight and Passenger Locomotives

Rail Category	Locomotive Type	Number of Locomotives
Class I Railroads	Interstate Line Haul	17,500
	MHP/Switcher	8,500
Shortline Railroads	MHP/Switcher	3,925
Passenger Railroads	Passenger Intrastate MHP	1,000
Military and Industrial Railroads (California only)[1]	MHP/Switcher	75
Total		**31,000**

1. Military and industrial railroads operate about 75 older, smaller MHP and switch locomotives in California. ARB staff does not have data for national military and industrial MHP and switch locomotives.

It is important to note the Canadian and Mexican railroads operate locomotives in the U.S. that either directly (via Canada's Memorandum of Understanding) or indirectly (via the acquisition of new or older U.S. diesel-electric locomotives) comply with U.S. EPA locomotive regulations. The total number of North American freight and passenger diesel-electric locomotives is about 38,000. (AAR, 2014; Progressive Railroading, 2014; U.S. DOT, 2015)

7. What are the current emission standards for locomotives?

Under the Clean Air Act (CAA), U.S. EPA has the sole authority to establish emissions standards for new locomotives. (42 United States Code (U.S.C.) §7547, (a)(5)) By regulation, U.S. EPA has defined "new" locomotives to include both those newly manufactured and those existing locomotives that are remanufactured or rebuilt.

Table ES-3 shows the level of stringency of each established U.S. EPA locomotive emission standard in grams of pollutant per brake horsepower-hour (g/bhp-hr) and the associated percent reduction compared to uncontrolled, pre-Tier 0 emission levels, for NOx, particulate matter (PM), and hydrocarbon (HC). The standards and test procedures are different for the two primary types of locomotives – the smaller switch locomotives and the larger, more powerful line haul locomotives. ARB's category of MHP locomotives is subject to the line haul emission standards. U.S. EPA estimates that national locomotive fleet turnover to the lower emission standards can take up to 30 years.

Table ES-3:
Federal Locomotive Emission Standards and Percent Control[1,2]

Line Haul Locomotives							
Emission Tier	Year of Manufacture	NOx		PM		HC	
		Standard (g/bhp-hr)	Percent Control	Standard (g/bhp-hr)	Percent Control	Standard (g/bhp-hr)	Percent Control
Pre-Tier 0	1973-1999	13.5[3]	n/a	0.6[3]	n/a	1.0	n/a
Tier 0	2000-2001	9.5	30	0.6	0	1.0	0
Tier 1	2002-2004	7.4	45	0.45	25	0.55	45
Tier 2	2005-2011	5.5	59	0.2	67	0.3	70
Tier 3	2012-2014	5.5	59	0.1	83	0.3	70
Tier 4	2015	1.3	90	0.03	95	0.14	86
Switch Locomotives							
Emission Tier	Year of Manufacture	NOx		PM		HC	
		Standard (g/bhp-hr)	Percent Control	Standard (g/bhp-hr)	Percent Control	Standard (g/bhp-hr)	Percent Control
Pre-Tier 0	1973-1999	17.4[3]	n/a	0.72[4]	n/a	2.1	n/a
Tier 0	2000-2001	14.0	20	0.72	0	2.1	0
Tier 1	2002-2004	11.0	37	0.54	25	1.2	43
Tier 2	2005-2011	8.1	53	0.24	67	0.6	71
Tier 3	2012-2014	5.0	71	0.1	86	0.6	71
Tier 4	2015	1.3	93	0.03	96	0.14	93

1. 40 CFR Part 1033.101, a.
2. U.S. EPA Fact Sheet EPA-420-F-09-025, April 2009.
3. U.S. EPA Locomotive Emissions Standards – Regulatory Support Document (U.S. EPA, 1998), p. 96 – Estimated NOx Emission Rates.
4. ARB staff assumed older pre-Tier 0 line haul and switch locomotives would be able to emit up to the Tier 0 PM emission standards, based on American Association of Railroads in-use emission testing (required to comply with U.S. EPA in-use emission testing requirements) for older switch locomotives with EMD 645 engines.

8. Which locomotives are covered by U.S. EPA requirements?

In California, UP and BNSF primarily operate newer or remanufactured locomotives. These locomotives are subject to the federal emissions standards during their specified useful life. Under the federal definition, the useful life for a freight interstate line haul locomotive can be between 30,000 and 40,000 megawatt-hours (MWh), which typically translates to about seven to ten years of operation.

If the owner of a locomotive that has approached the end of its useful life chooses to remanufacture it, that locomotive continues to remain under the federal program for another useful life period, and this process can continue throughout the full life of the locomotive (i.e., up to 30 to 50 years).

Many of the State's older shortline and military and industrial locomotives have not been remanufactured, and are considered "non-preempted" under federal law. Figure ES-2 shows a map with the location and number of California's remaining non-preempted locomotives in 2015. Nearly all of the non-preempted locomotives operating within the State are either shortline or military and industrial railroad locomotives.

Figure ES-2:
Non-Preempted Locomotives in California in 2015

9. What is the distribution of the locomotive fleet operating in the South Coast Air Basin by emissions tier?

As shown in Table ES-4, the 2014 locomotive fleet in the South Coast Air Basin was dominated by Tier 2 line-haul locomotives, with the number of newer Tier 3 units increasing in interstate service. By 2030, ARB projects that 85 percent of the locomotive work, in the form of megawatt-hours (MWh), will be performed by locomotives meeting Tier 4 emission standards. The rest of the State has similar fleet characteristics, but typically takes an additional five years to catch up with the South Coast Air Basin.

Table ES-4:
Percent of Work by UP & BNSF Locomotives in the South Coast Air Basin by Emissions Tier

Emissions Tier	Percent of Work by UP & BNSF Locomotives in the South Coast Air Basin	
	2014[1]	2030
Pre-Tier 0	0.2	0
Tier 0	17	0
Tier 1	20	1
Tier 2	45	4
Tier 3	18	10[2]
Tier 4	0	85
Totals	100	100

1. Based on reported UP and BNSF locomotive megawatt-hours (MWh) in the South Coast Air Basin in 2014.
2. Tier 3 includes about two percent for Ultra-Low Emitting Locomotives (ULELs).
Source: http://www.arb.ca.gov/railyard/1998agree/1998agree.htm

10. What does ARB staff consider as the baseline to assess more advanced locomotive technologies?

The baseline for locomotive technology is the current Tier 4 national emissions standards, which are being achieved by diesel-electric locomotives.

The railroad companies are also interested in natural gas as a locomotive fuel because of its potentially favorable economics as compared with diesel fuel. However, no emission reductions are anticipated with natural gas beyond the locomotives' certified emission levels (Tier 0 to Tier 3) for existing line haul locomotives. Additional technology is being developed to potentially have liquefied natural gas (LNG) locomotives meet Tier 4 standards in the future. Because these natural gas options do not exceed the emission reductions attributable to the Tier 4 standards, ARB staff believes that natural gas is most appropriately treated as part of the Tier 4 baseline.

11. What more advanced freight locomotive technologies are included in this technology assessment?

ARB staff assessed several technologies that could potentially achieve emission levels that are significantly lower than the Tier 4 standards in the future. Those technologies include:

- Aftertreatment controls: Selective catalytic reduction (SCR) for NOx control, and diesel oxidation catalyst (DOC) for $PM_{2.5}$ (i.e., PM with diameter equal to or less than 2.5 µm) control;
- Aftertreatment controls, augmented with on-board batteries;
- Fuel cell-powered locomotive (proton exchange membrane or solid oxide with gas turbine);
- Battery-powered locomotive or battery tender car; and
- Fully electric locomotive (charged by an overhead catenary system).

12. What does this assessment indicate are the most promising technologies for widespread deployment in the next decade?

Tier 4 Locomotive with Aftertreatment

ARB staff believes the most technologically feasible and cost-effective advanced technology for near-term deployment is the installation of a compact aftertreatment system (e.g., combination of SCR and DOC) onto new and remanufactured diesel-electric freight interstate line haul locomotives. This advanced aftertreatment could reduce emissions by 75 percent or more below Tier 4 levels – from 1.3 g/bhp-hr to 0.3 g/bhp-hr NOx, and from 0.03 g/bhp-hr to <0.01 g/bhp-hr PM.

However, ARB staff believes the actual in-use NOx and PM emission levels could be much lower (i.e., 0.2 g/bhp-hr NOx and 0.005 g/bhp-hr PM), which would be consistent with the existing emission standards for new heavy duty truck engines (0.2 g/bhp-hr NOx and 0.01 g/bhp-hr PM).

ARB staff believes there is adequate space available within the current Tier 4 locomotive envelope to accommodate about a one-ton compact SCR and DOC aftertreatment system. This system could be built into new locomotives and remanufactured with existing Tier 4 locomotives, as well as retrofitted onto much older Tier 2/3 locomotives.

A new Tier 4 freight interstate line haul locomotive costs about $3 million. ARB staff believes a compact SCR/DOC system could cost an additional $250,000 per locomotive by 2025, with railroads also incurring costs to provide a supply network and labor for the urea required by the SCR system.

Tier 4 Locomotive with Aftertreatment and On-Board Batteries

Staff also believes aftertreatment-equipped locomotives could be augmented with on-board batteries to provide an additional 10-25 percent reduction in diesel fuel consumption and greenhouse gas (GHG) emissions. On-board batteries could also provide zero-emission track-mile capabilities in and around railyards to further reduce diesel PM and the associated health risks. Table ES-5 shows the potential emissions levels and capital costs for both aftertreatment technology combinations, compared to the Tier 4 baseline.

Table ES-5:
Emission Levels Achievable with Next Generation of Locomotive Technologies

Emission Levels	**NOx** (g/bhp-hr)	**PM** (g/bhp-hr)	**GHG Reductions** (relative to Tier 4)	**Capital Cost per Locomotive** (Million $)	**Potential Control Technology**
a. Tier 4 Standard	**1.3**	**0.03**	0%	$3.0	EGR, turbos, cooling
– In-Use	1.0	0.015	N/A	N/A	
b. Tier 4 with Aftertreatment	**0.3**	**0.01**	0%	$3.25	Compact SCR and DOC
– In-Use	0.2	<0.0075	N/A	N/A	
c. Tier 4 with Aftertreatment and On-Board Batteries	**0.2**	**0.0075**	10-25%	$4.0	Compact SCR and DOC + On-Board Batteries
	With capability for zero-emission operation in designated areas.				
– In-Use	0.15	0.006	10-25%	N/A	

As shown in Table ES-5 and discussed above, aftertreatment-equipped locomotives could be augmented with on-board batteries to provide an additional 10 to 25 percent reduction in diesel fuel use and GHG emissions. GE demonstrated the technical feasibility of on-board battery technology with its GECX 2010 battery hybrid prototype locomotive, introduced in 2007. (GE, 2005; Railway Gazette, 2007) GE estimated that fuel savings of 10 to 15 percent could be achievable as compared to conventional locomotives. (GE, 2016) With battery technology improvements since 2007, ARB staff believes a locomotive equipped with on-board batteries could realize fuel savings of about 15 percent by 2025. Staff further believes that, with continued battery technology advancements in the near future, locomotives equipped with on-board batteries could realize a reduction in diesel fuel consumption of about 25 percent by 2030. For the purposes of this document, ARB staff assumes a 15 percent reduction in fuel use for aftertreatment equipped locomotives augmented with on-board battery technology with commercial availability by 2025. ARB staff also believes that further engineering advances could result in lighter materials to build locomotives in the future, such that the battery system could be accommodated within the locomotive size, height, and weight limits.

Next Generation of National Locomotive Emissions Standards

To provide regulatory certainty, new national “Tier 5” emissions standards are needed, based on the emissions achievable either with aftertreatment and on-board batteries, or with future technologies that are as cost-effective and reliable. ARB staff supports a performance based approach that achieves significant further reductions in NOx, $PM_{2.5}$, and GHG beyond Tier 4 levels, equal to or lower than the levels shown in Row c of Table ES-5 above.

Ideally, such a standard should apply to both newly manufactured locomotives and Tier 4 locomotives upon remanufacture. However, with the size of current battery technology, it may be most feasible to reflect the emissions benefits of aftertreatment and on-board battery technology just for newly manufactured locomotives, with a Tier 4 remanufacture standard based on just the aftertreatment.

A new federal standard could also facilitate development and deployment of zero-emission track-mile locomotives and zero-emission locomotives by building incentives for those technologies into the regulatory structure.

13. What does this assessment indicate are the most promising technologies for freight locomotives capable of zero-emission track-miles over the next decade?

ARB staff believes that advanced locomotive technologies, such as batteries and fuel cells, could be developed to play a critical role in providing California with locomotives capable of zero-emission track-miles for local and regional operation. As defined here, “zero-emission track-miles” means locomotives capable of operating with zero exhaust emissions for periods of time on existing railroad tracks, within a railyard or within a geographic region like an impacted community or air basin.

Possibilities include the use of a current hybrid diesel (or natural gas)-electric locomotive engine modified to switch from the diesel engine to another source of electricity. This source may be a bank of batteries or fuel cells located on the subsequent rail car (a “tender”) or an external power supply (like overhead electric catenary or in-ground wayside power). While running in zero-emission mode, the diesel engine would not be operating.

If such technology can be developed and successfully demonstrated to achieve zero-emission track-miles to meet air quality and public health needs, other key considerations include the capital costs to purchase battery/fuel cell tenders or install stationary charging infrastructure, and the need to exchange locomotive technology at the edge of the geographic area before the train could continue the rest of its interstate journey. As previously mentioned, ARB staff contracted with the University of Illinois to evaluate the operational and economic impacts of such exchange points on the national freight rail system. That analysis was published in June 2016.

In addition, battery and fuel cell technologies may be able to meet the energy demands of switch locomotives that are limited to railyard operations, and some MHP locomotives that are limited to operations within specified localities or regions.

14. What does this assessment indicate are the most promising zero-emission locomotive technology concepts for operation over the North American freight rail system in the longer-term?

ARB staff defines “zero-emission locomotive technologies” as those technologies that could potentially provide zero exhaust emissions for freight interstate line haul locomotives over the entirety of the North American freight rail system (i.e., up to 140,000 or more track-miles or more) on an annual basis.

The most promising example of a zero-emission locomotive technology is the concept of a solid oxide fuel cell-gas turbine (SOFC-GT) that may have the potential to achieve zero (or near-zero) emissions with sufficient thermal energy (heat) on-board the locomotive to power it across the North American freight rail system.

This type of technology would not need to be limited to specific localities or regions, and could potentially achieve an efficiency level of up 70 percent. However, there are significant engineering and safety challenges that need to be addressed, including the use of a gas turbine to operate a line haul locomotive in both steady and transient states.

15. What are estimated costs of the most promising technologies?

Table ES-6 summarizes potential advanced locomotive technologies and preliminary estimates of the capital costs. For the national fleet options, the capital costs and benefits would be shared across the country. About seven percent of the total annual interstate line haul locomotive activity by UP and BNSF occurs in California, so the table includes pro-rated “California share” costs as well.

Table ES-6:
Estimated Capital Costs of
Advanced Locomotive Technologies

Technology Type	Scope and Number of Units	Technology		
		Capital Cost/Unit (M)illions	Capital Cost (M)illions or (B)illions	Life (Yrs)
U.S. Freight Locomotives in National Fleet				
Line Haul with Aftertreatment	National 17,500 locomotives[1]	$0.25M/aftertreatment system (above Tier 4)	Nationwide: $4.4B CA share: $175M	15
Line Haul with Aftertreatment and On-Board Batteries	National 17,500 locomotives[1]	$1M/aftertreatment system+battery pack (above Tier 4)	Nationwide: $17.5B CA share: $700M	15
Fuel Cell (SOFC-GT) Line Haul Locomotive	National 17,500 locomotives[1]	$2-5M/locomotive (above Tier 4)	Nationwide: $35-87.5B CA share: $1.4-3.5B	15
UP and BNSF Freight Locomotives Operating with Zero-Emission Track-Miles in the South Coast Air Basin				
Battery/Fuel Cell Tender	South Coast 130 trains/day 4 locomotives/train 3 tenders/locomotive	$5M/tender and integration hardware + $15M total for 5 battery replacements/tender	South Coast Air Basin only: $39B	30
Freight Railroad Electrification	South Coast 500 route-miles	$50M/route-mile, including infrastructure and rolling stock	South Coast Air Basin only: $25B	30

1. Natural turnover of the national fleet to newly manufactured, advanced technology locomotives based on Tier 4 with aftertreatment and on-board batteries, and to remanufactured locomotives based on Tier 4 with aftertreatment, would occur over roughly two decades.

16. What are the next steps to develop and deploy freight locomotives with emissions lower than Tier 4 standards for California or national operation?

ARB staff recommends dual paths for locomotive technology development. One path is to seek significant criteria and toxic pollutant reductions beyond Tier 4 in the near to mid-term with aftertreatment, augmented by on-board batteries. The other path is to develop the zero-emission track-mile or zero-emission locomotive technologies needed in the mid to long-term (2025-2050). Potential ARB actions include:

a) Ask U.S. EPA to define the next generation of national emissions targets for locomotive engine manufacturers. Seek promulgation of "Tier 5" standards based on the performance achievable with aftertreatment with on-board batteries for new locomotives, and aftertreatment for remanufactured locomotives, to reduce NOx, PM, and GHG emissions, as well as fuel consumption. Such standards could also be crafted to reward development and deployment of zero-emission technologies.

b) Support development and demonstration of on-board battery technologies that could also provide zero-emission track-mile capabilities in and around railyards to further reduce diesel PM localized health risks. On-board battery technology has been demonstrated by GE with a prototype Tier 2 interstate line haul locomotive, augmented with battery packs. As battery energy density and costs improve, this could become a commercially viable technology in the near future.

c) For the longer term, advocate for development of the SOFC/GT concept because this is a potential technology that has the necessary energy, and added efficiency benefits of up to 70 percent, to be able to power an interstate line haul locomotive across the North American freight rail system.

d) In partnership with agencies of the federal government, California and other state governments, and local air and transportation agencies, support an aggressive national and California research, development, and demonstration program to ultimately commercialize zero-emission track-mile and zero-emission locomotive technologies.

e) Based on this assessment, staff believes the highest priorities for research and development programs should be improvements in battery and fuel cell energy density and costs to support introduction of:

   - Battery and/or fuel cell powered switch (yard) locomotives.
   - Battery and/or fuel cell tenders for regional operation of MHP and freight interstate line haul locomotives.
   - Fuel cell (SOFC/GT) freight interstate line haul locomotives.

I. NORTH AMERICAN AND CALIFORNIA RAILROAD OPERATIONS

Freight transport is the flow of goods between a supplier and point of consumption and occurs via ship, rail, truck and air. The management of this flow is referred to as logistics and is driven by cost, time, reliability, customer needs, etc. As the value of a shipment rises, it becomes more critical to move that good by a mode of transport that is faster, such as truck and air. Generally speaking, when the value is lower, the weight is heavier, or speed is not as critical, other modes like ship and rail are used.

Rail is efficient at moving freight long distances, while trucks excel at providing time-sensitive delivery for high-value goods transported over shorter distances.

<u>The Role of Freight Railroad Operations in North America</u>

Freight railroad operations play a significant role in the movement of goods and commodities in North America. Freight is moved by rail between ports, manufacturing hubs, agricultural processing facilities, and distribution centers.

Figure I-1 illustrates the volume of goods moved by rail across the county. Chicago is the major nexus and interchange for the seven North American railroads. Figure I-1 also indicates that California is a gateway for global goods movement.

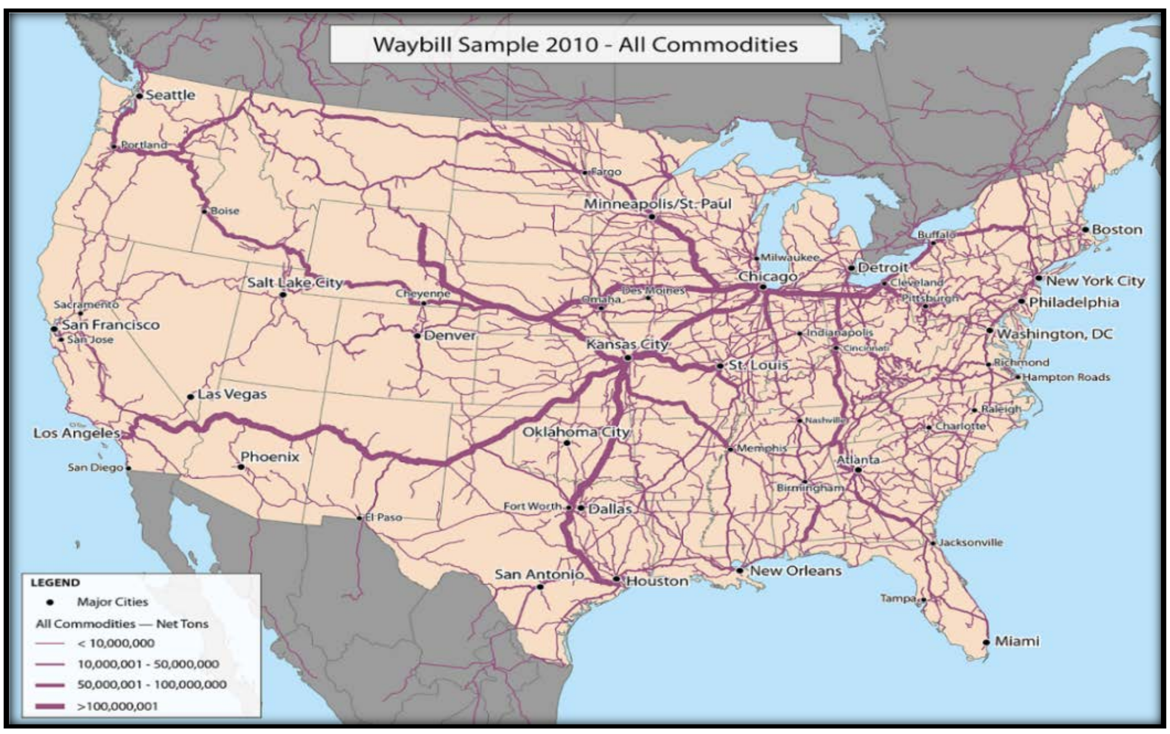


Figure I-1: Where Rail Freight Moves in the United States
(FRA, 2015)

In 2009, the railroads' share of revenue ton-miles for all freight transportation modes in the United States was about 40 percent; trucks accounted for almost 30 percent of ton-miles moved, pipeline 20 percent, water 12 percent, and air less than one percent (see Figure I-2).

Of rail freight nationwide, 91 percent (FRA, 2015) represents bulk commodities, such as agriculture and energy products, automobiles and components, construction materials, chemicals, coal, equipment, food, metals, minerals, and paper and pulp. The remaining nine percent is intermodal traffic, which generally consists of consumer goods and other miscellaneous products.

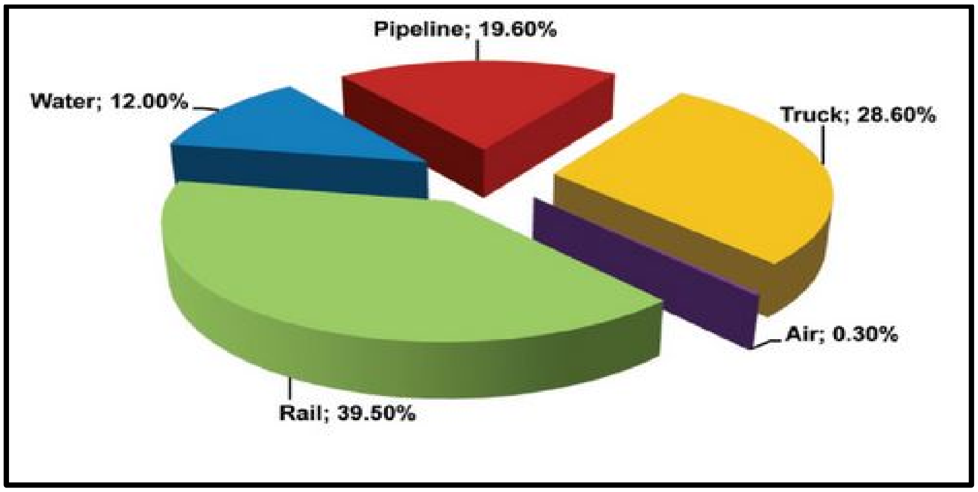


Figure I-2:
Distribution of Goods Moved in the United States by Mode on a Ton-Mile Basis
(FRA, 2015)

Due to California rail's proximity to the ports, intermodal traffic actually represents a much greater share of California rail activity (perhaps greater than 50 percent) (ARB, 2015a), whereas other types of traffic or commodities represent a much smaller share.

A. North American Class I Railroads

In 2012, there were 574 railroads in North America, with seven of the 574 identified as U.S. Class I freight railroads (see list below). The remaining freight railroads are non-Class I U.S. freight railroads (i.e., Class II or Class III railroads).

The Interstate Commerce Commission Termination Act (ICCTA) created the Surface Transportation Board (STB) in 1995. The STB determines the Class level for each freight railroad based on inflation-adjusted annual operating revenues (AOR). They are categorized into three classes: Class I, Class II, and Class III. As of 2013, the adjusted AORs (Winters, 2015) are provided in Table I-1.

Table I-1:
Class Railroads and Annual Operating Revenue

Railroad Class	Annual Operating Revenue (millions)
I (national)	467
II (regional)	>40
III (shortline)	<40

According to the American Association of Railroads (AAR), there are currently eleven railroads in North America designated as Class I (two Class I's are passenger rail). Seven of the eleven are identified as U.S. freight railroads, with two of the eleven identified as having trackage only in Mexico. (AAR, 2015)

Figure I-3 shows the rail network for the seven Class I U.S. freight railroads.

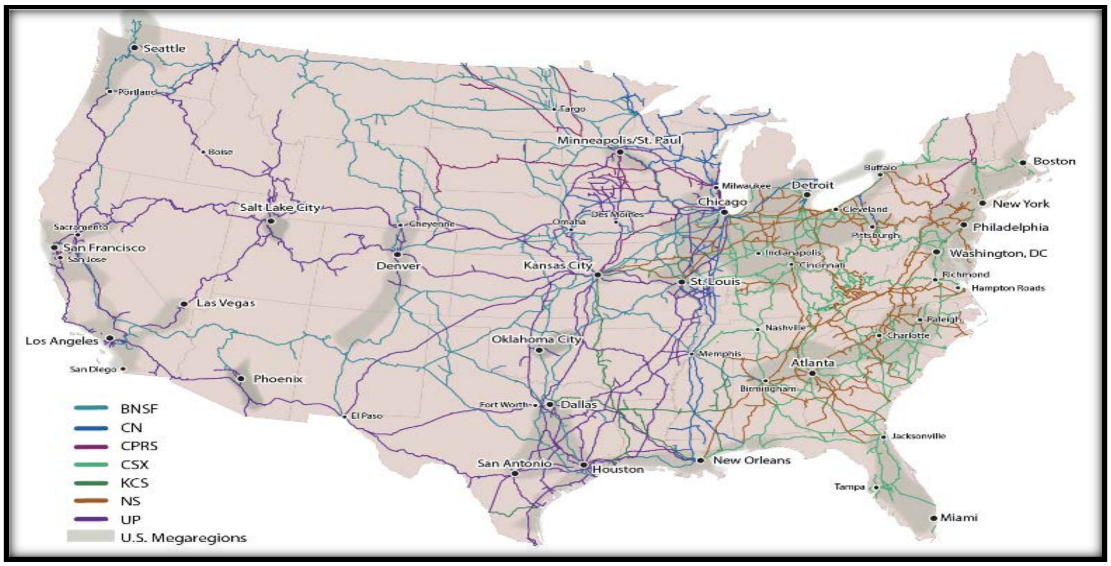


Figure I-3: Class I Railroads of North America
(FRA, 2015)

1. Class I Freight Railroads in U.S.: Number of Locomotives

In 2014, AAR estimated that the seven U.S. Class I railroads operated about 26,000 locomotives. AAR also estimated that with the Canadian and Mexican operations included, North America has a total of about 32,500 locomotives.

UP and BNSF operate about 15,000 locomotives nationally, which represents nearly 60 percent of the total number of locomotives for the U.S. Class I railroads. (AAR, 2015; UP, 2013a; BNSF 2013)

ARB staff estimates that of the UP and BNSF national fleet of about 15,000 locomotives; the two railroads combined operate about 10,000 interstate line haul locomotives (about 4,400 hp). Two-thirds of UP and BNSF's total national locomotive fleets primarily move trains across the U.S. and North America (e.g., Chicago to Los Angeles).

The other 5,000 UP and BNSF locomotives (generally less than 4,000 hp) are primarily assigned across the UP and BNSF national rail network to regional and local or railyard operations, such as regional haulers and switch (yard) locomotives.

2. Types of Locomotives

ARB has identified the three major categories of freight and passenger locomotives that primarily within California. The first category is interstate line haul locomotives, which are primarily 4,400 hp that traverse the North American freight rail system annually. The second category is made up of MHP locomotives, defined by ARB staff as typically between 2,301 and 3,999 hp. The third category is switch (yard) locomotives, specifically defined by U.S. EPA as between 1,006 and 2,300 hp. (40 CFR Part 1033.901)

a. Freight Interstate Line Haul Locomotives

"Interstate" line haul locomotives are defined as 4,000 hp or greater, and are typically newer (i.e., primarily built between model-years 2000 and the present). Interstate line haul locomotives can consume on average up to 300,000 gallons of diesel fuel annually, working 12 to 16 hours a day, as they traverse the North American freight rail system (e.g., Chicago to Los Angeles).

Some other key specifications:

- Built with a large medium speed engine (about 1,000 revolutions per minute, or rpm);
- Typically has 12 or 16 cylinders;
- Built with a 5,000 gallon fuel tank; and
- Operating, on average, up to 1,000 miles between refuelings.

Interstate units are nearly always six axles and weigh more than 400,000 pounds (i.e., 200 tons), which provides more adhesion to the track and pulling power. These units can exert between 150,000 and 200,000 pounds of force for pulling power (see Figure I-4).

Figure I-4:
Freight Interstate Line Haul Locomotive BNSF 8013
2014 Model Year – Tier 3 – (Up to 183,000 Pounds of Pulling Power)
(RR Picture Archives, 2014a)

Interstate freight trains are able to move goods, typically using four or more line haul locomotives in a locomotive consist (a set of locomotives under multiple unit control) that pulls trains that are up to two miles long. Interstate line haul locomotives traverse mountains, desert, and other challenging terrains as they cross the country.

An interstate line haul locomotive on a typical one-way train (e.g., from Chicago to Los Angeles about 2,200 miles) may operate within California about 10 to 15 percent of the total one-way miles, or about 200 to 300 miles of the trip (e.g., Needles, California to the Ports of Los Angeles / Long Beach). There are examples where a few interstate line haul locomotives have been assigned to operate in a particular area within California, but this is not typical.

b. Freight and Passenger Medium Horsepower (MHP) Locomotives

MHP locomotives are defined by ARB as between 2,301 and 3,999 hp. MHP's are older former freight interstate line haul locomotives, typically built between the 1970's and 1990's. These units have typically been cascaded down over time (i.e., generally after 15 years or more of interstate service) and are primarily limited to regional and local service.

Many of the MHP locomotives meet the "intrastate" definition, especially smaller MHP freight and locomotives. The remaining larger MHP locomotives typically operate between 50 and 90 percent of the time within California, and within the western region (e.g., Nevada, Arizona, and New Mexico).

MHP locomotives typically range between 75,000 and 150,000 pounds of force for pulling power. MHP locomotives consume about 25,000 to 100,000 gallons annually within and around the State. MHP units can be either four or six axles. An example of an MHP locomotive is shown in Figure I-5 below.

ARB staff includes the State's nearly 130 commuter passenger locomotives in the MHP group, as they are typically older and between 3,000 and 4,000 hp. Commuter passenger locomotives are also typically limited to operation within a specific area or region. Commuter passenger locomotives can consume between 100,000 to 200,000 gallons per year within the State, primarily due to the amount of time they spend at higher speeds and power settings.

Figure I-5:
UP 9900 Medium Horsepower Locomotive
(ARB, 2011a)

Passenger commuter operators are now beginning to order new higher horsepower (e.g., 4,000 to 5,000 hp) passenger locomotives that can achieve greater speeds, but more importantly pull more passenger cars. See Figure I-6 for the new generation of Tier 4 passenger locomotives.

Figure I-6:
New Metrolink EMD Tier 4 Passenger Locomotive
Caterpillar High-Speed 4,700 hp Engine
(Metrolink News, 2016)

c. Freight Switch (Yard) Locomotives

Switch (yard) locomotives are based on the federal definition of 1,006 to 2,300 hp. Switch locomotives are typically four axles. Their primary responsibility is to move small numbers of railcars in and around railyards, and to help assemble trains.

Switchers typically range between 40,000 and 100,000 pounds of force for pulling power, and consume between 10,000 to 50,000 gallons of diesel fuel annually within the State. A typical switcher locomotive is shown in Figure I-7.

Figure I-7:
LLPX 2317: Leased Switcher Locomotive Rated at About 2,000 hp
(RR Picture Archives, 2009)

3. Historical National Rail Fuel Consumption

In 2012, diesel fuel consumption by Class I railroads represented seven percent of all diesel fuel consumed in the United States at 3.6 billion gallons. (Annual Energy Outlook, 2014) Based on Bureau of Transportation Statistics data from 1960 to 2013, U.S. Class I railroads have historically averaged about 3.6 billion gallons of annual diesel fuel consumption. This mean has been consistent even when considering the changes in the industry over the past 50 years or so.

As shown in Table I-2, energy consumption by North American railroads decreased eight percent since 1980, while revenue ton-miles have nearly doubled. (Davis et al, 2014) This also equates to a rail energy consumption per ton-mile reduction of one half.

The reductions in energy consumption per ton-mile are the result of changes in technology and operations such as improvements in locomotive engines, idle reduction devices, dispatching systems, and changes in operations such as unit trains, double stacking, training, and improved scheduling.

U.S. Class I railroad fuel efficiency improvements have occurred for a number of key reasons including the following.

- Combustion Improvements: GE and EMD locomotive manufacturers have made continual progress in improving the fuel efficiency of their engines, primarily due to the use of electronic fuel injection and other types of combustion improvements.

- Tractive Effort (TE): GE's improvements in tractive effort can allow 600 ES44C4s, with alternating current (AC) to displace up to 800 older direct current (DC) locomotives and to save more than 70 million gallons of fuel annually. (Bachand, 2007a, Bachand, 2007b; Cotey, 2009)

- Distributed Power Units (DPUs): U.S. Class I freight railroads have made significant improvements to their operational efficiency, including an increase in the use of DPUs and trip optimizers and related types of systems on trains. DPUs have been used on up to 75 percent of Class I railroads trains (ARB, 2015a) and can reduce the number of locomotives needed to pull longer trains, which results in greater operational and fuel efficiencies.

Table I-2:
Historical Trends in Energy Consumption and Activity
(Davis et al., 2014)

Summary Statistics for Class I Freight Railroads, 1970–2012

Year	Number of locomotives in service[a]	Number of freight cars (thousands)[b]	Train-miles (millions)	Car-miles (millions)	Tons originated[c] (millions)	Average length of haul (miles)	Revenue ton-miles (millions)	Energy intensity (Btu/ton-mile)	Energy use (trillion Btu)
1970	27,077[d]	1,424	427	29,890	1,485	515	764,809	691	528.1
1975	27,846	1,359	403	27,656	1,395	541	754,252	687	518.3
1980	28,094	1,168	428	29,277	1,492	616	918,958	597	548.7
1981	27,421	1,111	408	27,968	1,453	626	910,169	572	521.0
1982	26,795	1,039	345	23,952	1,269	629	797,759	553	440.8
1983	25,448	1,007	346	24,358	1,293	641	828,275	525	435.1
1984	24,117	948	369	26,409	1,429	645	921,542	510	469.9
1985	22,548	867	347	24,920	1,320	665	876,984	497	436.1
1986	20,790	799	347	24,414	1,306	664	867,722	486	421.5
1987	19,647	749	361	25,627	1,372	688	943,747	456	430.3
1988	19,364	725	379	26,339	1,430	697	996,182	443	441.4
1989	19,015	682	383	26,196	1,403	723	1,013,841	437	442.6
1990	18,835	659	380	26,159	1,425	726	1,033,969	420	434.7
1991	18,344	633	375	25,628	1,383	751	1,038,875	391	405.8
1992	18,004	605	390	26,128	1,399	763	1,066,781	393	419.2
1993	18,161	587	405	26,883	1,397	794	1,109,309	389	431.6
1994	18,505	591	441	28,485	1,470	817	1,200,701	388	465.4
1995	18,812	583	458	30,383	1,550	843	1,305,688	372	485.9
1996	19,269	571	469	31,715	1,611	842	1,355,975	368	499.4
1997	19,684	568	475	31,660	1,585	851	1,348,926	370	499.7
1998	20,261	576	475	32,657	1,649	835	1,376,802	365	502.0
1999	20,256	579	490	33,851	1,717	835	1,433,461	363	520.0
2000	20,028	560	504	34,590	1,738	843	1,465,960	352	516.0
2001	19,745	500	500	34,243	1,742	859	1,495,472	346	517.3
2002	20,506	478	500	34,680	1,767	853	1,507,011	345	520.3
2003	20,774	467	516	35,555	1,799	862	1,551,438	344	533.9
2004	22,015	474	535	37,071	1,844	902	1,662,598	341	566.2
2005	22,779	475	548	37,712	1,899	894	1,696,425	337	571.4
2006	23,732	475	563	38,995	1,957	906	1,771,897	330	584.5
2007	24,143	460	543	38,186	1,940	913	1,770,545	320	566.9
2008	24,003	450	524	37,226	1,934	919	1,777,236	305	542.5
2009	24,045	416	436	32,115	1,668	919	1,532,214	291	446.6
2010	23,893	398	476	35,541	1,851	914	1,691,004	289	488.1
2011	24,250	381	493	36,649	1,885	917	1,729,256	298	514.6
2012	24,707	381	500	36,525	1,760	973	1,712,567	294	504.0
Average annual percentage change									
1970–2012	-0.2%	-3.1%	0.4%	0.5%	0.4%	1.5%	1.9%	-2.0%	-0.1%
2002–2012	1.9%	-2.2%	0.0%	0.5%	0.0%	1.3%	1.3%	-1.6%	-0.3%

B. Statistics on California Freight Railroad Operations

1. UP and BNSF: Number of California Locomotives

On average, UP and BNSF combined operate about 200 freight interstate trains per day within the California boundaries. The number of interstate trains can vary on a daily basis, depending of the corridor, types of trains, and normal fluctuations in business activity.

A subcategory of interstate trains is the intrastate line haul trains that travel from one region to another within California, but are operationally similar to interstate line haul trains, except for the length of travel distances.

UP and BNSF – Freight Trains Per Day within California

UP and BNSF, on average, operate about 3.5 locomotives per interstate train statewide. This would indicate UP and BNSF operate about 700 interstate line haul locomotives within California on any given day. (ARB, 2015a)

Of the 200 UP and BNSF interstate trains per day within California, about 130 trains per day, or two-thirds, operate within the South Coast Air Basin. If the estimate of 3.5 interstate line haul locomotives per train is used, UP and BNSF operate about 455 locomotives per day in the South Coast, as shown in Table I-3. (ARB, 2015a)

Table I-3:
UP and BNSF California Interstate/Intrastate Trains and Locomotives – On Any Given Day in 2013[1]

UP and BNSF	Trains Per Day	Locomotives Per Day
South Coast Air Basin	130	455
San Joaquin Valley Air Basin	60	210
San Francisco Air Basin	25	90
Statewide	200	700

1. It is important to note that summing individual air basin totals will not result in the statewide value. That's because, for example, trains that have originations/destinations in the South Coast Air Basin may also travel north and pass through the San Joaquin Valley, and even possibly to the Bay Area.

ARB staff estimates UP and BNSF operate about 10,000 national interstate line haul locomotives in California on an annual basis. (ARB, 1998a) In 2014, UP and BNSF operated about 10,000 individual interstate line haul locomotives in the South Coast Air

Basin, but up to five percent or more were “foreign power” locomotives, i.e., locomotives borrowed from other U.S. Class I railroads.

UP and BNSF operate about 400 to 500 intrastate freight MHP and switch locomotives within California. Since 2009, UP and BNSF have started a major shift to operate older higher horsepower or MHP locomotives as switchers and short haulers.

MHP locomotives provide greater operational flexibility than switchers since they are able to pull larger numbers of railcars and do both switch and local/regional hauler operations.

UP and BNSF Switch (Yard) Locomotives

UP and BNSF typically operate two distinct types of switch locomotives. The first type is the traditional large and older single engine diesel-electric switch locomotive. The second type is the newer multi-engine generator set (genset) switch locomotive.

Below is a summary of the number and types of UP and BNSF intrastate switch locomotives regularly operating in California in Table I-4:

Table I-4:
UP and BNSF Intrastate Switch Locomotives

UP/BNSF	Intrastate	Ultra Low-Emitting Locomotive[1]
California	129	92
South Coast	84	80
Rest of State	45	12

1. Ultra-Low Emitting Locomotives (ULELs) achieve emissions of 3.0 and 0.1 g/bhp-hr NOx and PM, respectively.

2. UP and BNSF: California Diesel Fuel Dispensed and Consumed

ARB staff, based on a number of sources, estimate that UP and BNSF consume about 220 million gallons for interstate line haul activity, and about 20 million gallons for the intrastate locomotive activity. In total for 2014, ARB staff estimates that UP and BNSF consumed an estimated 240 million gallons statewide.

3. California Shortline and Military/Industrial Railroads’ Diesel Fuel Consumption

There are about 26 Class III or shortline railroads that move freight and currently operate about 135 or more locomotives within California. The Carl Moyer Program has helped to fund the replacement of more than one-third (up to 45 locomotives) of the shortline railroads' older uncontrolled locomotives with new genset or comparable ULELs.

California's 26 shortline railroads consume about 3 million gallons of diesel fuel annually, which represents about one percent of total annual statewide freight and passenger locomotive diesel fuel consumption of about 260 million gallons. (UP and BNSF, 2010)

California also has a number of individual military and industrial operators (e.g., grain or minerals) that move freight and operate about 75 smaller locomotives statewide. Some examples of military and industrial railroads in the State include:

- Military: Naval Weapons Station in Concord, Marine Logistics Center in Barstow/Yermo, and the Sierra Army Depot in Herlong; and

- Industrial: GATX repair facility in Colton, Metropolitan Stevedore in the Port of Long Beach, A.L. Gilbert feed warehouse in Keyes, and Chevron refinery in Richmond.

Most of the military and industrial railroads are located in the San Joaquin Valley, South Coast Air Basin, and Mojave Desert Air Basin. However, there are similar operations in many other areas of the State as well. California's military and industrial locomotives consume about 1 million gallons of diesel fuel annually.

4. Summary of California Freight and Passenger Railroads Diesel Fuel Consumption

To summarize, total statewide locomotive diesel fuel consumption is about 260 million gallons annually. Of this total, UP and BNSF combined interstate and intrastate locomotives consume about 93 percent (240 million gallons), and California's passenger locomotives consume about six percent (15 million gallons), and shortline and military industrial railroad locomotives about one percent (4 million gallons).

II. PROGRAMS THAT REDUCE LOCOMOTIVE EMISSIONS IN CALIFORNIA

A. U.S. EPA Locomotive Emission Standards

Under the Clean Air Act (CAA), U.S. EPA has the sole authority to establish emissions standards for new locomotives. By regulation, U.S. EPA has defined “new” locomotives to include both those newly manufactured and those existing locomotives that are remanufactured or rebuilt.

U.S. EPA approved the first set of locomotive emission regulations in 1998. This initial set of regulations required emission controls for new locomotives beginning in 2000. Uncontrolled locomotives built from 1973 to 1999, were required to at least meet Tier 0 standards upon remanufacture, typically every seven to ten years.

U.S. EPA approved the second set of locomotive emission regulations in 2008. The 2008 regulations set more stringent standards and required older locomotives to achieve a 50 percent reduction in PM emission levels upon remanufacture. Tier 0 remanufactures must achieve a 20 percent reduction in NOx.

Table II-1 shows U.S. EPA line haul and switch locomotive emission standards and percent control from pre-Tier 0 level.

Table II-2 provides a comparison of the Tier 4 line haul locomotive emission standards with heavy-duty diesel trucks and large off-road engines. The table shows that line haul locomotives meet similar PM and HC emissions levels, but are significantly higher on NOx.

The most current ARB emission inventory, which is for 2012, estimates that UP and BNSF interstate line haul locomotives contribute about 85 percent of the statewide locomotive NOx emissions (e.g., NOx at 86 of 102 tons per day). UP and BNSF have 400 to 500 intrastate locomotives that contribute about another eight percent. Passenger locomotives contribute about six percent, while shortline and military/industrial railroad locomotives contribute the remaining one percent or more. (ARB, 2013)

Most of the UP and BNSF contribution is from interstate line haul locomotives, which do not concentrate their operations in specific local or regional areas in California, as many switchers and MHP intrastate locomotives do. Instead, interstate line haul locomotive operations are distributed over major routes and many areas of California as they regularly enter and exit the State over the course of a year.

Table II-1
Federal Locomotive Emission Standards and Percent Control[1,2]

Line Haul Locomotives							
Emission Tier	Year of Manufacture	NOx		PM		HC	
		Standard (g/bhp-hr)	Percent Control	Standard (g/bhp-hr)	Percent Control	Standard (g/bhp-hr)	Percent Control
Pre-Tier 0	1973-1999	13.5[3]	n/a	0.6[3]	n/a	1.0	n/a
Tier 0	2000-2001	9.5	30	0.6	0	1.0	0
Tier 1	2002-2004	7.4	45	0.45	25	0.55	45
Tier 2	2005-2011	5.5	59	0.2	67	0.3	70
Tier 3	2012-2014	5.5	59	0.1	83	0.3	70
Tier 4	2015	1.3	90	0.03	95	0.14	86
Switch Locomotives							
Emission Tier	Year of Manufacture	NOx		PM		HC	
		Standard (g/bhp-hr)	Percent Control	Standard (g/bhp-hr)	Percent Control	Standard (g/bhp-hr)	Percent Control
Pre-Tier 0	1973-1999	17.4[3]	n/a	0.72[4]	n/a	2.1	n/a
Tier 0	2000-2001	14.0	20	0.72	0	2.1	0
Tier 1	2002-2004	11.0	37	0.54	25	1.2	43
Tier 2	2005-2011	8.1	53	0.24	67	0.6	71
Tier 3	2012-2014	5.0	71	0.1	86	0.6	71
Tier 4	2015	1.3	93	0.03	96	0.14	93

1. 40 CFR Part 1033.101, a.
2. U.S. EPA Fact Sheet EPA-420-F-09-025, April 2009.
3. U.S. EPA Locomotive Emissions Standards – Regulatory Support Document (U.S. EPA, 1998), p. 96 – Estimated NOx Emission Rates.
4. ARB staff assumed older pre-Tier 0 line haul and switch locomotives would be able to emit up to the Tier 0 PM emission standards, based on American Association of Railroads in-use emission testing (required to comply with U.S. EPA in-use emission testing requirements) for older switch locomotives with EMD 645 engines.

Table II-2:
Comparison of Existing Truck, Off-Road, and Locomotive Emission Standards

Source	Horsepower	Engine Speed (rpm)	NOx (g/bhp-hr)	PM (g/bhp-hr)	HC (g/bhp-hr)
2010 Heavy Duty Trucks	500	1,800	0.2	0.01	0.14
2015 Off-Road Engines	750	1,800	0.4	0.02	0.14
2015 Line Haul Locomotives	4,500	1,000	1.3	0.03	0.14

B. 1998 Locomotive NOx Fleet Average Agreement in the South Coast Air Basin

In 1998, ARB signed an agreement (1998 Agreement) with UP and BNSF to achieve a Tier 2 NOx locomotive fleet average in the South Coast Air Basin by 2010. The combined benefits of the 1998 U.S. EPA locomotive regulations and the 1998 Agreement were estimated to provide about a 67 percent reduction in NOx emissions between 2000 and 2010. This measure was designed to reduce UP and BNSF South Coast Air Basin locomotive NOx emissions by 24 tons per day by 2010 (i.e., 36 to 12 tons per day from 2000-2010).

The 1998 Agreement also reduces locomotive particulate matter (PM) emissions by about 50 percent. This agreement provides emission reduction benefits to other regions of the State, a 15 percent or more spillover benefit, as locomotives enter/exit the South Coast Air Basin and in many cases travel throughout the rest of the State.

To comply with the 1998 Agreement, UP and BNSF are required to provide ARB staff with actual data on annual locomotive operations in the South Coast Air Basin by tracking either locomotive diesel fuel consumption or locomotive megawatt-hours (MWh). The annual railroads' data submittals are subject to ARB's review and approval for compliance, and made available to the public at http://www.arb.ca.gov/railyard/1998agree/1998agree.htm.

Table II-3 summarizes some key findings about the UP and BNSF locomotive fleets operating in the South Coast Air Basin from 2010-2014.

Table II-3:
UP and BNSF Locomotive Operations Within the South Coast Air Basin
(ARB, 1998a; ARB, 1998b)

Year	Total Number of Locomotives	Total Locomotive MWh	Percent MWh				Combined Fleet Average (g/bhp-hr)
			Tier 3 / ULEL	Tier 2	Tier 1	Tier 0[1]	
2010	6,053	403,855	13%	54%	20%	14%	5.9
2011	6,966	391,752	11%	57%	16%	15%	5.7
2012	7,786	444,022	15%	53%	16%	16%	5.7
2013	8,972	406,685	15%	52%	17%	16%	5.6
2014	10,342	412,009	18%	45%	20%	18%	5.6

1. Includes a small percentage of pre-Tier 0 locomotives.

C. 2005 ARB/Railroad Agreement

On June 30, 2005, the ARB and UP and BNSF (railroads) signed a diesel PM emissions reduction agreement. The 2005 Agreement was fully implemented by June 30, 2008, providing reductions in diesel PM in and around railyards statewide by up to 20 percent. The 2005 Agreement included the following major provisions (ARB, 2005):

- Phase-out on non-essential idling and installation of idle reduction devices on more than 400 UP and BNSF intrastate locomotives;

- Maximize the use of ultra-low sulfur diesel fuel (i.e., 15 parts per million) by January 1, 2007, which was up to six years earlier than required by federal regulation in 2012; and

- Identify and expeditiously repair locomotives with excessive smoke and ensure at least 99 percent of the locomotives operating in California pass federal smoke (opacity) standards.

In addition, the 2005 Agreement required the ARB and railroads to prepare health risk assessments (HRAs) for 18 major railyards and to use these studies to identify future feasible mitigation and risk reduction measures.

<u>Localized Health Risks near Railyards</u>

Between 2004 and 2008, ARB staff conducted HRA studies of 18 major railyards throughout the State as part of the 2005 Agreement. (ARB, 2004-2008) The railyard HRAs examined the increased cancer risk zones due to diesel PM emissions from locomotives, cranes, and yard equipment within facility boundaries as well as on/off site emissions from heavy-duty diesel trucks. The railroads provided extensive data on their activities for the studies.

These risk assessments were based on emissions that existed as of 2000 for the UP Roseville Railyard, and 2005 for all other railyards, using the 2003 State guidance on HRAs developed by the Office of Environmental Health Hazard Assessment (OEHHA). The results do not represent the much lower emission levels present today after implementation of extensive U.S. EPA and ARB regulatory incentive programs and railroad initiatives.

For the 18 railyards, the potential maximum individual cancer risk a decade ago was estimated to range between 40 and 2,500 chances per million for residents living around or nearby. The greatest risks were associated with the BNSF San Bernardino Railyard because of its high levels of locomotive and truck activity and the many densely populated neighborhoods that are located near and surround the railyard. The cluster of four railyards (UP Commerce, BNSF Hobart, BNSF Sheila Mechanical, and BNSF Commerce Eastern) operating in the densely populated Commerce area also resulted in high combined cancer risks.

In July 2011, ARB published updated cancer risk estimates for the four highest risk railyards in Southern California – BNSF San Bernardino, UP ICTF/Dolores, BNSF Hobart, and UP Commerce – in *Supplement to the June 2010 Staff Report on Proposed Actions to Further Reduce Diesel Particulate Matter at High-Priority California Railyards*. (ARB, 2011b) In that report, we used updated emissions and activity data to estimate the change in cancer risk from 2005 to 2010.

All four railyards showed a substantial decrease in risk, from 40 to over 70 percent due to the introduction of much cleaner trucks, locomotives, equipment, and fuels in this period. These changes resulted from the combination of ARB regulations, the two ARB/Railroad agreements, and incentives.

D. CARB Diesel Fuel Regulation – Intrastate Locomotives

Intrastate (diesel-electric) locomotives are defined as those locomotives that operate and fuel primarily (at or greater than 90 percent of annual fuel consumption, mileage, or hours of operation) within the boundaries of the State of California. On November 18, 2004, the ARB Board approved new regulations for fuel used in intrastate locomotives.

As of January 1, 2007, diesel fuel sold for use in intrastate locomotives operating in California must meet the specifications of CARB diesel fuel. CARB diesel provides up to a 14 percent reduction in PM, and six percent reduction in NOx as compared to U.S. EPA ultra-low sulfur (15 ppmw) diesel. (ARB, 2004)

The 2005 ARB/Railroad Agreement required UP and BNSF interstate line haul locomotives to refuel with at least 80 percent with U.S. EPA ultra-low sulfur diesel fuel beginning in January 2007. (ARB, 2005) U.S. EPA required locomotives nationally to use national ultra-low sulfur diesel fuel beginning in 2012.

UP and BNSF interstate line haul locomotives consumed about 220 million gallons annually within California in 2012. In 2014, up to 80 percent of the UP and BNSF fuel dispensed in California, most of this dispensed to freight interstate line haul locomotives, was CARB diesel fuel. (UP and BNSF, 2014) This is primarily due to the sole availability of CARB diesel in the California's fuel pipelines and to independent distributors of fuel by truck-to-locomotives.

As a result, California is receiving significantly greater emissions reductions than originally anticipated by the CARB diesel fuel regulation for intrastate locomotives and the 2005 ARB/Railroad Agreement for interstate line haul locomotives.

This page left intentionally blank

III. FRAMEWORK FOR TECHNOLOGY ASSESSMENT: KEY PERFORMANCE, OPERATIONAL, AND ECONOMIC CONSIDERATIONS

Performance, operational, and economic considerations are a common set of metrics used to evaluate and to guide development of advanced technologies. They describe the locomotive performance and operations, and lay the framework for how future technologies generally should perform to be commercialized.

These metrics address not only technology considerations (i.e. duty cycle, payload, etc.), but also operational, fuel and infrastructure aspects. In essence these performance metrics set a baseline level that advanced technologies generally should meet before they are considered to be ready for commercial introduction.

These metrics can be separated into three main categories:

A. Locomotive Performance
   1. Locomotive Height, Weight, and Width
   2. Tractive Effort
   3. U.S. EPA Locomotive Duty Cycles
   4. Locomotive Fuel Efficiency

B. Line Haul Locomotive Fueling Range

C. Operations
   1. Locomotive Useful Life
   2. National Locomotive Fleet Turnover Rates
   3. Leasing Locomotives
   4. Operating Conditions
   5. Maintenance Practices and Safety
   6. Compatibility with Existing National Fleet

While there are very specific metrics, the requirements for advanced technologies are flexible. For example, if the capital costs of an advanced locomotive are higher than the existing conventional, but there is a reasonable return on investment, then that technology may still be considered ready for commercial introduction.

A. Locomotive Performance

UP and BNSF freight interstate line haul locomotives are equipped with medium-speed diesel engines rated about 1,000 rpm, as compared to heavy-duty diesel trucks that operate with high speed engines at about 1,800 rpm. U.S. diesel-electric freight locomotive engines are built to operate for up to 30 to 50 years or more.

Table III-1 provides some of the key specifications for GE and EMD interstate line haul locomotives built since 2005 (i.e., Tier 2 and Tier 3 locomotives). These two types of locomotives perform up to two-thirds of the work (MWh) in the South Coast Air Basin.

Table III-1:
Specifications for GE and EMD: Tier 2/3 Freight Interstate Line Haul Locomotives

Key Locomotive and Engine Specifications	**GE Evolution** (Bachand, 2007a)	**EMD SD70ACe** (Craig, 2006)
Locomotive Weight (Pounds)	432,000	408,000
Locomotive Length	73’2”	74’3”
Locomotive Height	15’5”	15’11”
Locomotive Cab Width	10’3”	10’3”
Locomotive Starting Tractive Effort (STE) (Pounds of Force)	183,000	191,000
Locomotive Continuous Tractive Effort (CTE) (Pounds of Force)	166,000	157,000
Engine Maximum Rated Speed (RPM)	1,050	904
Engine Cycle/Stroke	Four	Two
Engine Cylinders	12	16
Engine Horsepower	4,400	4,300
Fuel Tank Capacity (Gallons)	5,000	4,900
Maximum Rated Locomotive Speed (MPH)	About 75	About 75

Table III-2 provides similar specifications for conventional (single large diesel engine – typically about 2,000 hp) and genset (single to multiple generator set diesel engines – typically three 700 hp engines) switch locomotives.

1. Locomotive Length, Height and Width

American Association of Railroads (AAR) Standard S-5510 Plate L requirements (AAR, 2008) fundamentally limit the height and width of an interstate line haul locomotive (i.e., locomotives used for interchange service) to about 16 feet and 11 feet, respectively. These standards are designed to ensure U.S. freight locomotives can operate on or under the various bridges, tunnels, and other infrastructure across North America. Track curvature and operational handling characteristics typically limit locomotive length to about 75 feet. (Trainweb, 2002; Trainweb, 2003) Double-stacked intermodal trains can have higher height limits (up to 20 feet 2” above top of rail), but are often constrained to specific rail routes due to clearance and other infrastructure limitations along the North American rail system.

Table III-2:
Older Conventional vs Genset Switch Locomotive Specifications

Key Locomotive and Engine Specifications	**EMD GP38-2** (Bachand, 2006a)	**National Railway Equipment Company (NREC) 3-Engine Genset** (NRE, 2016a)
Locomotive Weight (pounds)	250,000	268,000 (4 axle) 395,000 (6 axle)
Locomotive Length	59'2"	62'6"
Locomotive Height	15'4"	16'3"
Locomotive Cab Width	10'4"	N/A
Locomotive Starting Tractive Effort (STE)	61,000	80,000
Engine Maximum Rated Speed (RPM)	800	1,800
Engine Cycle/Stroke	Two	Four
Engine Cylinders	16	6
Engine Horsepower	2,000	2,100 (3 x 700 hp)
Fuel Tank Capacity (Gallons)	1,700	2,900
Maximum Rated Locomotive Speed (MPH)	65	70

2. Tractive Effort

The force which a locomotive can exert when pulling or pushing a train is called its *tractive effort*. Therefore, the term tractive effort is often used synonymously with tractive force to describe the pulling or pushing capability of a locomotive to move a train. The term tractive effort is often specified as: 1) starting tractive effort, 2) continuous tractive effort, and 3) maximum tractive effort. (Worden et al., 2013)

Starting Tractive Effort (STE)

STE is the tractive force that can be generated at a standstill. This value is important on railways because it determines the maximum train weight that a locomotive can set into motion. (Worden et al., 2013)

Maximum Tractive Effort (MTE)

MTE is defined as the highest tractive force that can be generated under any condition that is not injurious to the vehicle or machine. In most cases, MTE is developed at low speed and may be the same as the STE. (Worden et al., 2013)

Continuous Tractive Effort (CTE)

CTE is the tractive force that can be maintained indefinitely, as distinct from the higher tractive effort that can be maintained for a limited period of time before the power transmission system overheats. (Worden et al., 2013)

U.S. freight locomotives are designed to produce higher maximum tractive effort than passenger units of equivalent horsepower, which is due to the greater weight of a typical freight train. In modern locomotives, the gearing between the traction motors and axles is selected to suit the type of service in which the unit will be operated. As traction motors have a maximum speed at which they can rotate without incurring damage, gearing for higher tractive effort is at the expense of top speed. Conversely, the gearing used with passenger locomotives emphasizes speed over maximum tractive effort.

Table III-3 shows a comparison of STE and CTE and locomotive weights for the most common interstate line haul, MHP, and switch locomotives that operate nationally and within California.

Table III-3:
Comparison of Tractive Effort for U.S. Freight Diesel-Electric Locomotives
(Bachand, 2006a; Bachand, 2006b; Bachand, 2006c; Bachand, 2007a; Craig, 2006; NRE, 2016b)

Type of Locomotive	STE (lbs. force)	CTE (lbs. force)	Weight (Pounds)	Horsepower
Tier 2/3 Interstate Line Haul Locomotives (2005-2014)				
GE ES44AC	183,000	166,000	432,000	4,400
EMD SD70ACe	191,000	157,000	408,000	4,300
MHP Locomotives: Former Interstate Line Haul Locomotives (1972-1995)				
EMD SD60 (1984-1995)	98,250	100,000	368,000	3,800
EMD SD40 (1972-1986)	115,000	82,100	368,000	3,000
Switcher Locomotives: 1970's or Gensets (2007-Present)				
EMD GP38-2 (1972-1987)	61,000	54,700	250,000	2,000
NREC Genset[1] (3GS21C) (2007-2014)	117,000	71,630	395,000	2,100

1. Note that the NREC genset locomotive repowers have up to a 50 percent improvement in STE, and nearly a 25 percent increase in CTE. This TE enhancement is due to an anti-wheel slip and traction control system with individual traction motor controller.

3. U.S. EPA Locomotive Duty Cycles

The operational duty cycles of high horsepower interstate line haul locomotives are dominated by higher power notch settings (i.e., Notches 5-8) when traveling cross country on main rail lines. When interstate line haul locomotives do operate within railyards (e.g., to trim with railcars to form trains or receive fuel, service, or maintenance) they typically operate in idle or lower power settings. Idle time represents about 40 percent of their total operational time.

Table III-4 shows an average duty cycle for line haul locomotives as defined by U.S. EPA. Note that the average duty cycle for a locomotive nationwide differs from the average duty cycle for a line-haul locomotive in California.

Table III-4:
U.S. EPA Line Haul Locomotive Duty Cycle
(40 CFR Part 1033.530)

Test Mode	**Percent Time in Mode**
Low and Normal Idle	38%
Dynamic Brake	12.5%
Notch 1	6.5%
Notch 2	6.5%
Notch 3	5.2%
Notch 4	4.4%
Notch 5	3.8%
Notch 6	3.9%
Notch 7	3.0%
Notch 8	16.2%
Total	100%

Table III-5 (next page) presents an average duty cycle for switch locomotives as defined by U.S. EPA. As a side note, this duty cycle does not account for the benefits of idle reduction devices, which can provide a ten percent reduction in switch locomotive idling, and a three percent reduction in line haul locomotive idling. (ICF, 2008) Under the 2005 ARB/Railroad Agreement, idle reduction devices were required to be installed on greater than 99 percent of the intrastate locomotive fleet by June 2008.

Beyond idling, the U.S. EPA duty cycle assumes switch locomotives primarily operate in the lower locomotive power (notch) settings (i.e., Notch 1-4) for most of the operating times. This duty cycle also reflects the distribution of diesel fuel consumption for a switch locomotive over a range of eight power (notch) settings.

Table III-5:
U.S. EPA Switch Locomotive Duty Cycle
(40 CFR 1033.530)

Test Mode	Percent Time In Mode
Low and Normal Idle	59.8%
Dynamic Brake	0%
Notch 1	12.4%
Notch 2	12.3%
Notch 3	5.8%
Notch 4	3.6%
Notch 5	3.6%
Notch 6	1.5%
Notch 7	0.2%
Notch 8	0.8%
Total	100%

4. Locomotive Fuel Consumption and Efficiency

Locomotives fuel consumption varies significantly by power setting. In idle or power setting Notch 1, a line haul locomotive may consume between 3 to 20 gallons per hour, whereas in Notch 8 a line haul locomotive may consume 220 gallons per hour or more, as shown in Table III-6.

Table III-6:
U.S. Freight Interstate Line Haul Locomotive

Power Setting	Fuel Consumption (Gallons Per Hour)
Idle	3-5
Dynamic Brake	5-10
Notch 1	10-20
Notch 2	25-35
Notch 3	55-65
Notch 4	80-100
Notch 5	110-120
Notch 6	150-170
Notch 7	180-200
Notch 8	210-230

Note: Actual brake-specific fuel consumption rates are “company confidential”.

With respect to efficiency enhancements, digital, smart, and fuel-efficient solutions connect the entire rail ecosystem, thereby minimizing downtime, reducing fuel use, and delivering significant emissions reductions. Two GE Transportation digital technologies are already deployed on locomotives system wide (GE, 2016):

- Distributed Power: a control and communication system that enables coordinated braking and traction power distribution between lead and remote locomotives, resulting in faster stopping times and shorter stopping distances.

- Trip Optimizer: a smart, automated cruise control system that uses data to take into account route topology and conditions and make a fuel-efficient plan, realizing an average of 10 percent fuel savings.

One metric of efficiency in the rail industry is the gross ton-mile. A gross ton-mile is a measure of the movement of one ton of freight or equipment over one mile. In calculating gross ton-miles, the total weight (including the weight of rail cars and locomotives) is included. Statewide, system wide fuel efficiency for line haul locomotives is about 650 gross ton-miles/gallon. (ARB, 2014a)

B. Line Haul Locomotive Fueling Range

Interstate line haul locomotives have fuel tanks with up to a 5,000 gallon capacity. As part of train and with multiple locomotives, an interstate line haul locomotive has a refueling range between 800 to 1,200 miles, or about 1,000 miles on average.

For example, UP or BNSF intermodal trains leaving the Ports of Los Angeles and Long Beach for Chicago will typically fuel first at the Ports before departure and then refuel at El Paso, Texas (UP) or Belen, New Mexico (BNSF), respectively, about 850 miles from the Ports. UP and BNSF trains will then typically refuel in Kansas City, or similar distance location, prior to taking the last leg of the trip to Chicago.

C. Operations

1. Locomotive Useful Life

GE and EMD, the latter of which was acquired by Caterpillar/Progress Rail (CAT/PR) in 2010, are the only two major freight diesel-electric interstate line haul locomotive manufacturers in the U.S. GE controls about two-thirds of the annual sales of new freight interstate line haul locomotives, with EMD accounting for about the remaining one-third. (Tita and Hagerty, 2014)

Historically, the North American Class I railroads have purchased virtually all of the locomotives freshly manufactured, with Class I railroads average life about 30 years. However, as the freshly manufactured locomotives lifetimes exceed twenty years, the locomotives can be cascaded down from interstate line haul service to Class I railroad regional hauler or switch (yard) locomotive service. Interstate line haul locomotives begin to gradually transition to regional and local service after about 15 to 20 years.

Also, as the Class I railroads replace their older locomotives with freshly-manufactured units, the older units can either be sold to smaller railroads, are scrapped, or are purchased for remanufacture and ultimate resale (or leasing) by companies specializing in this work.

A few freight locomotives that first serviced Class I railroads, and then serviced shortline railroads, have recorded total useful lives of up to 50 years or more.

2. National Locomotive Fleet Turnover Rates

Fleet turnover is the time required, starting with a base year, for the locomotive fleet to be entirely composed of locomotives that were not in service as of the base year. Class II (regional) and III (shortline) railroads generally buy used locomotives from Class I railroads, although some will purchase new switchers (e.g., new genset switchers with public incentive funding) and a few new line-haul locomotives.

Due to the total life span of locomotives and their engines, annual replacement rates of existing locomotives with freshly-manufactured units are low. U.S. EPA estimated a replacement rate for locomotives and locomotive engines based on historical data supplied by American Association of Railroads (AAR).

According to U.S. EPA, sales of new locomotives averaged approximately 770 units per year from 1996 to 2004. Of the total sales volumes during that period, UP and BNSF averaged about 564, or about 75 percent, of new line haul locomotive acquisitions.

The UP and BNSF share of new acquisitions (75 percent) was much greater than their proportion of the national locomotive fleet at about 60 percent. UP and BNSF were motivated to acquire a large amount of new locomotives during this period due to a number of key factors:

- Recent mergers, in which UP and BNSF acquired and retired or scrapped a large number of older locomotives from former companies;
- UP and BNSF made it a high priority to significantly improve locomotive fuel efficiency with newer locomotives;
- UP and BNSF needed new locomotives to comply with U.S. EPA locomotive regulations; and
- UP and BNSF needed new locomotives to comply with the 1998 Agreement in the South Coast Air Basin by 2010.

The national locomotive replacement rate from 1996 to 2004 (767 units per year) indicates a fleet turnover rate of the U.S. Class I railroad fleet (25,000 units) of about 30 years.

In UP and BNSF's case, the current UP and BNSF national locomotive fleet of about 15,000, at a new acquisition rate of 500 units per year from 1996 to 2014, would take about 30 years to replace.

3. Leasing Locomotives

Locomotives are also available for lease[1] from original engine manufacturers (OEMs), remanufacturers, and a small number of specialized leasing companies formed for that purpose. The lease duration ranges between 30 days and five years, with the average being three years. UP and BNSF typically either purchase or enter into long-term non-cancelable leases for new interstate line haul locomotives. The lease periods for new interstate line haul locomotives are typically up to 20 years or more.

According to U.S. EPA, leasing has been a continuing trend among Class I railroads, with almost two-thirds of the locomotives placed into service in 2004 were leased locomotives. Leasing among Class II and III railroads is not nearly as widespread.

There is another type of leasing with a short-terming borrowing of locomotive power under a credit system. (U.S. EPA, 1998) When Class I railroads borrow locomotive power over shared routes with other Class I railroads, the Class I railroad that loaned the locomotive power can accumulate locomotive credits that can be used over time. The Class I railroads keep track of this loaned power, and use the credits as needed.

4. Operating Conditions

The North American Class I railroads operate freight trains across the continental United States and parts of Canada and Mexico. While traveling throughout these regions locomotives are subject to extreme temperatures, and operate on mountain grades, and varying elevations.

UP and BNSF operate over mountain grades up to three percent or more, on specific track in certain areas. For example, in California UP and BNSF operate on the Cajon Pass, Beaumont Pass, Cima (Hill) Subdivision, UP Donner, UP Feather River, and UP Black Butte Subdivision, and the grades can range from 1.4 up to 3.0 percent.

[1] Leasing practices appear to be fairly standardized throughout the industry. Although lease contracts can be tailored on an individual basis, most leases seem to incorporate boilerplate language, terms and conditions. Under a typical lease, the lessee takes on the responsibility for safety certification and maintenance (parts and scheduled service) of the locomotive (including the engine) although these could be made a part of the lease package if desired.

Mountain grades have a significant impact on the number and types of locomotives used to push 10,000 to 20,000 ton trains over mountain passes. These mountain grades can impact system-wide levels of diesel fuel consumption.

Ascending mountain grades, interstate line haul locomotives are typically in the highest power setting (Notch 8), where diesel fuel can be consumed at a rate of 200 gallons per hour or more. For perspective on some of the impacts of California's mountain grades, the U.S. average is about 800 gross ton-miles (GTM) per gallon, and California is about 650 GTM per gallon.

5. Maintenance Practices and Safety

U.S. Class I freight railroads locomotive maintenance practices also present some unique considerations. As is the case with other mobile sources, locomotive maintenance activities can be broken down into a number of subcategories including:

- Routine servicing;
- Scheduled maintenance; and
- Breakdown maintenance.

Routine servicing consists of providing the fuel, oil, water, sand (which is applied to the rails for added traction), and other expendables necessary for day-to-day operations.

Scheduled maintenance can be classified as light (e.g., inspection and cleaning of fuel injectors) or heavy, which can range from repair or replacement of major engine components (such as power assemblies) to a complete engine remanufacture.

Wherever possible, scheduled maintenance (particularly the lighter maintenance) is timed to coincide with periodic federally-required safety inspections, which normally occur at 92-day intervals. Federal Railroad Administration (FRA) safety requirements in 49 CFR Part 229 provide for various levels of maintenance based on the inspection period (Daily, 92 Days, 184 Days, Annual).

In addition, a locomotive may have an engine overhaul. U.S. EPA, GE, and EMD contracts require a locomotive remanufacture at its "useful life". U.S. EPA defines a locomotive "useful life" in terms of locomotive megawatt-hours (MWh). U.S. EPA calculates "Useful life" by multiplying the locomotive hp (e.g., an interstate line haul locomotive of 4,400 hp) by 7.5, which in this example is about 33,000 MWh. For an interstate line haul locomotive, with such a high activity level, the remanufacture typically occurs about every seven to ten years. U.S. EPA defines the minimum useful life as ten years. (40 CFR Part 1033.101g)

A high degree of locomotive maintenance is necessary for safety, reliability, and durability factors. The railroads need to ensure train safety, especially regarding ongoing air brake and wheel maintenance, but also to ensure that a locomotive will be consistently reliable in-service. Locomotive failures can result in congestion of major train routes, backing up the train system as there may not be comparable timely alternatives available.

6. Compatibility with the Existing National Fleet

Figure III-1 presents an example of a UP interstate line haul locomotive's operations over a 60 day period. Class I railroads treat interstate line haul locomotives as the "power" needed to move a train. The Class I railroads do not typically assign individual interstate line haul locomotives to specific trains, routes, or jobs.

On any given day, North American Class I railroads will employ or lease interstate line haul locomotives to other Class I railroads at a rate as high as between five to ten percent or more of their total national fleets.

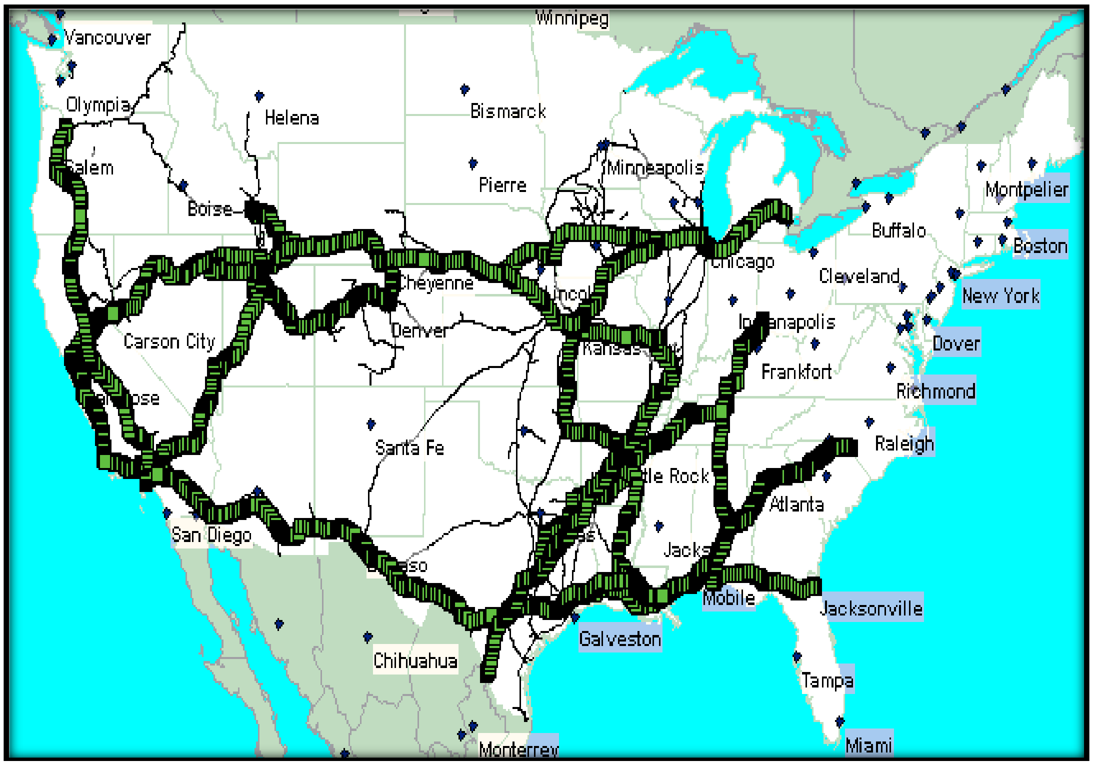


Figure III-1:
Sample of Union Pacific Railroad (UP) Interstate Line Haul Locomotive's Operations over a 60 Day Period
(UP, 2009)

IV. DEVELOPMENT TIMELINES AND TECHNOLOGIES TO MEET CURRENT NATIONAL LOCOMOTIVE EMISSIONS STANDARDS

Historically, it has taken about seven years for U.S. locomotive manufacturers to implement new U.S. EPA engine emissions standards. For example, it took GE and EMD more than seven years to design, laboratory test, build prototypes, and field demonstrate a number of pre-production locomotives (about 20 to 80) over a couple of years, to be ready for commercial production of both Tier 2 and Tier 4 interstate freight line haul locomotives.

A. Tier 2 Development Timelines and Technologies

The original U.S. EPA locomotive regulations were published on April 16, 1998. Under these regulations, the U.S. EPA Tier 2 locomotive emissions standards became fully effective on January 1, 2005 and were applicable to locomotives commercially built between model-years 2005-2011. Table IV-1 is the timeline to develop, test, and demonstrate Tier 2 line haul locomotives. (Craig, 2015a; Craig, 2015b; Craig, 2016a; Craig, 2016b; RR Picture Archives, 2015; GE, 2009; ARB, 2006a)[2]

Table IV-1:
GE and EMD Tier 2 Interstate Freight Line Haul Locomotive Development Schedule

Tier 2 Stages of Development	Years						
	1999	2000	2001	2002	2003	2004	2005
Concept/Design							
Laboratory Engine Testing							
Prototype/Demo Locomotives							
Pre-production Locomotives (74 Field Tests)							
Commercial Production							

[2] GE Tier 2 pre-production locomotives: BNSF 5718-5747 (built 10/2003-4/2004). UP 5348-5352 (built 12/2002-2/2003). NS 7500-7514 (built 03/2004-5/2004). Total = 50.

EMD Tier 2 pre-production locomotives: CSX 4831-4850 (SD 70ACe built 04/2004-09/2004). GMDX 70-73 (built 04/2003-05/2003). Total = 24.

Tier 2 freight interstate line haul locomotive emission levels were primarily achieved with:

- Enhanced cooling systems (e.g., enlarged radiators);
- Improvements in combustion such as electronic fuel injection (EFI) systems; and
- Individual axle control options to reduce track slippage.

B. Tier 3 Development Timelines and Technologies

The new Tier 3 emission standards went into effect for model-years 2012 to 2014. Tier 3 required a 50 percent reduction in PM emissions from the Tier 2 PM emission levels (i.e., 0.2 to 0.1 g/bhp-hr). There were no changes in NOx emissions from Tier 2 to Tier 3 emission standards. U.S. EPA Tier 2^+ (plus) or remanufacture standard requires the same PM levels as the new Tier 3 emission standards (0.1 g/bhp-hr). The timeline for development of the new Tier 3 PM emission standards was about four years (2008 to 2012).

The key technologies used by GE and EMD to achieve the U.S. EPA Tier 3 PM emissions standards were high pressure common rail injection and closed crankcase ventilation (CCV) control. These two technologies played a critical role in laying the foundation for GE and EMD to ultimately be able to meet the Tier 4 emission standards.

<u>High Pressure Common Rail Injection Systems</u>

With regard to enhancements to existing diesel technologies, locomotive engines equipped with common rail fueling systems have the ability to control and optimize fuel injection which provides smoother, quieter running engines with better performance and greater combustion efficiency. Conventional diesel engines inject pressurized fuel into each cylinder at a rate dependent on the rotational speed of the engine.

Common rail injection systems (see Figure IV-1) allow for a more controlled fuel injection rate across all engine speeds by storing fuel at high pressures (i.e., up to 2,000 bars) along a common rail connected to each cylinder. (Railway Strategies, 2008) High injection pressures generate very fine atomization of the fuel yielding more efficient combustion.

Furthermore, common rail systems control the point in the engine cycle that fuel is injected into the cylinder and the duration of the injections using an electronic fuel injection system which enhances the fuel combustion process. Locomotive engines equipped with common rail configurations can be applied as a retrofit or as engine replacements.

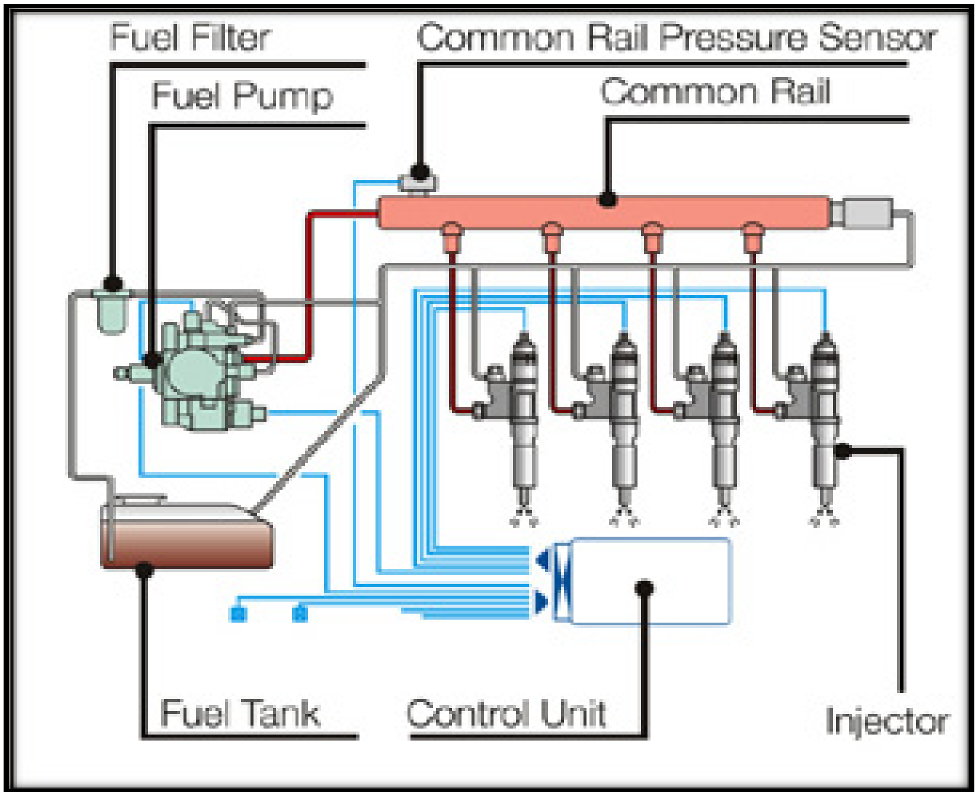


Figure IV-1:
Design of a Common Rail Injection System
(Hitachi, 2005)

<u>Closed Crankcase Ventilation (CCV) control</u>

The CCV system is necessary to stop the blow-by (i.e., unburned fuel and lubricating oil) from escaping into the atmosphere from the cylinders. This blow-by consists of the same gases that are traveling down the exhaust system. The blow-by is a very small amount of gases that leak by the compression rings on each cylinder during the ignition cycle of the engine. In locomotives, the blow-by can contribute to a significant amount of PM and HC emissions. Organic carbon PM primarily consists of lubricating oil and partial combustion products of lubricating oil.

The CCV system for a medium speed locomotive diesel engine employs an eductor that uses compressed air to draw crankcase gases through a coarse coalescing filter. The outlet of the crankcase ventilation system can be clearly seen from the outlet of the locomotive's exhaust stack.

Tubing from a crankcase ventilation system removed downstream of a coarse coalescing filter can have considerable wetting of the inner wall of the tubing with lubricating oil. As a result, further improvements can be designed to improve CCV filtration to further reduce soluble organic fraction (SOF) fuel and lubricating oil emissions. (U.S. EPA, 2007)

C. Tier 4 Development Timelines and Technologies

U.S. EPA approved the new Tier 4 locomotive emissions standards in 2008. Under the federal regulations, manufacturers were required to build complying Tier 4 locomotives beginning on January 1, 2015.

Technologies Employed

GE and EMD have indicated that they will meet Tier 4 NOx levels without the use of SCR for NOx control. Instead, both GE and EMD employed exhaust gas recirculation (EGR) and other technologies to meet the Tier 4 NOx standard.

Below is a list of the technologies that have been employed in the commercially ready Tier 4 locomotives.

- EGR – NOx control. Used to lower peak combustion temperatures, which results in a reduction of oxides of nitrogen.
- Major enhancement of cooling radiators – NOx and temperature control. Needed due to utilization of cooled EGR. Cooled EGR transfers exhaust heat to engine coolant.
- Enhanced common rail injection (see Tier 3 technologies). Higher system pressure for fuel injectors.
- Miller Cycle. A thermodynamic cycle used in internal combustion engines. Reduces in-cylinder combustion temperature by reducing the effective compression ratio and is used for reducing NOx specific emissions, but negatively impacts volumetric efficiency and engine power. Usually combined with highly boosted turbocharging system (e.g., two stage) to recover lost power.
- Two stage turbocharger. Two turbo chargers connected in series increasing intake air charge creating higher power density, in conjunction with the Miller Cycle, results in reduced exhaust emissions and lower fuel consumption.
- Variable Valve Timing (VVT). VVT is the process of altering the timing of the valve lift event to improve performance, fuel economy, or emissions.

Technology Performance: Emission Reductions and Fuel Efficiency

Tier 4 locomotives will reduce NOx and PM emissions, beyond Tier 2 levels, by up to 76 percent for NOx and 85 percent for PM. GE and EMD claim fuel efficiency could be similar to Tier 3 (five percent better than Tier 2).

Operational and Infrastructure Considerations

It is expected that Tier 4 locomotives will be compatible with the national fleet and not require additional fueling infrastructure. However, Tier 4 locomotives will likely require additional training for maintenance operations.

D. Capital Costs for New Tier 2 to Tier 4 Freight Interstate Line Haul Locomotives

Tier 2 Capital Costs

From model-years 2005 to 2011, a new Tier 2 interstate freight line haul locomotive capital cost ranged between about $1.8 to $2.2 million per unit, depending on the types of equipment that may be added to the locomotive (the cost range is primarily the difference between the use of direct current (DC) and alternating current (AC) traction power). (U.S. EPA, 2008)[3] On average, the cost of a Tier 2 interstate line haul locomotive (2005-2011) was about $2 million. (AAR, 2013)

Tier 3 Capital Costs

A new Tier 3 interstate line haul locomotive (2012 to 2014) was estimated to cost on average about $2.5 million. This capital cost estimate is primarily based on the increased costs associated with the installation of common rail injection, closed crankcase ventilation systems, enhanced cooling systems, and advanced computer controls discussed later in this document. (ARB, 2014b; ARB, 2015b; ARB, 2015c)

Tier 4 Capital Costs

U.S. EPA required a new interstate freight line haul locomotive to meet Tier 4 emission standards beginning on January 1, 2015. Based on the Tier 4 additions of EGR, twin turbochargers, enhanced cooling systems, and the next level of complexity of systems integration, ARB staff uses an approximate Tier 4 freight interstate line haul locomotive cost of $3 million, depending on the type of equipment ordered. The capital cost increase of about $500,000 is similar to the cost increase between Tier 2 and Tier 3. On October 18, 2014, GE announced an order for about 1,000 Tier 4 locomotives, for model-years 2015 to 2017, at a total order amount of about $3 billion. This translates to about $3 million per Tier 4 interstate line haul locomotive. (Black and Clough, 2014)

[3] U.S. EPA, *Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less than 30 Liters Per Cylinder*, EPA420-R-08-001 (U.S. EPA, 1998), p. I-50. The cost of a locomotive can vary between $1.5 million to $2.2 million, depending on the configuration and options installed. Figure 1-1-7 on p. I-50 shows data from the AAR's Railroad Ten-Year Trends 1995-2004 publication. Some of the variation from year to year can be attributed to differences in features, but it appears the overall trend in the price of AC locomotives is downward, while DC locomotive pricing remains steady. ARB staff estimates that new Tier 2 line haul locomotives from model years 2005-2011, especially DC, were slightly higher due to new equipment such as electronic fuel injection, enhanced cooling, and systems integration costs.

The Tier 2 to Tier 4 interstate line haul locomotive average capital costs have been confirmed through ARB staff personal conversations with locomotive manufacturers, various internet sources, and information provided in applications for locomotive emission reduction projects funded through State incentive programs.

ARB staff has not been provided operating and maintenance costs by the railroad industry for Tier 2 to 4 interstate line haul locomotives.

E. Tier 4 Current Status

In 2012, GE built two Tier 4 locomotive prototypes (GECX 2014 and GECX 2015). (The Diesel Shop, 2015) These two prototypes have been primarily limited to use as development test beds at GE's locomotive manufacturing facility in Erie, Pennsylvania.

In mid-2013, GE built five new Tier 4 demonstrator locomotives (GECX 2020-2024) to perform an initial set of small-scale field demonstrations. GECX 2020 has not left the GE facility at Erie, Pennsylvania since 2013. In late 2013, GECX 2022 was sent to the Transportation Technology Center, Inc. (TTCI) located at Pueblo Colorado. GECX 2023-2024 were sent to TTCI in early 2014. GECX 2021-2024 were also performing a variety of minor field demonstrations across the country, including mountain grade and tunnel testing on Donner Pass in California in the spring of 2014. (Trainorders, 2013; Trainorders, 2014a)

In late 2014, GE began production of 20 pre-commercial production locomotives to perform full-scale demonstrations (GECX 2025-2044). (The Diesel Shop, 2015) These full-scale demonstrators have also been operating across the North American freight rail system between late-2014 to 2016. In the past, GE would have liked to have up to two years of full-scale field demonstrations prior to full-scale commercial production.

U.S. EPA locomotive regulations required manufacturers (GE and EMD) to build Tier 4 interstate line haul locomotives beginning on January 1, 2015. Since January 2015, U.S. EPA has allowed GE to sell Tier 3 credit locomotives (i.e., that meet U.S. EPA Tier 3 emissions levels) that can be offset by future orders of fully complying Tier 4 locomotives. (Trains, 2015; Trainorders, 2015)

As of mid-2015, ARB staff confirmed the deployment of the first batch of GE Tier 4 interstate line haul commercial production locomotives. BNSF 3916 was photographed at the GE locomotive manufacturing facility in Fort Worth, Texas in April 2015, and spotters suggested that BNSF 3916 went to Southwest Research Institute (SwRI) in San Antonio, Texas for federal emission testing certification in June 2015.

As of August 2015, ARB staff believes GE went into full scale commercial production of Tier 4 interstate line haul locomotives by the fall/winter of 2015. As of January 2016, ARB staff believes up to 350 commercial Tier 4 units were delivered to four Class I railroads during calendar year 2015.

EMD has publicly stated they will not produce full scale commercial production Tier 4 interstate line haul locomotives until at least late 2016 or early 2017. (Cotey, 2014)

F. Status of Development for Tier 3 and Tier 4 Natural Gas/Diesel Dual-Fuel Freight Interstate Line Haul Locomotives

Interest in the potential for fueling freight locomotives with natural gas has grown recently (2012-2014), and there are a number of key reasons for the railroad industry's more recent interest in natural gas. The reasons include the following:

- Lower natural gas prices compared to crude oil, and the substantial growth in domestic natural gas production. The railroads recently began to investigate (2012) using natural gas as a fuel for locomotives because of its potentially favorable economics compared with diesel fuel on a diesel gallon equivalent (DGE) basis. Some industry officials suggest there could be up to a 50 percent price differential.

- The locomotive manufacturers and railroads are currently interested in retrofitting existing Tier 0 to Tier 3 line haul locomotives to run on a mixture of natural gas and diesel (i.e., about 80 percent natural gas and 20 percent diesel). The objective is to lower fuel costs, but not necessarily to reduce emissions beyond current U.S. EPA emission certification levels (i.e., Tier 0 to Tier 3, rather than Tier 4).

- The locomotive manufacturers and railroad industry are also working on research to develop natural gas locomotive technologies in the future (e.g., with high pressure direct injection (HPDI) and up to a 95/5 natural gas and diesel fuel ratio) that can potentially be built to meet Tier 4 standards.

As of January 2016, the locomotive manufacturers and railroads are not focused on pushing liquefied natural gas (LNG) technologies beyond current Tier 0 to Tier 4 emissions levels. At this time, there is no commercially available Tier 4 natural gas freight interstate line haul locomotive.

<u>Key Challenges to Transition to Natural Gas Freight Interstate Line Haul Locomotives</u>

There are, however, a couple of key issues to address for railroads to make the transition to natural gas:

- From an operational standpoint, the most significant difference between natural gas and diesel is energy density (the amount of energy produced per unit volume of fuel). As shown in Figure IV-2 below, LNG has approximately 60 percent of the energy density of diesel fuel, whereas compressed natural gas (CNG) only has about a quarter of the energy of diesel fuel. (UP, 2013b)

- A volume of natural gas equivalent to a typical interstate line haul locomotive fuel tank (i.e., about 5,000 gallons in volume) would still not be a sufficient amount of fuel for line haul locomotive refueling distances (i.e., on average about 1,000 miles). Consequently, a natural gas fuel tender would be needed to provide a sufficient amount of natural gas to fuel an acceptable refueling range for a line haul freight locomotive.

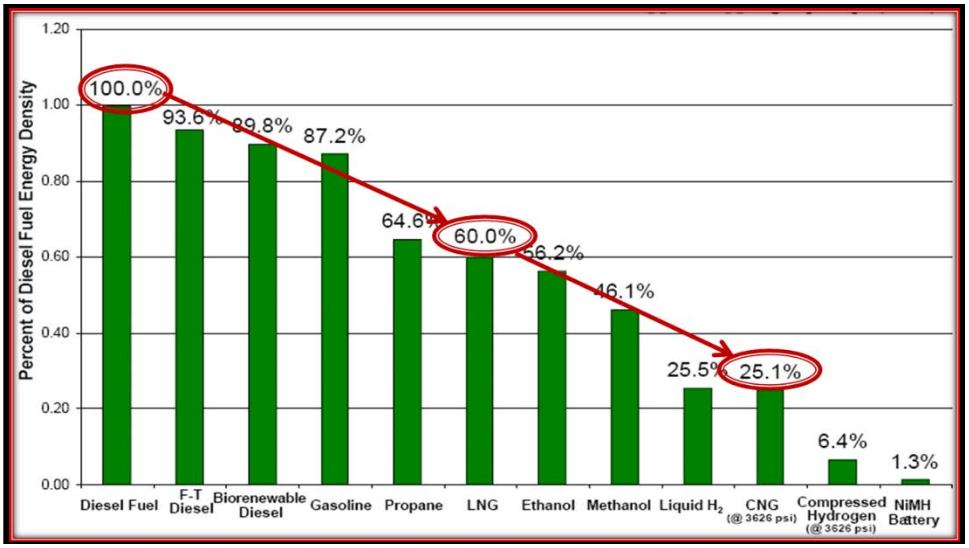


Figure IV-2:
Comparison of Energy Density of Diesel, LNG, and CNG
(UP, 2013b)

1. Technology Options

Internal combustion engines powered by natural gas can make use of spark ignition or compression ignition. With a spark ignition combustion system, internal combustion engines can operate on natural gas alone. Compression ignition engines can operate on natural gas (such as LNG), but also require a small amount of diesel fuel mixed with the natural gas as a pilot to initiate combustion during the compression cycle.

2. Technology Performance: Potential for Emission Reductions and Fuel Efficiency

Switch Locomotives

No studies have yet been done on duty-cycle emissions from CNG-fueled locomotives under the federal test procedure. However, the four LNG-fueled switch locomotives operated by Los Angeles Junction (LAJ) Railway from the early 1990’s through 2012 had a spark ignition combustion system, as is typically used for a CNG-fueled switcher locomotive.

Line Haul Locomotives

The emissions benefits of LNG in line-haul freight service are still unclear. Southwest Research Institute (SwRI) performed an emission test on BNSF 1201 in 2008, a natural gas-fueled spark-ignited switcher locomotive, according to the procedures and requirements of Title 40 CFR Part 92. (SwRI, 2008)

The emissions for BNSF 1201 are consistent with the Tier 3 U.S. EPA emission standards, and comparable to a diesel ULEL genset switcher.

However, the results only represent 100 percent natural gas-fueled combustion. Current LNG prototypes may provide more insight on emission benefits for line-haul locomotive service.

LNG/diesel dual-fuel locomotives utilize the same traction system and have the same relative combustion efficiency as conventional diesel locomotives, so overall energy consumption should be similar to current conditions. However, because of the difference in energy density of natural gas (UP, 2013b) there will be more fuel required to move the same ton-mile.

3. Operational and Infrastructure Considerations

For use of natural gas in locomotives, there is one main operational and infrastructure consideration: fuel tenders.

Figure IV-3: BNSF LNG Tender
(RR Picture Archives, 2014b)

Given the fact that its energy density is higher than that of CNG, LNG will likely be the form of natural gas used by interstate line haul locomotives. CNG would likely be restricted to switch locomotives and regional haulers.

Although LNG's fuel density is more than twice that of CNG, a volume of LNG (about 60 percent energy density of diesel) equivalent to a typical locomotive fuel tank would still not be sufficient for longer-distance line haul operations. Consequently, an LNG tender would be needed to provide sufficient LNG to fuel an acceptable range for a freight interstate line haul locomotive.

The LNG fuel tender, which is an appurtenance to the locomotive, includes an insulated cryogenic tank for storing the LNG and other equipment used to convert the LNG to a gas for delivery to the locomotive for combustion.

Figure IV-4 presents a configuration of an LNG tender coupled between two locomotives: it can supply LNG to both of the locomotives.

Figure IV-4:
Canadian National LNG (Natural Gas) Test Locomotives and Tender
(Piellisch, 2013a)

4. Costs

Below is a cost summary for current CNG/LNG locomotive projects.

<u>CNG Switch Locomotives</u>

The Indiana Harbor Belt (IHB) Railroad is the largest switch carrier in the U.S., with 54 miles of mainline track and 266 miles of additional yard and siding track. The IHB main line circles Chicago from near O'Hare to Northwest Indiana. (Indiana Harbor Belt, 2015)

As of early 2014, the IHB Railroad was converting 31 of its locomotives from diesel fuel operation to CNG-diesel dual fuel operation. Each CNG conversion was expected to be about $1.7 million. (Stagl, 2014a) IHB also expects to reduce its annual diesel consumption by about one million gallons, or about 32,000 gallons per locomotive.

<u>LNG Line Haul Locomotives</u>

Should the railroads choose to implement LNG for line haul locomotives, capital investment in a natural gas supply infrastructure would be an add-on, whether by the railroads themselves or by a third party. Such a natural gas supply infrastructure would include liquefaction plants and fueling stations, and could potentially include pipelines.

At locations of high demand, there could be capital investment in liquefaction plants fed from pipeline connections. Given the cost, it is probable that LNG will be delivered by tanker truck, with the cost of liquefaction included in the delivered cost of the fuel as an operating expense. (Office of the Federal Coordinator, 2013)

Based on available data (Ditmeyer, 2013), ARB staff estimated the costs of LNG line haul locomotives and tenders as follows:

Table IV-2:
LNG Locomotive Costs

LNG Line Haul Locomotive Components	**Cost Per Locomotive Set ($ millions)**	**Cost Per Locomotive ($ millions)**
Retrofit Kit (two kits – one per locomotive)	$1.0 ($0.5 x 2)	$0.5
Tender (one tender)	$1.0	$0.5
Total Costs	$2.0	$1.0

Maintenance costs of LNG/diesel dual-fuel locomotives may increase compared to conventional diesels due to the cryogenics of LNG itself and the need for a tender and the additional glycol pump system used to evaporate the LNG before it is fed to the locomotive. More information, however, is needed to quantify the net effect on operational and maintenance costs.

<u>LNG Fuel Costs and Savings</u>

Typically, Class I railroads do not pay retail prices for diesel fuel. Class I railroads purchase diesel fuel wholesale, and in bulk, and typically are exempt from both federal and State fuel taxes. ARB staff has assumed the same conditions would be true for Class I railroads’ purchase of LNG fuel in the future.

According to ARB staff estimates, the average interstate line haul locomotive (e.g., Chicago to Los Angeles) consumes about 300,000 gallons of diesel fuel per year. At an estimated railroad cost of $3 per gallon, this works out to an annual fuel cost of about $1 million per line haul locomotive. (Annual Energy Outlook, 2014)

ARB staff estimates the payback is about five years, using a natural gas price differential of about $1.50 DGE in 2014, as estimated in the Energy Information Administration's (EIA) report *Annual Energy Outlook 2014*, based on:

- Current prototype designs for retrofit kits that substitute LNG for 60 to 80 percent of diesel fuel; and

- An assumption of the midpoint for both diesel fuel substitution and fuel cost savings, with 70 percent diesel substitution with LNG at a savings of 47.5 percent per gallon of diesel fuel substituted, and that the cost of liquefaction is included in the delivered cost of the fuel as an operating expense, annual fuel cost savings would be about $330,000 per locomotive.

5. Current Status

Below is a summary of the current CNG/LNG locomotive projects.

CNG Locomotives

<u>The Napa Valley Wine Train</u>

The Napa Valley Wine Train, with Carl Moyer Program funding, successfully retrofitted a diesel locomotive (NVRR 73) to run on CNG in May 2003. NVRR 73 is now the Napa Valley Wine Train's primary locomotive. (Piellisch, 2013c)

Figure IV-5:
Napa Valley Wine Train – Natural Gas Locomotive
(RR Picture Archives, 2010a)

Indiana Harbor Belt Railroad

IHB planned to convert 31 of its 46 switcher locomotives to CNG-diesel dual fuel operation, funded primarily by a Congestion Mitigation and Air Quality (CMAQ) grant. (Indiana Harbor Belt, 2014; Piellisch, 2013b) As of early 2014, IHB expected to have the first converted locomotive by the second quarter of 2015. (Stagl, 2014a). No updated data are available.

Norfolk Southern (NS) CNG Line Haul and Switch Locomotives

In late 2014, NS acquired 50 new EMD SD70ACe (4,300 hp) line haul locomotives with a natural gas dual-fuel system. Two were planned to be fully equipped for dynamic gas blending in 2015. (Vantuono, 2014) No updated data are available.

In late 2014, Norfolk Southern (NS) converted one of its EMD GP38-2 switchers to a CNG locomotive, which would be fueled by a slug tender. The CNG tender was completed in September 2014. (Myers, 2014a)

LNG Line Haul Locomotives

There are a number of LNG dual-fuel line haul locomotive test programs currently being conducted by various manufacturers and railroads, summarized as follows.

Canadian National (CN) had two LNG/diesel dual-fuel compression-ignited locomotives testing in regular line-haul service during 2013.

BNSF Railway took delivery of four LNG/diesel dual-fuel compression-ignited test Tier 2 interstate line haul locomotives in late 2013. Two of the four are EMD Tier 2 line haul locomotives (BNSF 9130-9131), and two are GE Tier 2 line haul locomotives (BNSF 5815 and GECX 3000). See GE LNG test locomotive discussion below.

Dual-Fuel 4,300 Horsepower Interstate Line Haul Locomotives: Low-Pressure Direct Injection (LPDI) and High-Pressure Direct Injection (HPDI)

In early 2014, Westport Innovations developed a pilot LPDI LNG/diesel dual-fuel locomotive for CN. (Smith, 2014) In March 2015, Westport completed delivery of the four prototype LNG tenders. (Piellisch, 2015)

Westport has also been collaborating with Caterpillar Inc. to develop the first HPDI locomotive, which was scheduled for demonstration in 2014. (CN, 2012) However, as of early 2016, the HPDI locomotive demonstration has not yet taken place.

BNSF LNG Test Locomotives

BNSF has two EMD SD70ACe interstate line haul locomotives, BNSF 9130 and BNSF 9131, that were converted to LNG/diesel dual-fuel in 2013. Both were built in November 2007, and meet Tier 2 U.S. EPA emission standards. (RR Picture Archives, 2016a; RR Picture Archives, 2016b)

GE LNG/Diesel Dual-Fuel Test Locomotives

In November 2013, GE Transportation's work on LNG locomotives led to the development of the NextFuel™ natural gas retrofit kit, which is a dual-fuel locomotive retrofit kit. The NextFuel™ natural gas retrofit kit is designed for locomotives that meet Tier 2^+ / Tier 3 U.S. EPA emission standards. (GE, 2014)

As of early 2016, there are two GE Evolution series locomotives that have been retrofitted with the NextFuel™ retrofit kit, BNSF 5815 and GECX 3000. (RR Picture Archives, 2005; Trainorders, 2014b; Locomotive Wiki, 2015)

Union Pacific Railroad (UP) and LNG

UP was planning to test and evaluate LNG as a fuel source for locomotives in early 2016. Through testing and analysis, UP will determine whether LNG is a reliable and economical locomotive fuel. (UP, 2016)

Brazil and LNG

An iron ore railroad in Brazil has been testing five 4,000 hp GE locomotives operating on LNG since 2008. The locomotives are supplied by three LNG fuel tenders. (Carvalhaes, 2013) In 2010-11, three GE Dash 9 locomotives with 7FDL16–EFI engines were converted with Energy Conversions, Inc. (ECI) dual-fuel kits to inject natural gas. (Ditmeyer, 2013)

6. Key Challenges and Next Steps

- Spark-ignition technologies have a lower compression ratio, resulting in lower performance in torque and thermal efficiency. Therefore, it is most likely that natural gas locomotives will be built using dual-fuel engines with compression ignition (Vantuono, 2013), especially for line haul locomotives.

- While line haul locomotives using natural gas as a fuel will likely use LNG, Class I railroads have also expressed some interest in the development and use of CNG in local rail operations and with switch locomotives.

- Compression ignition LNG/diesel dual-fuel locomotives also have the capability to operate on pure diesel fuel. The pathway to implement natural gas fuel locomotives can be either within North America (including Canada and Mexico) with a system wide fueling infrastructure, or California only with locomotive-exchange for LNG-to-diesel fuel at the State border.

- The railroad companies are focused on natural gas as a locomotive fuel because of its potentially favorable economics as compared with diesel fuel. However, no emission reductions are anticipated with natural gas beyond the locomotives' certified emission levels (Tier 0 to Tier 3) for existing line haul locomotives. HPDI is being developed to have LNG locomotives meet Tier 4 standards in the future.

- ARB will continue to monitor the railroads' interest in the applicability of natural gas to their locomotive fleets. In addition, ARB is undertaking a study with the University of Illinois, which will assess the potential economic and operational impacts and benefits of alternative locomotive technologies, including LNG locomotives.

This page left intentionally blank

V. BASIS FOR TIGHTER NATIONAL LOCOMOTIVE EMISSIONS STANDARDS

This chapter describes the emissions levels that ARB staff believes would be achievable with a new generation of national emissions standards for new locomotives, including both newly manufactured and remanufactured units. The discussion focuses on existing technology that could be employed to reach the lower emission levels to address local, regional, and global air pollution concerns in California, and in other states with high levels of railyard activity or rail traffic.

<u>Tier 4 Locomotive with Aftertreatment</u>

ARB staff believes the most technologically feasible advanced technology for near-term deployment is the installation of a compact aftertreatment system (e.g., combination of SCR and DOC) onto new and remanufactured diesel-electric freight interstate line haul locomotives. This advanced aftertreatment could reduce emissions by 75 percent or more below Tier 4 levels – from 1.3 g/bhp-hr to 0.3 g/bhp-hr NOx, and from 0.03 g/bhp-hr to <0.01 g/bhp-hr PM.

However, ARB staff believes the actual in-use NOx and PM emission levels could be much lower (i.e., 0.2 g/bhp-hr NOx and 0.005 g/bhp-hr PM), which would be consistent with the existing emission standards for new heavy duty truck engines (0.2 g/bhp-hr NOx and 0.01 g/bhp-hr PM).

<u>Tier 4 Locomotive with Aftertreatment and On-Board Batteries</u>

Staff also believes aftertreatment-equipped locomotives could be augmented with on-board batteries to provide an additional 10-25 percent reduction in diesel fuel consumption and GHG emissions. On-board batteries could also provide zero-emission track-mile capabilities in and around railyards to further reduce diesel PM and the associated health risks.

Table V-1 shows the potential emissions levels and capital costs for both of the aftertreatment technology combinations, compared to the Tier 4 baseline.

Table V-1:
Emission Levels Achievable with Next Generation of Locomotive Technologies

Emission Levels	**NOx** (g/bhp-hr)	**PM** (g/bhp-hr)	**GHG Reductions** (relative to Tier 4)	**Capital Cost per Locomotive** (Million $)	**Potential Control Technology**
a. Tier 4 Standard	**1.3**	**0.03**	0%	$3.0	EGR, turbos, cooling
– In-Use	1.0	0.015	N/A	N/A	
b. Tier 4 with Aftertreatment	**0.3**	**0.01**	0%	$3.25	Compact SCR and DOC
– In-Use	0.2	<0.0075	N/A	N/A	
c. Tier 4 with Aftertreatment and On-Board Batteries	**0.2**	**0.0075**	10-25%	$4.0	Compact SCR and DOC + On-Board Batteries
	With capability for zero-emission operation in designated areas.				
– In-Use	0.15	0.006	10-25%	N/A	

As shown in Table V-1 and discussed above, aftertreatment-equipped locomotives could be augmented with on-board batteries to provide an additional 10 to 25 percent reduction in diesel fuel use and GHG emissions. GE demonstrated the technical feasibility of on-board battery technology with its GECX 2010 battery hybrid prototype locomotive, introduced in 2007. (GE, 2005; Railway Gazette, 2007) GE estimated that fuel savings of 10 to 15 percent could be achievable as compared to conventional locomotives. (GE, 2016) With battery technology improvements since 2007, ARB staff believes a locomotive equipped with on-board batteries could realize fuel savings of about 15 percent by 2025. Staff further believes that, with continued battery technology advancements in the near future, locomotives equipped with on-board batteries could realize a reduction in diesel fuel consumption of about 25 percent by 2030. For the purposes of this document, ARB staff assumes a 15 percent reduction in fuel use for aftertreatment equipped locomotives augmented with on-board battery technology with commercial availability by 2025.

ARB staff also believes that further engineering advances and efficiency enhancements could result in lighter materials to build locomotives in the future, such that the battery system could be accommodated within the locomotive size, height, and weight limits.

Next Generation of National Locomotive Emissions Standards

To provide regulatory certainty, new national “Tier 5” emissions standards are needed, based on the emissions achievable either with aftertreatment and on-board batteries, or with future technologies that are as cost-effective and reliable. ARB staff supports a performance based approach that achieves significant further reductions in NOx, $PM_{2.5}$, and GHG beyond Tier 4 levels, equal to or lower than the levels shown in Row c of Table V-1 above.

Ideally, such a standard should apply to both newly manufactured locomotives and Tier 4 locomotives upon remanufacture. However, with the size of current battery technology, it may be most feasible to reflect the emissions benefits of aftertreatment and on-board battery technology just for newly manufactured locomotives, with a Tier 4 remanufacture standard based on just the aftertreatment.

A new federal standard could also facilitate development and deployment of zero-emission track-mile locomotives and zero-emission locomotives by building incentives for those technologies into the regulatory structure.

Table V-2:
Potential Emissions Levels for Remanufactured Line Haul Locomotives Utilizing Aftertreatment

Baseline Tier Level	**Existing U.S. EPA Emissions Standards** (g/bhp-hr)		**Aftertreatment Approach**	**Achievable Emissions Levels with Remanufacture** (g/bhp-hr)	
	NOx	**PM**		**NOx**	**PM**
Tier 2+ / Tier 3	5.5	0.1	Retrofit to Tier 4	1.3	0.03
Tier 4	1.3	0.03	Retrofit to Tier 4+ (with aftertreatment)	0.3	<0.01

A. Technology Options

ARB staff considers a traditional SCR, DOC, and diesel particulate filter (DPF) combination aftertreatment system as technically feasible on locomotives. This determination is based on the 2008 U.S. EPA locomotive regulations and supporting analyses (see Chapter 4 of the 2008 U.S. EPA Regulatory Support Document).

1. Limited Space Available for a Traditional SCR, DOC, and DPF Aftertreatment System on Locomotives

ARB staff believes, however, that the current generation of SCR, DOC, and DPF locomotive aftertreatment systems may be too large to fit within the existing locomotive carbody. These aftertreatment systems, on a freight interstate line haul locomotive, could possibly be 8 to 10 tons or more in weight and up to 900 cubic feet in size.

This estimate is based on the UP 9900 Tier 2 certified EMD locomotive prototype. UP 9900 has a new Tier 2 certified two-stroke medium speed engine rated at 3,150 hp. This MHP locomotive was retrofitted with EGR and a prototype combination

DOC and DPF aftertreatment system. The latter elements were about 4.5 tons and nearly 700 cubic feet. (SMAQMD et al., 2012)

See Figure V-1 for a picture of the UP 9900 DOC and DPF aftertreatment system. With aftertreatment, UP 9900 achieved Tier 4 PM emission levels (<0.03 g/bhp-hr), and about halfway between Tier 2 and Tier 4 NOx levels (about 3.5 g/bhp-hr). (ARB, 2015d)

Based on the above, the traditional SCR, DOC, and DPF combination aftertreatment system may be too large to fit within the current freight interstate line haul locomotive envelope, which is already encumbered with a larger 4,400 hp engine and other larger components to meet Tier 4 emission levels.

Figure V-1:
UP 9900: DOC/DPF Aftertreatment System (left picture)(About 4.5 tons)
(SMAQMD et al., 2012)

The other major constraint is the current locomotive carbody size limitations. The locomotive carbody is limited by national standards designed to ensure locomotive access across the country through bridges and tunnels while accounting for track curvature. Federal Railroad Administration (FRA) Plate L requirements limit the height (about 16') and width (about 10') of a locomotive, and track curvature and other operational considerations limit the length of a locomotive to about 75 feet. (AAR, 2008; Trainweb, 2002; Trainweb, 2003)

2. Alternative: Compact SCR and DOC Aftertreatment Systems

Due to the space needed for a traditional DOC and DPF aftertreatment system, ARB staff decided to focus on the next generation of locomotive technology, which is a Tier 4 locomotive retrofit with a "compact" SCR and DOC aftertreatment system complemented with a package of on-board batteries.

Compact SCR and DOC Aftertreatment System

The compact SCR and DOC aftertreatment system is much smaller in size, and may be able to fit within an existing line haul locomotive carbody. The compact SCR and DOC aftertreatment system may be able to provide a 75 percent or more reduction in NOx and PM emissions. Staff believes with future further advancements in SCR and DOC (and particle oxidation catalyst (POC)) technologies and supportive systems (e.g., onboard engine heating systems) and the use of renewable fuels, the actual in-use NOx reductions could be 90 percent or more and PM reductions 75 percent or more (see discussion below on potential emissions reductions).

<u>Compact SCR and DOC Aftertreatment and On-Board Batteries</u>

Staff also believes the compact SCR and DOC aftertreatment-equipped locomotives could be augmented with a separate package of on-board batteries (like GECX 2010 – located under the locomotive walkway, as shown below in Figure V-2).

Figure V-2:
GECX 2010 Battery Pack
(Trainorders, 2007)

Based on the GECX 2010 battery line haul locomotive prototype, diesel fuel consumption can be reduced by up to ten percent or more. With future advancements in battery technology (i.e., with increases in battery energy density), staff believes on-board batteries could provide up to a 25 percent reduction in freight interstate line haul locomotive diesel fuel consumption and GHG emissions.

Most importantly, when operating primarily in the lowest power settings of idle to Notches 1 and 2 in and around railyards, on-board batteries could potentially allow freight interstate line haul locomotives to achieve zero exhaust emission levels, at least for a significant portion of railyard operations. These potential zero exhaust emission levels could further reduce the primary contributor (i.e., freight interstate line haul locomotives) to diesel PM emissions and the associated health risks in and around railyards. Depending on the type of railyard, freight interstate line haul locomotives can contribute to 70 to 100 percent of remaining railyard diesel PM emissions.

Current Use of Compact SCR and DOC Aftertreatment Systems on Freight and Passenger Locomotives

The compact SCR and DOC aftertreatment system has been tested and demonstrated on a number of MHP locomotives in California. Below are three examples of MHP and line haul freight and passenger locomotives that have been retrofitted with compact SCR and DOC aftertreatment systems (see below). One of the locomotive manufacturers (Caterpillar/Progress Rail) has been ARB verified to be able to achieve Tier 4 emissions levels.

Caterpillar/Progress Rail (CAT/PR) Tier 4 MHP Locomotive with Compact SCR and DOC Aftertreatment System

In 2008, CAT/PR repowered five older pre-Tier 0 MHP locomotive medium speed engines with new Tier 2 compliant Caterpillar 3516 “high-speed” engines (3,005 hp, 1,800 rpm). The new Tier 2 engines were retrofitted with a compact SCR and DOC system to achieve Tier 4 levels. (LMOA, 2013) ARB verified the CAT/PR MHP locomotives to be able to meet Tier 4 emissions levels (i.e., 1.3 and 0.03 g/bhp-hr for NOx and PM, respectively). (ARB, 2011c)

Over the past few years, the CAT/PR Clean Emissions Module or CEM (see Figure V-3) has been retrofitted onto a total of nine (9) MHP locomotives (i.e., BNSF 1320-1323 and SJVR 3000-3004) that have been operating in California. (Progressive Railroading, 2012; Craig, 2012) CAT/PR refers to these locomotives as Progress Rail (PR) 30’s or PR30’s models.

The CAT/PR compact SCR and DOC aftertreatment system is about 3 tons and 170 cubic feet. (LMOA, 2013) In comparison, the UP 9900 locomotive with EGR and DOC and DPF aftertreatment system weighed nearly 8 to 10 tons and was up to 900 cubic feet in volume. (SMAQMD et al., 2012) The CEM is about 7 feet in length, 8 feet in width, and 3 feet in height for about a total of 170 cubic feet of volume. (LMOA, 2013)

The CEM aftertreatment system was built and designed for a retrofit onto a 3,005 hp high speed engine. This system might need to be scaled up in size for a 4,400 hp medium speed engine in a freight interstate line haul locomotive. Also, note that the PR30 locomotive and CEM does not include a DPF.

See Figure V-3 for the CAT/PR MHP locomotive with a Tier 2 engine repower and retrofit with a compact SCR and DOC aftertreatment system.

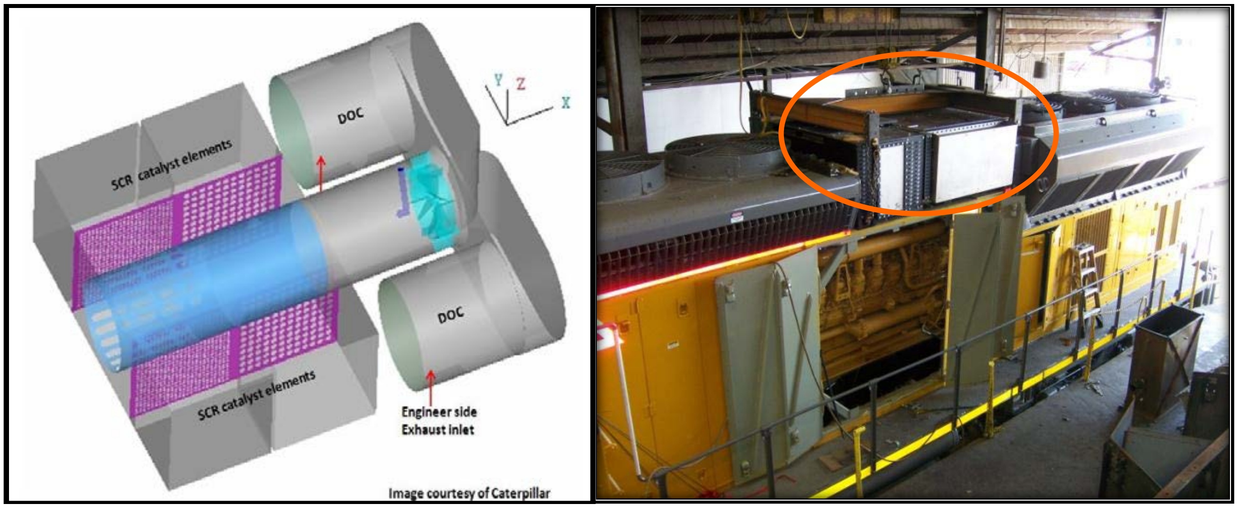


Figure V-3:
CAT/PR 30 – MHP Locomotive: Tier 2 Engine Repower with Retrofit of Compact SCR and DOC Aftertreatment System
(SwRI, 2007)

<u>Engine, Fuel and Emissions Engineering, Inc. (EF&EE) Compact SCR and DOC Locomotive Aftertreatment System</u>

EF&EE designed a compact SCR and DOC aftertreatment system, somewhat based on the Danish Haldor Topsoe aftertreatment system for heavy duty diesel trucks in Europe. (ARB, 2008) EF&EE worked with the Southern California Regional Rail Authority (SCRRA) and the South Coast Air Quality Management District (SCAQMD) from 2008 to 2010 to demonstrate this compact SCR and DOC system retrofitted onto an older uncontrolled Metrolink passenger locomotive. (EF&EE, 2010a)

The passenger locomotive demonstrated was identified as SCAX 865, a pre-Tier 0 (i.e., prior to U.S. EPA locomotive regulations) locomotive powered by an older medium speed EMD 710 engine, for passenger locomotive model F59PH. The F59PH EMD 710 is built with a medium-speed (904 rpm) engine, with 12 cylinders and rated at 3,000 hp. (EF&EE, 2010a)

Figure V-4 shows a compact SCR and DOC system (within the circle on top) by EF&EE installed on the SCAX 865 locomotive.

Figure V-4:
An EF&EE Compact SCR and DOC System Retrofitted Onto a Metrolink Passenger Locomotive
(EF&EE, 2010b)

The EF&EE compact SCR and DOC system, however, was able to reduce the older uncontrolled passenger locomotive NOx and PM emissions by 70 and 60 percent, respectively. The older passenger locomotive NOx and PM emissions were reduced from 9.0 to 2.64 and 0.29 to 0.115 g/bhp-hr, respectively. (EF&EE, 2010a) Typically, an SCR system is designed to reduce NOx emissions by up to 90 percent, but SCR systems do not typically operate at optimum levels until locomotive combustion temperatures are high enough, which is usually achieved at Notch 2 or higher power levels.

The EF&EE compact SCR and DOC system is estimated to be about the same size as the Caterpillar CEM system, about 3’ in height, 7’ in width and 8’ in length, for a total of about 170 cubic feet. ARB staff also estimates that the weight of the EF&EE compact SCR and DOC system is about 2,000 pounds, or one ton. (EF&EE, 2010a)

<u>GE Demonstration of SCR and DOC Retrofit onto Existing GE Tier 2 Interstate Line Haul Locomotives</u>

In November 2007, GE was beginning to participate in a Sustainable Development Technology Canada (SDTC) project to demonstrate the retrofit of a SCR and DOC aftertreatment system to fit within available space on a newer but existing Tier 2 interstate freight line haul locomotives. (SDTC, 2015; Businesswire, 2007) The objective of the SDTC clean diesel locomotive demonstration was to reduce Tier 2 locomotive NOx and PM emissions by up to 65 and 85 percent, respectively. (Businesswire, 2007)

GE began this effort with an SCR and DOC aftertreatment system design, with plans to add a DPF in later demonstration phases. (SDTC, 2015; Businesswire, 2007) ARB staff does not have the specific weight and size of the GE aftertreatment system (more information was not available to ARB staff), but it was designed to fit within the existing Tier 2 locomotive carbody. In late 2010, the SCR approach was placed into limbo when GE and EMD decided to turn to EGR and other technologies in order to achieve Tier 4 NOx levels.

<u>On-Board Batteries on a GE Prototype Freight Locomotive (GECX 2010)</u>

The GE Evolution battery-hybrid line haul locomotive (see Figure V-5), a working prototype built in 2007, was equipped with a small volume of on-board batteries. This technology has the capability to be able to capture and store energy when the locomotive is operating in the dynamic braking mode or while maintaining speed. (Railway Gazette, 2007)

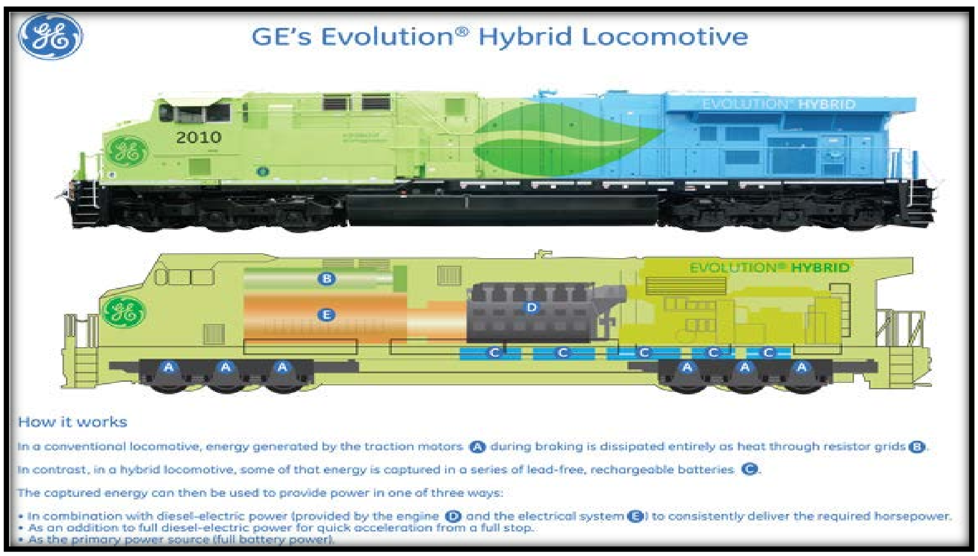


Figure V-5: Picture of GE Evolution Battery-Hybrid Line Haul Locomotive
(EV World, 2010)

B. Technology Performance: Potential for Emission Reductions and Fuel Efficiency

ARB staff believes that a compact SCR and DOC aftertreatment system of this size, or somewhat larger, could be built with or retrofit onto new and remanufactured Tier 4 freight interstate line haul locomotives. This system, built new or upon remanufacture of existing Tier 4 locomotives, could potentially achieve a 75 percent reduction in NOx and PM emission levels, beyond Tier 4. Based on current field experience, ARB staff believes that any fuel penalties are likely to be minimal.

Basis for Tier 4 with Compact SCR and DOC Aftertreatment (75-90 Percent Reduction in NOx and PM)

ARB staff has had conversations with the locomotive manufacturers, railroads, and researchers about the potential NOx and PM emission reduction levels beyond Tier 4. These conversations led to some of the following considerations:

Selective Catalytic Reduction (SCR) – a 75-90 Percent NOx Reduction

A compact SCR aftertreatment system has proven effective in reducing Tier 2 NOx emissions levels (5.5 g/bhp-hr) to Tier 4 NOx emission levels (<1.3 g/bhp-hr) by up to 75 percent or more. This is consistent with the assessment made by U.S. EPA for the 2008 national locomotive regulations. (U.S. EPA, 2008)

U.S. EPA estimated that SCR NOx reductions could be as high as up to 90 percent or more, but that locomotive engine temperatures in lower power settings (i.e., idle, Notches 1 and 2) would not achieve optimum emission control levels until the engine temperatures achieved at Notch 3. As a result, U.S. EPA estimated that the NOx reductions with SCR would be about 76 percent (i.e., 5.5 to 1.3 g/bhp-hr).

ARB staff believes a number of technology advancements will occur in the near future to ensure that SCR can provide up to 90 percent reductions of in-use NOx emissions. Those advancements include:

- Ongoing advancements in SCR washcoats which should result in more robust chemical reactions, and greater levels of NOx reductions;

- Small engine heating systems developed for light-duty vehicles could be developed for locomotives to ensure optimum engine temperatures are achieved in the lower power settings (i.e., idle, Notch 1 and 2) to provide greater levels of NOx reductions; and

- Historically, GE and EMD have continued to develop advancements in combustion cooling, and systems integration (e.g., Tier 2/3/4 locomotive technologies) that could result a cleaner and more fuel efficient locomotive by 2025.

Additionally, ARB is currently considering the development of a renewable diesel fuel standard, which would require up to 50 percent renewable diesel fuel, phased in from 2020 to 2030. This use of renewable diesel fuel could provide greater NOx and PM emissions reductions with SCR and DOC.

Diesel Oxidation Catalyst (DOC) and Particulate Oxidation Catalyst (POC) – Up to a 75 Percent PM Reduction by 2025

DOCs have historically provided about a 50 percent reduction in PM emissions. POCs have been found to provide up to a 60 to 70 percent PM reduction. ARB staff believes advancements in both DOC and POC aftertreatment will allow locomotive manufacturers to achieve up to a 75 percent reduction in in-use PM emissions by 2025.

ARB staff expects Tier 4 PM in-use emission levels to be about 0.02 g/bhp-hr, to comply with Tier 4 PM emission standard of 0.03 g/bhp-hr. A 75 percent reduction in in-use PM emissions could mean locomotives in-use PM emissions levels as low as 0.005 g/bhp-hr. This would allow locomotive manufacturers to achieve a $<$0.01 g/bhp-hr PM emissions standard.

On-Board Batteries – A 10 to 25 Percent Reduction in Diesel Fuel Consumption and GHG Emissions

GE estimates that the battery-hybrid freight interstate line haul locomotive demonstrator, as compared with existing Tier 2 line haul locomotives, could reduce diesel fuel consumption and associated NOx and PM emissions by up to an additional ten percent**.** (GE, 2005).

ARB staff believes with future advances in battery technology (i.e., increases in energy density) that the on-board batteries, even with the limited number available based on the space available on the locomotive, could provide up to a 25 percent reduction in a freight interstate line haul locomotive’s diesel fuel consumption and GHGs.

C. Operational and Infrastructure Considerations

Compact SCR and DOC Aftertreatment System

The compact SCR and DOC aftertreatment system, if used to meet future U.S. EPA locomotive emission standards, would be compatible with the national fleet. However, there will be a need for a urea supply, distribution, transportation, and depots. GE has estimated that the urea infrastructure costs could be as high as $1.5 billion. (GE Global Research, 2014)

On-Board Batteries

ARB staff does not have information regarding the type of infrastructure needed to support locomotive battery charging or any associated costs. Under this approach, regenerative braking is used to capture lost brake energy to recharge the batteries.

A key with this technology is having a region with significant and consistent downhill terrains (e.g., Cajon and Beaumont passes in southern California). In these settings, locomotive braking is deployed more of the total operational time. Regenerative braking can then capture more electrical energy during braking to recharge the batteries.

D. Capital Costs for Freight Interstate Line Haul Locomotives with Aftertreatment and On-Board Batteries

For more details on the capital costs for Tier 2, Tier 3, and Tier 4 freight interstate line haul locomotives see Chapter IV, Section D. Below is a summary of potential capital costs for freight interstate line haul locomotives equipped with both aftertreatment and on-board batteries.

Compact SCR and DOC Aftertreatment System

ARB staff estimates that building a new beyond Tier 4 freight interstate line locomotive with a compact SCR and DOC aftertreatment package would add $250,000 to Tier 4 capital costs of roughly $3 million. This would result in total capital costs of $3.25 million for each aftertreatment-equipped locomotive.

In addition, there might be an increase in associated maintenance and operational costs with aftertreatment. For example, the compact SCR and DOC would likely need to be serviced and maintained at the federally required 184-day maintenance intervals. Also, the compact SCR and DOC may need to be replaced upon each remanufacture (i.e., every seven to ten years), due to deterioration and wear and tear, and urea supply.

On-Board Batteries

ARB staff estimates that a Tier 4 freight interstate line haul locomotive, with compact SCR and DOC aftertreatment and on-board batteries, would have total capital costs of about $4 million. This cost estimate is based on conversations with locomotive manufacturers and researchers. This would represent an increase over the new Tier 4 freight interstate line haul locomotive capital costs of about $3 million, or about an additional $1 million beyond Tier 4.

Based on a ten percent reduction in diesel fuel consumption, there would be about $90,000 in annual fuel savings per locomotive. In this case, with an incremental cost about $1 million, the return on investment (ROI) could occur within about eleven years. For perspective, the average freight interstate line haul locomotive is in freight interstate service for about 15 years.

The estimated capital costs and ROI do not include battery replacement or maintenance costs. GE has not provided information on battery replacement intervals, or any potential additional maintenance costs, as this technology has not yet been commercialized.

ARB staff suggests that U.S. EPA consider requiring the retrofit of compact SCR and DOC systems on existing Tier 4 locomotives when those locomotives are scheduled for remanufacture. As the locomotive would already need to be out-of-service for the remanufacture, this timing would reduce the out-of-service cost for the retrofit of the locomotive with a compact SCR and DOC aftertreatment system.

E. Current Status

Current Status of Compact SCR and DOC Aftertreatment System on Locomotives

A compact SCR and DOC aftertreatment system built or retrofitted onto future new locomotives or remanufactured Tier 4 freight interstate line haul locomotives is still in the concept phase, and would require several years to design, test, validate, and demonstrate.

As discussed earlier, there are examples of existing older locomotives that have been repowered with newer cleaner engines (i.e., Tier 2 certified) and retrofitted with a compact SCR and DOC aftertreatment.

These applications may not have direct application to building or retrofitting a new locomotive or remanufactured Tier 4 freight interstate line haul locomotive with aftertreatment, but they do provide some insight on the potential size of aftertreatment that may be needed. These experiences provide significant information how to address some of the key challenges for future generations of freight interstate line haul locomotives.

Current Status of On-Board Batteries on Locomotives

In 2007, GECX 2010, the GE battery-hybrid freight interstate line haul locomotive working prototype and demonstrator, was a rebuild of one of GE's existing Tier 2 demonstrator fleet. This battery-hybrid locomotive was exhibited as a work-in-progress prototype, rather than a finished product.

This technology still needs both mid- and full-scale demonstrations in locomotive field service (i.e., at least up to two years) prior to being ready for full scale commercial production. GE does not currently have plans to put this technology into production.

F. Key Challenges and Next Steps

Challenges for Compact SCR and DOC Aftertreatment Systems on Locomotives

The two critical technical challenges with the traditional aftertreatment approach include limited locomotive space and the potential for aftertreatment to further restrict engine exhaust flow, which could potentially result in related fuel penalties. (SwRI, 2007) Furthermore, as with all the advanced technologies, significant funding will be needed for research, design, development, and demonstration work.

The critical issues with freight locomotives utilizing aftertreatment systems are:

- Space availability on an interstate line haul locomotive (AAR Plate "L" requirements about 16' height x 10' width, and track curvature constraints that limit length to about 75');

- Packaging and designing an aftertreatment system to fit within the limited space available within a locomotive to accommodate urea tankage (i.e., up to 500 gallons) and a dosing control cabinet;

- The complexity of integrating engine combustion, cooling systems, sensors, and aftertreatment system devices to operate effectively in unison; and

- Ensuring the aftertreatment systems do not constrain exhaust flows such that engine backpressure is created, or create significant fuel penalties.

<u>Challenges for Aftertreatment plus On-Board Batteries on Locomotives</u>

One of the challenges for an on-board battery package on freight interstate line haul locomotives is the lack of available on-board space to store more batteries. The lack of available space limits the volume of batteries available to store the energy needed for heavy-duty interstate rail operations. The battery-augmentation approach with GECX 2010, with a small volume of current technology batteries, reduces fuel consumption about ten percent. ARB staff believes that with future advances in battery technology (i.e., energy density), this approach could provide up to a 25 percent reduction in fuel consumption.

To achieve zero-emission levels with freight interstate line haul locomotives, on-board battery technologies will require additional research, development, and demonstration to significantly increase the energy density and to determine the reliability, durability, safety, and costs. Further study will also be needed to identify the criteria, optimal design, and associated challenges of the charging infrastructure needed to support on-board battery technology for locomotives.

Staff believes with the necessary research, development, and demonstration that on-board batteries, even with the limited space available on freight interstate line haul locomotives, could become a viable technology to augment the use of a compact SCR and DOC aftertreatment system.

Staff believes future advances in battery technologies could allow freight interstate line haul locomotives to achieve up to a 25 percent reduction in diesel fuel consumption and GHGs. Further, these batteries may ultimately allow interstate line haul locomotives to achieve zero exhaust emission levels for a significant portion of operations in and around railyards while in lower power settings (i.e., idle, Notches 1 and 2).

As freight interstate line haul locomotives are now the primary contributor of diesel PM emissions in and around railyards (depending on type of railyard, between 70 to

100 percent of railyard diesel PM emissions), this approach could provide significant health risk improvements in and around highly impacted communities.

This page left intentionally blank

VI. BATTERY TECHNOLOGIES TO POWER LOCOMOTIVES

This chapter will provide an assessment of advanced locomotive battery technologies that have the potential to provide partial to full power for freight and passenger locomotives. The objective(s) with locomotive battery technologies is to provide criteria and toxic pollutant reductions beyond the emissions levels discussed in Chapter V for locomotives with aftertreatment and on-board batteries, and to also provide further reductions in fuel consumption and GHG. The goal is to achieve zero locomotive exhaust emissions over a specified number of rail track-miles or hours of operation, which ARB staff refers to as "zero-emission track-miles".

There are three battery technology options assessed in this chapter:

1. All-battery, or near-*all battery, powered switch (yard) locomotives*;

2. *On-board battery-augmented freight interstate line haul locomotives*, with the capability to operate *across the North American freight rail system*; and

3. *Battery tenders (railcars)* to fully power freight interstate line haul locomotives over local to regional distances.

Staff has identified three key factors that may currently limit the potential applications of batteries to fully power diesel-electric freight locomotives. Those factors are:

- Current battery technologies lack the energy density needed to fully power freight interstate line haul locomotives over long distances and under extreme duty cycles (e.g., across the entire North American freight system, or up to 3,000 miles);

- Locomotives currently lack any significant level of on-board space to store more energy with a greater number of batteries (the federally-mandated locomotive carbody size limits the potential volume of batteries that can be placed on-board an existing freight locomotive); and

- Based on the lack of on-board space, freight interstate line haul locomotives will require large battery railcars (i.e., tenders) to provide the potential energy needed to fully power them. At this time, due to the extreme power demands of freight interstate line haul locomotives, battery tenders would be limited to full power operation over short local or regional distances (e.g., Ports of Los Angeles / Long Beach to Barstow, California).

Three applications were assessed for battery-powered locomotives: switch (yard) operations, line haul operations, and regional operations.

1. Switch (Yard) Operations: Locomotives, with an all-battery power system, may have the greatest potential to utilize on smaller switch (yard) locomotives (<2,000 hp). These small horsepower, typically light duty cycle, locomotives do not generate the sustained and peak-level electrical energy demands of a freight interstate line haul locomotive. However, the current battery technologies need to improve to be able to support more severe switch duty cycles, and to operate effectively in extreme climatic conditions (e.g., extreme cold and heat).

2. Line Haul Operations: A small volume of batteries could be placed on-board to augment power on freight interstate locomotives. On-board batteries can capture electrical energy currently lost in locomotive resistor grids, during braking operations, and use that energy through regenerative braking to recharge and store energy in the batteries. The advantage of this technology is the locomotive can still be operated over the entire North American freight rail system.

   The limited number of batteries that can be placed on-board an existing freight locomotive, due to the lack of any significant available space, will limit the potential fuel and emissions reductions to about ten percent or more. With future advancements in battery energy density, staff believes this approach could potentially provide up to a 25 percent reduction in diesel fuel consumption and emissions. This approach may also allow freight interstate line haul locomotives to operate in zero-emissions mode or zero-emission track-miles, in and around railyards, to reduce localized emissions and associated health effects.

3. Regional Operations: Another approach is a large volume of all-battery packages placed inside a railcar, referred to as a battery tender. The larger battery tender package could potentially power freight interstate line haul locomotives over short local or regional distances, or what staff refers to as zero-emission track-miles. Current concepts for battery tenders suggest the potential to store up to 5 MWh of available electrical energy. Staff estimates that three battery tenders would be needed to power a single freight interstate line haul locomotive about 180 miles, or from the Ports of Los Angeles / Long Beach to Barstow, California.

The average freight train has about four locomotives, at three battery tenders per locomotive, and would require 12 battery tenders per freight train to travel across the South Coast Air Basin. Under this scenario, staff believes the railroads would likely release the battery tenders from the freight train at a designated exchange point (i.e., railyard) just outside the South Coast Air Basin. This would occur due to the power limitations of battery tenders, their significant costs, and the lost revenues from 12 non-revenue railcars on an average 100 railcar train.

There could be potential time delays while the railroads transitioned from an all-battery tender powered freight train to a traditional diesel-electric freight train operation. Any significant delays could potentially cause a mode shift to trucks, and could also increase infrastructure and operational costs. The forthcoming study that ARB commissioned the University of Illinois to perform examines these potential impacts in detail.

A. All-Battery Powered Switch (Yard) Locomotives

Below is information on all-battery, or nearly all-battery, powered switch (yard) locomotives.

1. Technology Options

<u>Railpower (RP) Green Goat Battery-Hybrid Switch Locomotive</u>

The RP Green Goat incorporates a small diesel generator and a large bank of 330 truck sized lead-acid batteries into a battery-hybrid yard locomotive (see Figure VI-1 below). (ARB, 2008; ARB, 2009) The Green Goat has the equivalent of about 2,000 hp. In this configuration, the on-board diesel generator is rated between 130 and 290 hp. The diesel generator is used to recharge the batteries as they are depleted. (Progressive Railroading, 2005; EERE, 2005)

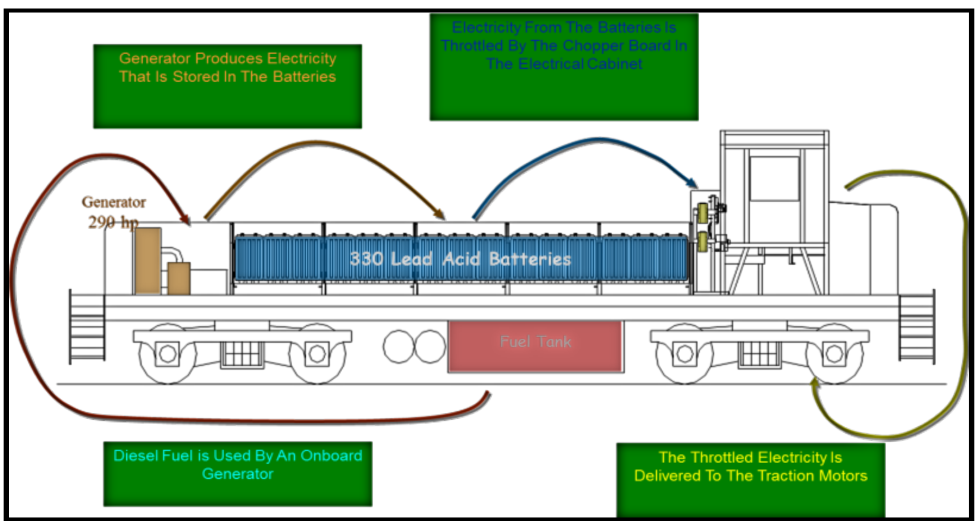


Figure VI-1:
Diagram of a Green Goat Switch Locomotive
(Railpower, unknown date)

The large bank of batteries replace the conventional large single diesel engine (about 2,000 hp), which is the typical power plant of a traditional switch locomotive. The batteries provide electrical energy directly to the locomotive traction motors and wheels

The entire battery-hybrid system is built on the recycled frame of an older locomotive. Regenerative braking could potentially be utilized to recharge the batteries, however, from the available information the Green Goats were not built with this technology.

Norfolk Southern (NS) All-Battery Powered Switch (Yard) Locomotive

In September 2009, NS introduced its first all battery-powered switch locomotive, the NS 999. The 1,500 hp prototype is powered by 1,080 rechargeable, 12 volt, lead-acid batteries (see Figure VI-2).

This technology does not rely on an on-board diesel generator to charge the batteries. Instead, the batteries on this locomotive are recharged using electric infrastructure installed in the railyard. Staff does not currently have information on the NS 999 battery recharging durations or intervals. The NS 999 locomotive also includes a regenerative braking technology, which partially recharges the battery while the locomotive operates. (Norfolk Southern, 2009)

Figure VI-2:
NS 999 Battery-Powered Switch Locomotive
(Norfolk Southern, 2009)

2. Potential for Emission Reductions and Fuel Efficiency

RP Green Goat Hybrid Switch (Yard) Locomotive

The nearly all battery-powered switch (yard) locomotive has the potential to significantly lower switch (yard) locomotive emissions. The ARB verified the Green Goat battery-hybrid locomotive at near Tier 4 NOx emission levels (i.e., about 1.3 g/bhp-hr). (ARB, 2006b) ARB staff believes the diesel PM would be near to or would achieve Tier 4 PM levels with a newer Tier 4 diesel-generator. The only emissions from a Green Goat battery-hybrid switch locomotive are produced by the small on-board diesel generator (i.e., <300 hp) that is used to recharge the 330 lead-acid batteries.

A typical switch locomotive in California can consume between 10,000 to 50,000 gallons of diesel fuel annually. This technology could reduce fuel consumption by up to 80 percent or more, saving up to $120,000 in fuel costs annually.

<u>NS All Battery-Powered Switch (Yard) Locomotive</u>

NS 999 would be considered a zero exhaust emissions locomotive, with only the indirect power plant emissions associated with stationary electric infrastructure used to provide the electrical energy needed to charge the batteries. In all-battery power mode, this technology could reduce a typical switch locomotive's diesel fuel consumption by 100 percent.

3. Operational and Infrastructure Considerations

ARB staff does not have information regarding the type of infrastructure needed to support locomotive battery charging or any associated costs. The infrastructure would need to be capable of charging multiple battery powered locomotives at once, similar to modern locomotive refueling infrastructure in place today.

4. Costs

<u>RP Green Goat Battery-Hybrid Switch Locomotive</u>

In 2006, Green Goat switch locomotives cost about $750,000 (Wong, 2009); at the time, they were comparable in price to new genset switch locomotives which cost about $1 million to $1.5 million per locomotive.

<u>NS All-Battery Powered Switch (Yard) Locomotive</u>

ARB staff does not have capital or operating costs for the newer NS on-board all battery-powered switch locomotive. However, ARB staff spoke with a number of experts in the field, and based on those conversations, has assumed that a new all battery-powered switch locomotive would cost about $3 million. ARB staff has estimated that the cost of a new Tier 4 genset switch locomotive could be about $2 million.

Assuming an all-battery powered switch locomotive could save up to 100 percent on annual diesel fuel consumption, at about 33,000 gallons annually at $3 per gallon, the annual diesel fuel cost savings could be up to $100,000.

For the $1 million incremental capital cost of an all-battery powered switcher, over the capital cost of a Tier 4 genset switcher at $2 million, the ROI would take about ten years. For perspective, the typical life of a current genset switch locomotive is about 15 years.

5. Current Status

The all-battery powered switch locomotive still needs both mid-and-full scale demonstrations in locomotive field service (i.e., at least up to two years) before the technology can be fully commercialized.

RP Green Goat Battery-Hybrid Switch (Yard) Locomotive

The Green Goats had been operating in different parts of the country, but primarily in California and Texas where they were supported by state incentive funding programs. Most of the Green Goats were limited to light-duty applications. These limitations were primarily due to batteries being depleted too quickly under heavier workloads, and the significant amount of time needed to recharge the batteries.

UP operated ten upgraded Green Goats[4] in Southern California (UPY 2310-2319), primarily at the UP Mira Loma auto railyard and smaller railyards in the South Coast Air Basin from 2008-2013. (Trainweb, 2015a; Moore, 2008) In 2013, UP transferred the ten Green Goats to Texas. UP recently informed ARB staff that the ten Green Goats were retired due to battery replacement costs and ongoing operational issues (e.g. vibrational impacts, battery leakage) with this type of technology.

In 2001, the first Green Goat underwent extensive testing and demonstration in both Canada and the United States for a year, in conjunction with a smaller, 1,000 hp unit, called the "Green Kid". Between 2001 and 2007, RP built 56 Green Goat and 10 Green Kid locomotives. (Trainweb, 2015b; Trainweb, 2015c)

NS All Battery-Powered Switch (Yard) Locomotive

While early demonstrations showed that the NS 999 could potentially do the required work, the batteries selected for the locomotive were not able to withstand the tremendous regenerative braking loads of a switch locomotive. As a result, NS began a search for a better energy storage alternative. (Petersen, 2012)

NS tested hydrogen fuel cells and nickel metal hydride, lithium iron phosphate, sodium beta, and a variety of lead-acid batteries. NS decided that Axion's lead-carbon (PbC) advanced lead-carbon battery was best suited for the particular needs of the NS 999. Axion’s PbC is similar to a lead-acid battery, but comprises a series of cells. Axion announced the initiation of a development relationship with NS in June 2010. (Petersen, 2012)

In July 2014, the NS 999 was rebuilt with PbC batteries, and this unit is currently undergoing field research and demonstration tests. (Myers, 2014b) Upon completion of

[4] As of early 2016, RP (now R.J. Corman) no longer manufactures the Green Goats. (R.J. Corman, 2016)

the NS 999 rebuild, NS plans to build a larger six-axle locomotive for testing in long haul hybrid train applications. (Petersen, 2012)

Figure VI-3: UPY 2315 – Green Goat Assigned to the UP Mira Loma Railyard
(RR Picture Archives, 2007)

6. Key Challenges and Next Steps

All battery-powered, and battery-hybrid, switch (yard) locomotives have been proven technically feasible, but with significant operational and cost challenges. On-board battery switch locomotives, especially the Green Goats, were limited to light-duty cycle work and short operational timeframes.

As battery technology improves, and costs begin to lower, there should be greater potential to expand the role of all battery-powered switch locomotives. With future advances in battery technologies, this technology may be able to scale up to medium-duty local and regional rail operations.

There may also be the potential to displace the on-board diesel engine used to recharge the batteries in the Green Goat, with hydrogen fuel cell or on-site electric recharging facilities, as demonstrated with NS 999.

Pursuing these on-board battery technologies will require additional research, development, and demonstration to determine the reliability, durability, safety, and costs. Further study will also be needed to identify the criteria, optimal design, and associated challenges of the charging infrastructure needed to support all battery-powered technology for switch (yard) locomotives.

Staff has provided suggested pathways to demonstrate zero-emission track-mile technology in Chapter X.

B. Battery-Augmented Freight Interstate Line Haul Locomotives

Figure VI-4 is an example of a diesel-electric freight interstate line haul locomotive that has been augmented with a small volume of batteries. This approach is estimated to reduce freight line haul locomotive diesel fuel consumption and emissions by up to ten percent or more. Battery augmentation of an existing diesel-electric freight locomotive would not be limited to use on local or regional operations, and could be capable of operation across the entire North American freight rail system

1. Technology Option

General Electric (GE) Evolution Battery-Hybrid Freight Interstate Line Haul Locomotive

The GE Evolution battery-hybrid line haul locomotive (see Figure V-5) is equipped with a small volume of on-board batteries. This technology has the capability to be able to capture and store energy when the locomotive is operating in the dynamic braking mode or while maintaining speed. (Railway Gazette, 2007)

The GE prototype (GECX 2010) is powered by GE's GEVO-12 engine, which produces 4,400 hp. The on-board batteries are capable of providing up to an additional 2,000 hp to the locomotive for short periods of time. (Railway Gazette, 2007) The batteries on the locomotive use GE’s Durathon technology which is based on the chemistry of sodium and nickel.

Durathon batteries are designed to have:

- Continued daily cycle performance over extended periods of time;
- Extended cycle life with a deep depth of discharge; and
- The capability to operate at temperatures between -40°F and 149°F. (GE, 2015)

2. Technology Performance: Potential for Emission Reductions and Fuel Efficiency

GE estimates that the battery-hybrid freight interstate line haul locomotive, as compared with Tier 2 line haul locomotives, could reduce diesel fuel consumption and associated NOx and PM emissions by up to an additional ten percent. (GE, 2005)

3. Operational and Infrastructure Considerations

ARB staff does not have information regarding the type of infrastructure needed to support locomotive battery charging or any associated costs. Under this approach, regenerative braking is used to capture lost brake energy to recharge the batteries.

A key with this technology is having a region with significant and consistent downhill terrains (e.g., Cajon and Beaumont passes in southern California). In these settings, locomotive braking is deployed more of the total operational time. Regenerative braking can then capture more electrical energy during braking to recharge the batteries.

4. Costs

ARB staff estimates that a new freight interstate line haul locomotive, with aftertreatment and on-board batteries, would have total capital costs of about $4 million. This cost estimate is based on conversations with locomotive manufacturers and researchers. This would represent an increase over the new Tier 4 freight interstate line haul locomotive capital costs of about $3 million, or about an additional $1 million beyond Tier 4.

Based on a ten percent reduction in diesel fuel consumption, there would be about $90,000 in annual fuel savings per locomotive. In this case, with an incremental cost about $1 million, the return on investment (ROI) could occur within about eleven years. For perspective, the average freight interstate line haul locomotive is in freight interstate service for about 15 years.

The estimated capital costs and ROI do not include battery replacement or maintenance costs. GE has not provided information on battery replacement intervals, or any potential additional maintenance costs, as this technology has not yet been commercialized.

5. Current Status

GECX 2010, the GE battery-hybrid freight interstate line haul locomotive demonstrator, is a rebuild of one of GE's existing Tier 2 demonstrator fleet. This demonstrator was exhibited as a work-in-progress prototype, rather than a finished product.

This technology still needs both mid and full scale demonstrations in locomotive field service (i.e., at least up to two years) prior to being ready for full scale commercial production. GE does not currently have plans to put this technology into production.

6. Key Challenges and Next Steps

One of the challenges for on-board battery locomotives for freight interstate line haul locomotives is the lack of available on-board space to store more energy. The lack of available space limits the volume of batteries available to store the energy needed for heavy-duty interstate rail operations. At this time, the battery-augmentation approach, with a small volume of batteries will limit fuel and emissions reductions benefits to about ten percent or more.

Pursuing on-board battery technologies will require additional research, development, and demonstration to determine the reliability, durability, safety, and costs. Further study will also be needed to identify the criteria, optimal design, and associated challenges of the charging infrastructure needed to support on-board battery technology for locomotives. Staff has provided suggested pathways to demonstrate zero-emission track-mile technology in Chapter X.

C. Battery Tenders to Fully Power Freight Interstate Line Haul Locomotives Over Local and Regional Distances

In addition to using battery technology to augment the diesel-electric engine for periodic zero-emission track-miles, ARB staff examined the potential for fully battery powered operation with the same diesel-electric engine.

1. Technology Options

<u>Transpower Concept for a Battery-Tender to Fully Power a Freight Interstate Line Haul Locomotive Over Local and Regional Distances</u>

Transpower has developed a concept for a fully integrated battery system that would be installed in a standard rail car or tender. The battery tender would transmit its stored electricity via a cable to the locomotive's central electrical bus, and then transmit the electricity to the locomotive traction motors to power and turn the locomotive wheels.

Transpower refers to this battery tender concept as the "Rail-Saver". Figure VI-4 shows a conceptual layout of the battery tender. The Rail-Saver allows for zero-emission operation because the diesel engine on the locomotive(s) pulling a train can be shut down while the battery tender is providing electrical power to the locomotive alternator and traction motors.

The Rail-Saver battery-tender consists of a large bank of lithium-ion batteries, bi-directional inverters to direct and recharge battery energy, and energy management controls. Transpower indicates Rail-Saver could potentially provide enough energy to pull a 100 car freight train at a speed of 30 miles per hour, in zero-emissions mode, for up to 50 miles. (Transpower, 2013)

Figure VI-4:
Transpower Concept for Battery Tender
(Transpower, 2012)

Rail-Saver would be capable of providing direct current (DC) or alternating current (AC) electricity to the electric motors on the locomotive. The lithium ion batteries in the tender(s) could be recharged with the locomotive diesel engine operating, or from a stationary railyard electric infrastructure providing electricity to the batteries from the electrical grid. Transpower estimates that the batteries could be re-charged in as little as two hours, when electrical power is provided directly from the electrical grid. (Transpower, 2013)

<u>Transpower Concept for the South Coast Air Basin</u>

The Transpower battery concept is designed to store up to 6.2 MWh of energy. The batteries would be capable of supplying up to 80 percent of available stored energy, or about 5 MWh. This design is matched to the power rating of the largest modern freight diesel-electric interstate line haul locomotives (i.e., 3.3 megawatts (MW), or 4,400 hp). (4rail, 2015a)

At about 30 miles per hour, Transpower estimates that a 100 car train would require about 0.1 MWh of energy per mile. At this rate, Transpower estimates that two to three battery tenders would be needed to power a 100 car freight train from the Ports of Los Angeles / Long Beach to Victorville, California, or about 150 miles. (Transpower, 2013) As part of this trip, the freight train would traverse the up to three percent grade over the summit of the Cajon Pass and on to Victorville located just outside the South Coast Air Basin boundaries. Figure VI-5 shows the major operating routes for UP and BNSF in the South Coast Air Basin.

Figure VI-5:
Map of UP and BNSF Major Rail Routes in the South Coast Air Basin

ARB staff compared Transpower's energy estimates with locomotive activity data[5], provided by UP and BNSF, for freight trains actually operating within and outside of the South Coast Air Basin. Specifically, this includes data for freight trains operating from the Ports of Los Angeles / Long Beach to destinations east of California. Based on this analysis, ARB staff estimates that a single locomotive would require about 7.5 MWh of energy to travel from the Ports of Los Angeles / Long Beach to Barstow, California (about 180 miles). See earlier discussion on why Barstow was identified as a likely exchange point.

ARB staff estimates a single freight interstate line haul locomotive would require three battery tenders to complete the 7.5 MWh trip from the Ports of Los Angeles / Long Beach to Barstow, California. This estimate is primarily based on the assumption that each battery tender would only be allowed a depth of discharge of 50 percent – this is to account for railroad industry operating and safety margins that would likely be necessary for battery tender operations. Specifically, of the 5 MWh available in the proposed battery tender, only 2.5 MWh on average could be used in actual railroad operations.

[5] These data are classified as company confidential information.

ARB staff estimates that, on any given day, about 455 UP and BNSF interstate line haul locomotives are operating in the South Coast Air Basin. If each locomotive requires three battery tenders to operate, a total of about 1,365 battery tenders would be needed. Moreover, ARB staff estimates that at least a one-third margin in additional battery tenders (i.e., about 455) would be needed in a battery tender pool to account for battery tenders that will be undergoing regular maintenance, or be unavailable due to damage, battery depletion, or any other miscellaneous operational needs. As a result, ARB staff estimates that, for full freight interstate rail operations in and around the South Coast Air Basin, UP and BNSF would need a total of up to 1,820 battery tenders.

2. Technology Performance: Potential for Emission Reductions and Fuel Efficiency

At this time, there is insufficient data to estimate potential emission reductions. However, should this technology be able to provide zero-emission track-miles, it could potentially provide significant levels of regional and local emissions and public health risk reductions.

Zero-emission track-miles are possible whenever the locomotive is powered only by the battery tender. At this time, staff does not have enough information to determine to what extent battery tenders could be partially or fully deployed within the South Coast Air Basin. For example, a freight train could run on the battery tenders for part of a trip within the South Coast Air Basin, and then switch back to the conventional diesel electric engine. Transpower suggests that the locomotive diesel engine could be used to charge the battery tender while the train is in operation. However, with the locomotive diesel engine in operation, zero-emission miles would not be achieved.

<u>Limitations of Locomotive Regenerative Braking</u>

GE uses regenerative braking to capture energy losses from locomotive braking to recharge on-board batteries. (GE, 2005) Regenerative braking is designed to capture energy that is typically dissipated as heat, via locomotive resistor grids, when the locomotive is in dynamic brake mode. Estimates on the amount of recoverable energy vary with locomotive duty cycle, route, and grade profile.

Regenerative braking could potentially extend the battery tender’s range. However, the amount of usable energy from regenerative braking will vary depending on the efficiency of the battery system, volume of batteries available to store the energy, the efficiency of the traction motors, and the amount of transmission losses.

GE estimated that battery-hybrid line haul locomotives (e.g., GECX 2010) with regenerative braking could reduce diesel fuel consumption by up to ten percent, as compared to a Tier 2 line haul locomotive. (GE, 2005)

3. Operational and Infrastructure Considerations

ARB staff does not have information regarding the type of infrastructure needed to support locomotive battery charging or any associated costs. Battery tenders are still in the conceptual stage; however, demonstration of this technology could provide information on locomotive battery charging infrastructure and cost. The infrastructure would need to be capable of charging multiple battery powered locomotives at once, similar to modern locomotive refueling infrastructure in place today. The Long Beach Container Terminal (LBCT) may provide some insights on the operational and infrastructure needs related to battery use for rail.

4. Costs

Transpower estimates the costs for battery tenders at $5 million per tender. Recurring battery replacement is estimated to occur every five years, at an estimated cost of $3 million per battery pack. (Transpower, 2013) Over a 15-year useful life, (i.e., the typical contract period for ARB incentive funded locomotive projects and the average period of interstate service for a line haul locomotive), the total cost of a battery tender is about $11 million.

<u>Forecast of Future Battery Costs</u>

A number of the studies (CALSTART, 2013; CE Delft, 2013) have forecasted that battery component costs could decrease by about two-thirds (Shulock and Pike, 2011) between 2012 and 2030 diminishing the cost differential between conventional diesel locomotives and near-zero or zero-emission technology alternatives.

Staff used the projected costs for batteries used in heavy-duty vehicle applications to estimate battery costs for a battery tender. ARB staff reviewed a variety of studies that suggest that battery costs should decrease. The majority of these studies estimated costs based on batteries used in light-duty vehicle applications. There is a concern on how easily near-zero and zero-emission technologies from the light-duty sector will transfer to the medium- and heavy- duty vehicle sectors.

Transferring near-zero and zero-emission technologies to locomotives will require additional research and development to satisfy the high power requirements of line haul locomotives (about 3.3 MW or 4,400 hp) as discussed in Chapter X of this report.

Table VI-1 shows the estimated costs by major component for the battery tender concept. Staff assumed that component costs for the rail car tenders and the components to connect battery tenders to diesel-electric locomotives (i.e. multiple unit cables, AC/DC inverters, etc.) would remain relatively constant between 2015 and 2030.

Table VI-1:
Current and Forecasted Battery Tender Costs

Components	2015 Cost	2030 Cost
Batteries	$3,000,000	$1,000,000
Battery Subsystem	$ 800,000	$ 800,000
Tender and Connections	$1,200,000	$1,200,000
Total Cost	$5,000,000	$3,000,000

Source: Transpower

When the projected decrease in battery costs, discussed previously, is applied to the battery components only, the estimated lifetime cost (15 years) of a single battery tender is expected to decrease from $11 million to about $5 million by 2030.

At this time, battery tender technology is in the conceptual stage; operating and maintenance costs are unknown. In addition, major infrastructure investments will be needed to ensure the success of near-zero and zero-emission technologies and will vary by application and operational needs.

5. Current Status

This concept is still in the research stage.

6. Key Challenges and Next Steps

One of the challenges for battery tenders to power freight interstate line haul locomotives is the lack of energy required for heavy-duty interstate rail operations (e.g., Chicago to Los Angeles). A significant breakthrough in battery energy density could increase the use of locomotive operations in the zero-emissions mode, over longer distances. At this time, the battery tenders are currently limited to being able to power freight interstate line haul locomotives over shorter local and regional distances.

Pursuing battery tender technologies will require additional research, development, and demonstration to determine the reliability, durability, safety, and costs. Further study will also be needed to identify the criteria, optimal design, and associated challenges of the charging infrastructure needed to support battery tender technology for freight interstate line haul locomotives.

This concept will have greater potential as there are future advances in battery technology to be able to meet the power demands of a freight diesel-electric interstate line haul locomotive. ARB staff recommends further research and development of battery technologies (i.e., battery switcher, on-board battery line haul, and battery tender).

ARB staff recommends that the battery tender concept could be assessed initially in a prototype demonstration with a switch (yard) locomotive, with much lower power demands. Based on the success of a switch locomotive demonstration program, the next step could be to transition the demonstration to a larger (e.g., MHP) locomotive. Ultimately, this technology could be demonstrated on a freight interstate line haul locomotive over local and regional distances.

Class III railroads could participate in a demonstration with switch (yard) and possibly MHP locomotives. Class I railroads could also demonstrate the technology with switch and MHP locomotives, but Class I railroads would be needed to demonstrate the technology with freight interstate line haul locomotives.

See Chapter X for more discussion on research, development, and demonstration of battery locomotive technologies.

VII. FUEL CELL TECHNOLOGIES TO POWER LOCOMOTIVES

This chapter will provide an assessment of fuel cell technologies that have the potential energy density to power freight and passenger locomotives. The benefits of locomotive fuel cell technologies are that they provide criteria and toxic pollutant reductions beyond Tier 4 with aftertreatment and on-board batteries, and also provide further reductions in fuel consumption and GHG emissions. The goal is to achieve zero locomotive exhaust emissions over a specified amount of rail track-miles or hours of operation, which ARB staff refers to as "zero-emission track-miles."

There are two fuel cell technology options assessed in this chapter. The first approach is proton exchange membrane fuel cells, also known as polymer electrolyte membrane (PEM) fuel cells (PEMFC), combined with a large bank of batteries or PEMFC/battery hybrid. The second approach is a concept developed by University of California, Irvine (UCI) for a solid oxide fuel cell-gas turbine (SOFC-GT) hybrid interstate line haul locomotive.

Staff has identified several factors that may limit the potential application of fuel cell technologies in the near term.

- Fuel cell technologies to power locomotives, in most cases, rely on battery packages to supplement the power generated by fuel cells. Battery technologies require further development to provide the necessary energy density or storage capacity needed to power locomotives under typical duty cycles.

- PEMFC technologies require further development to provide the necessary power density needed to power locomotives under typical switch (yard) locomotive duty cycles. One experimental prototype demonstrator switch locomotive (i.e., BNSF 1205) has been built.

- SOFC-GT technology, in theory, may have the necessary energy density needed to power a freight interstate line haul locomotives across the North American freight rail system. However, this technology is conceptual at this point. Aggressive research and development will be required to determine the viability of this technology

- Large capital expenditures will be required for a hydrogen fuel infrastructure.

A. PEMFC/Battery Hybrid Switch Locomotive Technology

Vehicle Projects LLC, the U.S. Department of Defense (DoD), BNSF, and a number of other key partners, worked together to design and build a prototype of a PEMFC low horsepower switch (yard) locomotive by 2009. Below is information on this prototype locomotive.

1. BNSF 1205: PEMFC/Battery Hybrid Switch Locomotive

The BNSF 1205 locomotive is powered by a PEMFC that uses hydrogen as a fuel and is coupled to a large battery system. The BNSF fuel cell locomotive is the first of its kind under development for freight applications. (Miller et al., 2007)

The BNSF locomotive utilizes hydrogen to fuel its PEM fuel cell and a large battery system to power the locomotive. BNSF 1205 was publicly demonstrated as a first of its kind fuel cell switch locomotive for freight applications in July 2009 at BNSF Topeka, Kansas. (Trainweb, 2015d) See Figure VII-1 (below).

Figure VII-1:
BNSF 1205 PEMFC/Battery Hybrid Switch Locomotive
(RR Picture Archives, 2010b)

Figure VII-2 shows the three major components of the BNSF 1205 PEMFC switch locomotive. Those major components are:

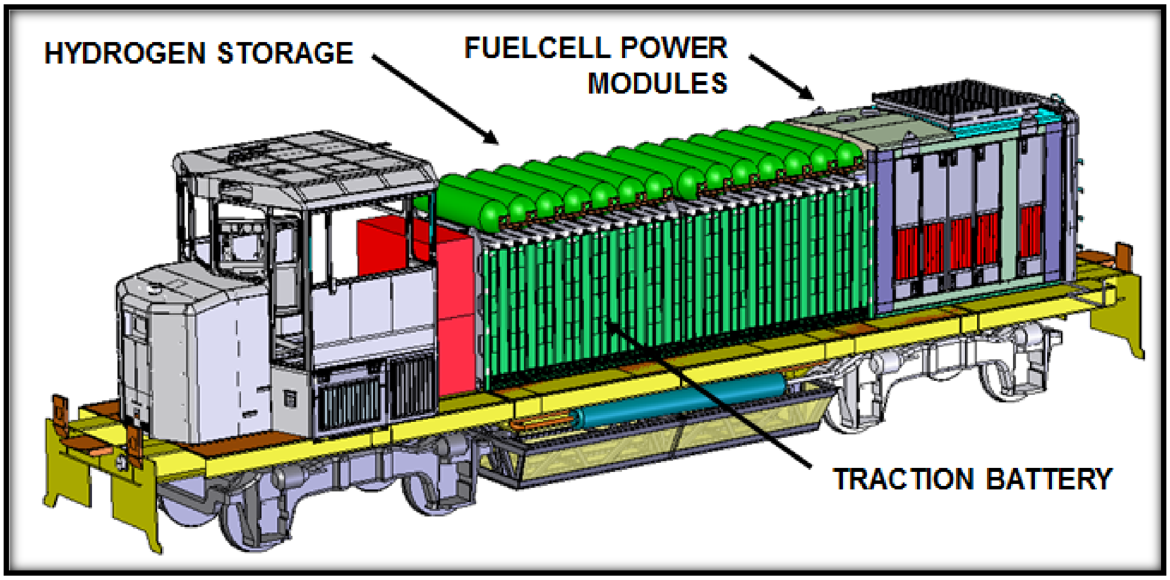


Figure VII-2:
Three Major Components of BNSF 1205
(Miller, 2006)

- Hydrogen storage tanks, battery ventilation module (under the tanks), the traction battery (below the ventilation module), and the ballast (under the traction batteries) housed in the central portion of the locomotive;
- The fuel cell power plant, power converter (DC to DC converter), and cooling module, which are all housed in the rear of the locomotive;
- Other locomotive related components, such as the air compressor and blower motor that provide cooling for the traction motors, are located below the power converter; and
- The locomotive operator’s cab is on the front (Hess, 2010; Miller et al., 2007).

Figure VII-3 shows an expanded view of the BNSF 1205 major locomotive components.

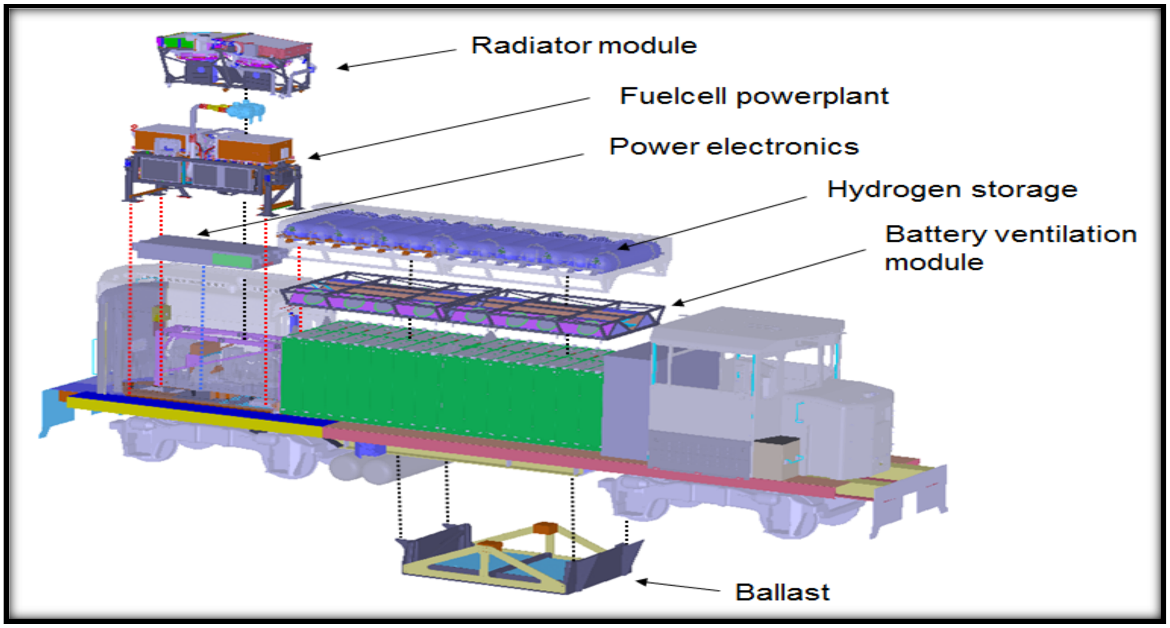


Figure VII-3:
Expanded View – Major Components of BNSF 1205
(Hess, 2010)

<u>How Does BNSF 1205 Work?</u>

Both the fuel cell power converter and the traction battery supply power to a single high voltage bus that then distributes power to the existing locomotive systems as well as the 600 volt DC traction motors. Continuous power is provided by the fuel cell and peak power requirements are provided by the on-board traction battery. (Miller et al., 2007).

The auxiliary power storage device or battery must supply sufficient energy to provide power in excess of the fuel cell's continuous power rating (250 kilowatts (kW)) up to the peak power requirement of the locomotive (1,100 – 1,500 kW). (Miller et al., 2007) For perspective, a typical switcher locomotive (EMD GP38-2) generates about 1,500 kW. See Figure VII-4 for an illustration of the BNSF 1205 system layout.

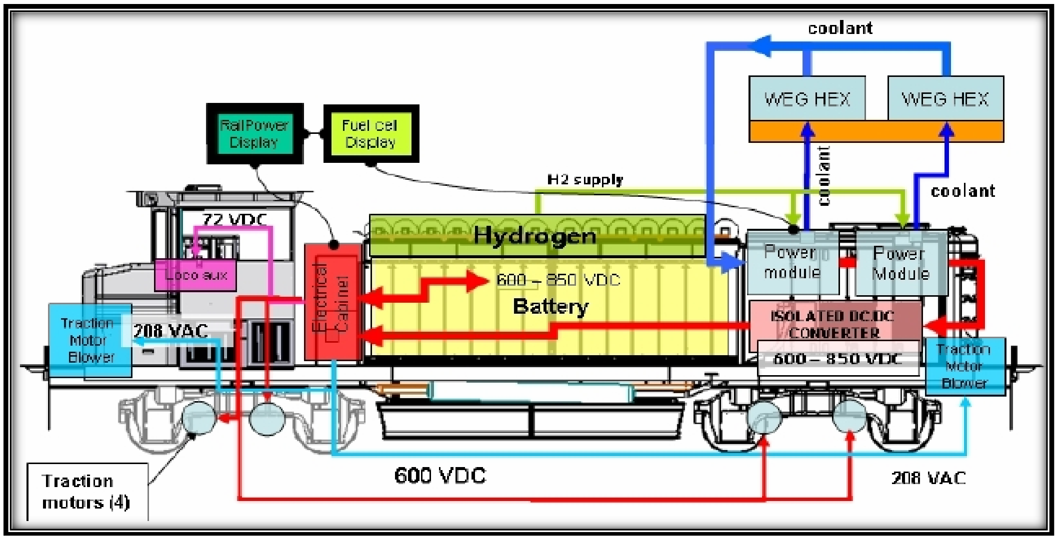


Figure VII-4:
BNSF 1205 System Layout
(Miller et al., 2007)

<u>Fuel Cell and Battery Power Plant Size for BNSF 1205</u>

The fuel cell power requirements were designed using a typical locomotive switch duty cycle as a starting point. This represents a typical or average in-use duty cycle for a switch (yard) locomotive. Under the U.S.EPA switch locomotive duty cycle (see Table III-5), a switch locomotive spends over 80 percent of the time in idle and Notch 1 through 2. The remaining percent of time is spent between Notch 3 through 5, with brief periods of time in the highest power settings for peak power (Notches 6 to 8).

For BNSF 1205, Vehicle Projects, LLC analyzed multiple in-use duty cycle sets from various railroads and found that the power requirements were similar to the U.S. EPA switch locomotive duty cycle. Using the U.S.EPA switch locomotive duty cycle, and in-use duty cycle set from various railroads, resulted in a mean power level range of 20 to 100 kW and energy consumption range of 0.75 to 1.4 MWh.

The auxiliary power storage device or battery package must supply sufficient energy to provide power in excess of the continuous power rating (250 kW) of the fuel cell and up to the peak power requirement of the locomotive (1,100 to 1,500 kW). This power and energy must be available while not exceeding allowable depth of discharge of the battery, which significantly increases the size of the battery. Balancing the size of the fuel cell, and battery is not only duty cycle dependent, but also dependent on the operators in-service needs. (Miller et al., 2007)

In 2010, BNSF 1205’s fuel cell power plant was upgraded from 250 kW net power to 500 kW net. The resulting 500 kW standard power module or power building block will be the basis of future multi-megawatt railway locomotives. (Vehicle Projects, 2016)

2. Potential for Emission Reductions and Fuel Efficiency

A fuel cell operating on pure hydrogen has no tailpipe emissions. There will be emissions associated with the production of hydrogen fuel. PEMFC's have greater energy efficiency than internal combustion engines, up to 60 percent.

3. Operational and Infrastructure Considerations

This system will require a hydrogen fuel infrastructure. Performance standards will have to be developed that will support the safety, interoperability, interchangeability, regulatory, and maintainability needs of a railroad operator.

4. Costs

The BNSF 1205 demonstrator fuel cell locomotive retrofit of an existing older locomotive (e.g., use existing body frame, cab, traction motors) capital cost is estimated to be about $3.5 million. Hydrogen fueling infrastructure cost data for this application are not available. In addition, maintenance and operational costs are needed.

See Chapter X for further discussion of costs and pathways for research and development of fuel cell locomotive technologies.

5. Current Status

BNSF 1205 is a prototype hydrogen fueled fuel cell-battery (power modules) hybrid switch (yard) locomotive that has primarily been tested in urban and military base rail applications. It was originally built as an EMD GP9 switch locomotive (CP 1544) in 1957. Canadian Pacific (CP) ordered the older switcher to be rebuilt as a Railpower Green Goat battery-hybrid switch locomotive (CP 1704) in early 2007[6].

CP chose to cancel the order for CP 1704, and the Railpower Green Goat switch locomotive was sold to BNSF in 2008. BNSF 1205, as a fuel cell battery hybrid locomotive, was presented for the first time to the public in July, 2009.

Table VII-1 summarizes the key specifications for BNSF 1205 PEMFC/battery hybrid switch locomotive.

[6] See Chapter VI for a detailed description of the Railpower Green Goat battery-hybrid switch locomotive.

Table VII-1:
Key Specifications for BNSF 1205 – PEMFC/Battery Hybrid Switch Locomotive
(Miller et al., 2007; Vehicle Projects, 2016)

Key Specification	Actual Specification
Continuous power (PEMFC)	500 kW or 670 hp
Transient power (Battery)	1 MW or about 1,340 hp
14 Hydrogen Tanks	154 pounds at about 5,070 psi
Locomotive Weight	280,000 pounds

In 2010, the fuel cell power plant in BNSF 1205 was upgraded, increasing the net power output from 250 kW to 500 kW of continuous power. (Vehicle Projects, 2016) The auxiliary battery provides transient power demands between 500 kW and 1 MW.

The BNSF 1205 PEMFC is considered a prime candidate for vehicle and other mobile applications of all sizes. Fabrication, assembly, and testing of the BNSF 1205 fuel cell powered switch locomotive were completed at BNSF Railway's Topeka, Kansas, rail shop.

In-service field demonstrations have been conducted (e.g., Los Angeles, CA; Hill AFB, UT; and Topeka, KS). BNSF 1205 is currently assigned to the BNSF maintenance and locomotive repair facility in Topeka.

6. Key Challenges and Next Steps

The PEMFC/battery hybrid switch locomotive technology is at the experimental prototype stage. Vehicle Projects, LLC has built a working prototype that has allowed it to test this research concept for switch locomotives. Please see Chapter X for potential pathways, costs, and timelines for research and development of fuel cell locomotive switch (yard) technologies.

B. SOFC-GT Hybrid Locomotive Technology

The SOFC-GT concept is designed to provide the potential energy needed to power a freight interstate line haul locomotive across the entire North American freight rail system. In addition, this technology has the potential to increase fuel efficiency by up to 20 percent or more, as compared to current freight diesel-electric line haul locomotives.

1. SOFC-GT Hybrid Locomotive Design Concept

Recently, researchers at UCI prepared a paper on the concept of the potential application of an SOFC-GT hybrid system. This study was funded jointly by ARB and the SCAQMD.

Solid oxide fuel cells (SOFCs) are used as auxiliary power units in vehicles to stationary power generation with outputs from 100 W to 2 MW. An SOFC has the potential to provide even greater efficiency, space, and weight benefits when compared to PEMFC. In addition, a typical locomotive's power requirement is similar to the theoretical target power range of SOFCs. Whereas the PEMFC/battery hybrid targets a power range applicable to a switch locomotive operating over the U.S. EPA switch duty cycle, the SOFC-GT was designed to target a higher power range more applicable to a freight interstate line haul locomotive operating over the line haul duty cycle, and potentially across the entire North American freight rail system. (Samuelsen and Brouwer, 2008)

How Does an SOFC Work?

SOFCs differ in many respects from other fuel cell technologies. First, SOFCs are composed of solid state materials. The anode, cathode, and electrolyte are all made of ceramic substances. Second, because of the all ceramic make-up, the cells can operate at high temperatures – 1,300 to 1,800°F with zirconia-based electrolytes, and as low as 930°F with ceria-based electrolytes. The high-temperature operation makes it an attractive candidate for linking with a gas turbine in a hybrid configuration. (Samuelsen and Brouwer, 2008; EERE, 2010; Smithsonian Institute, 2015; Fuel Cells 2000, 2015; FuelCellToday, 2012)

Figure VII-5 shows an illustration of how an SOFC works:

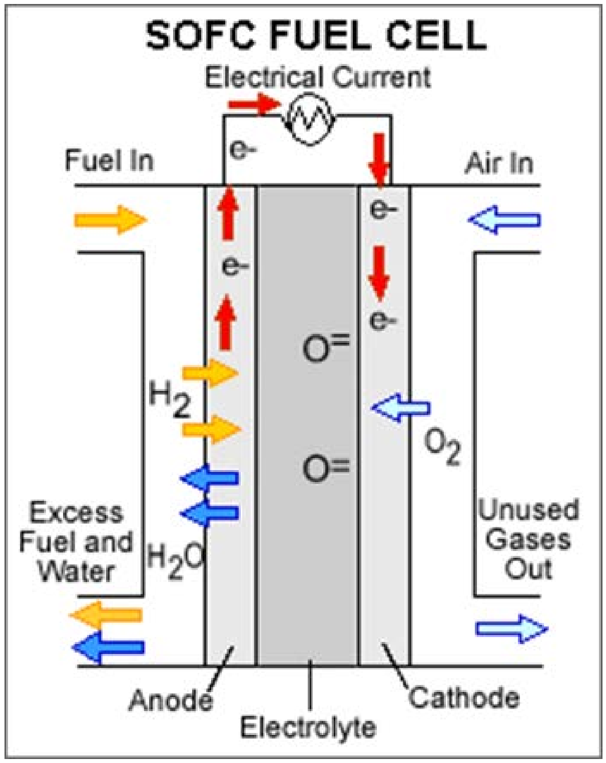


Figure VII-5:
Schematic Mechanism of Solid Oxide Fuel Cell
(Department of Energy, 2016)

Some SOFC specifications (Samuelsen and Brouwer, 2008; Fuel Cells 2000, 2015):

- Electrolyte: A solid ceramic, typically yttria-stabilized zirconia (YSZ).
- Catalyst: High operating temperature permits the use of lower-cost, non-platinum group catalysts.
- Operating Temperature: About 1,200 - 1,800°F
- Fuel: Hydrogen, light hydrocarbon fuels (e.g., methane, propane, butane, natural gas, fermentation gas, gasified biomass) and diesel (reformer needed).
- Electrical Efficiency: 50-60 percent for an SOFC, and 60-70 percent when combined with a gas turbine

How Does the SOFC-GT Hybrid Configuration Work?

An SOFC-GT hybrid system is an advanced power system that combines the electrochemical energy conversion of fuel cell with the traditional, combustion-driven energy conversion of a gas turbine into a single, cooperatively-acting power unit. The SOFC-GT hybrid system receives air from the gas turbine compressor outlet, which results in a pressurized SOFC. The hot, high pressure exhaust of the SOFC and combustor can be used to spin a gas turbine, which can then be used to generate an additional source of electricity when coupled to a generator (see Figure VII-6). The combustor in the SOFC-GT is significantly downsized from a stand-alone GT, operates at a lower temperature, and performs combustion on a proportionally smaller amount of fuel because the SOFC handles most of the oxidation.

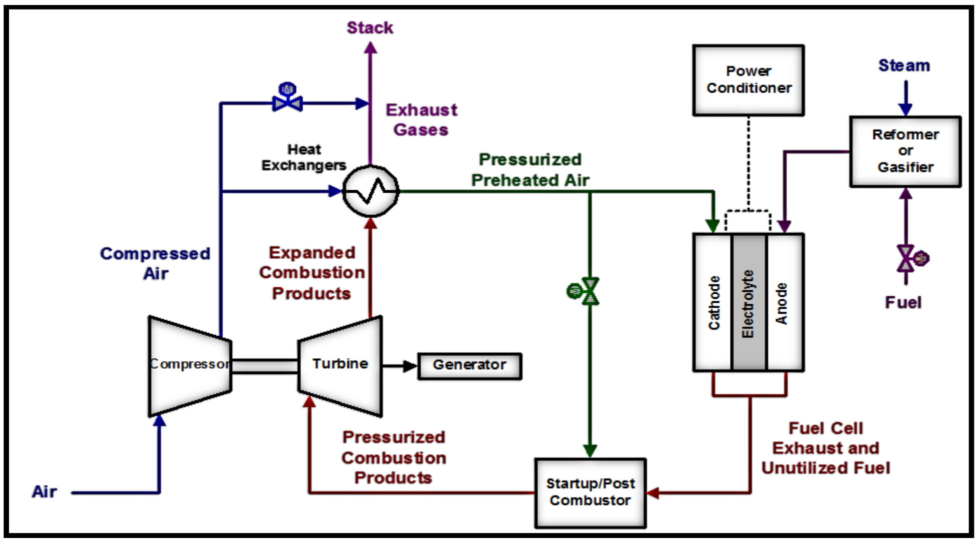
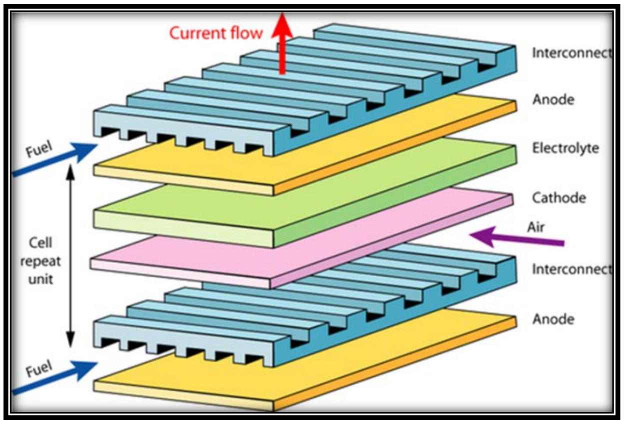


Figure VII-6:
SOFC-GT Hybrid System
(Samuelsen and Brouwer, 2008)

The SOFC operates at very high temperatures, typically between 900 and 1,800°F. At these temperatures, SOFCs do not require expensive platinum catalyst material, as is currently necessary for lower-temperature fuel cells such as PEMFCs, and are not vulnerable to carbon monoxide catalyst poisoning.

Unlike most other types of fuel cells, SOFCs can have multiple geometries. The planar design geometry is the typical sandwich type geometry employed by most types of fuels cells, where the electrolyte is sandwiched between the electrodes. SOFCs can also be made in tubular geometries where either air or fuel is passed through the inside of the tube and the other gas is passed along the outside of the tube. The tubular design is advantageous because it is much easier to seal air from the fuel. The performance of the planar design is better than the tubular design because the planar has a lower resistance comparatively. Figure VII-7 shows the differences in the geometries of a planar and tubular SOFC.



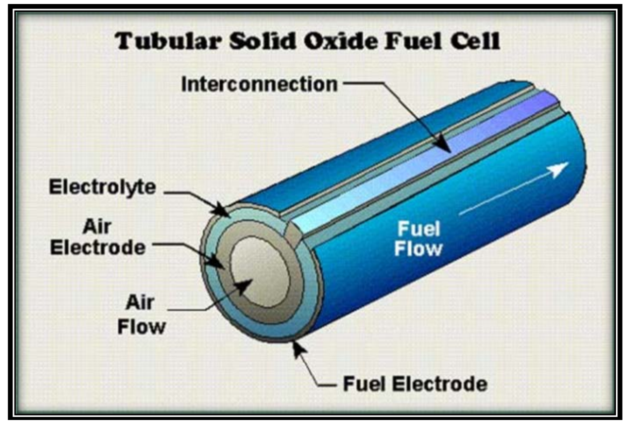


Figure VII-7:
Planar Versus Tubular SOFC
(University of Cambridge, 2015; Smithsonian Institute, 2015)

2. Potential for Emission Reductions and Fuel Efficiency

An SOFC-GT could potentially be designed with a reformer on-board the locomotive to process any hydrocarbon-based fuel to provide energy for the fuel cell. The fuel cell could also be operated with hydrogen as the primary fuel. Depending on the type of fuel source for the fuel cell, an SOFC-GT freight interstate line haul locomotive could be potentially built with near-zero to zero stack emissions.

The fuel-to-electricity efficiencies of SOFCs are around 50 percent. If the hot exhaust of the cells is used in a hybrid combination with gas turbines, the electrical generating efficiency may exceed 70 percent. In applications designed to capture and utilize the systems waste heat, overall fuel use efficiencies could top 80 to 85 percent. (Martinez et al., 2012a)

Although SOFC power systems have not yet been seriously considered as a viable technology for mobile applications, recent investigations indicate the feasibility of such a system is high. Recent developments suggest SOFC technology can achieve very high power density and when combined with a gas turbine, a hybrid SOFC-GT system could provide even higher power density and efficiency. This hybrid SOFC-GT system is roughly equivalent to the diesel standard, requiring a slightly larger footprint, but occupying less overall volume. (Martinez et al., 2012b)

The major advantage of the SOFC-GT hybrid system is that combination of these two technologies allows for a synergistic advantage in overall system efficiency, allowing the system to achieve a higher theoretical efficiency than either of the two devices alone. Synergy occurs because the exhaust from the SOFC is used to drive the gas turbine. The gas turbine (exhaust driven) drives a generator to produce electricity and pressurizes the incoming air for the SOFC. By doing so, waste heat and un-oxidized fuel are utilized to further increase overall system efficiency.

As shown in Figure VII-8, efficiencies of over 70 percent are possible, which are much higher than the theoretical maximum efficiencies of current internal combustion technologies. (Samuelsen and Brouwer, 2008; Fuel Cells 2000, 2015; FuelCellToday, 2012; EERE, 2010)

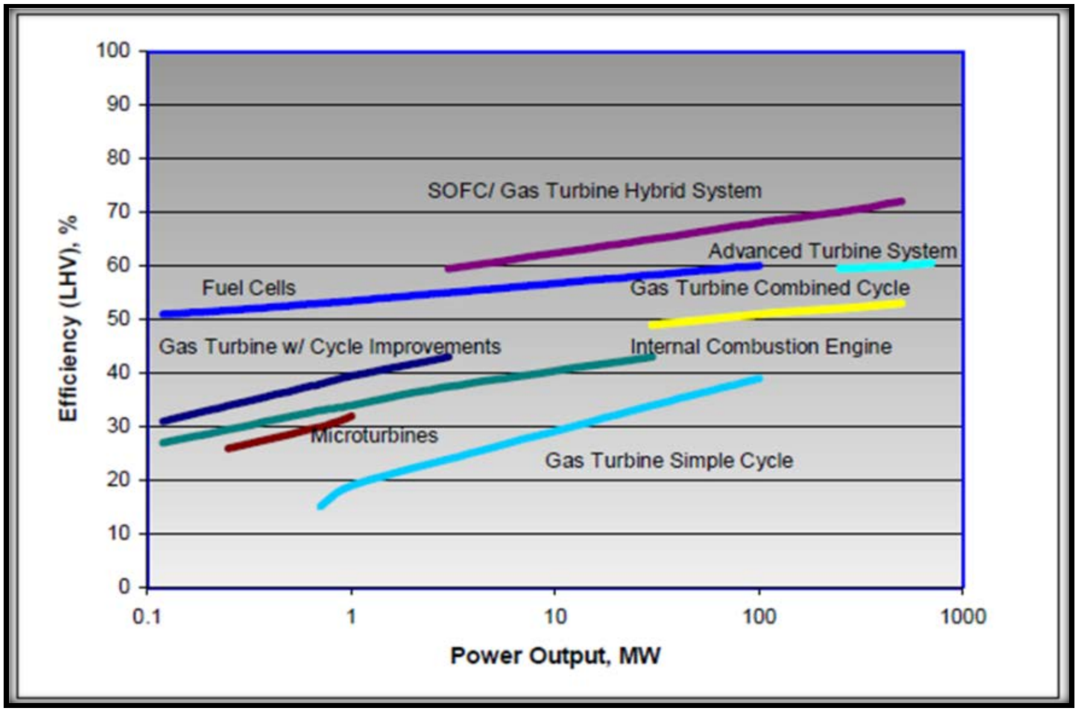


Figure VII-8:
Percent Efficiency and Power Outputs of Various Power Systems
(Samuelsen and Brouwer, 2008)

3. Operational and Infrastructure Considerations

As the SOFC-GT is a concept, ARB staff does not have information regarding the type of infrastructure needed to support this technology approach. Further research is needed to finalize the conceptual design to better understand operational and infrastructure needs.

4. Costs

Cost estimates for the SOFC-GT Hybrid system only (i.e., power plant) are approximately $6.5 million dollars. Adding the remaining hardware which would include the locomotive platform, mechanical and traction components, electrical and auxiliary systems is estimated to cost an additional $1.5 million dollars. ARB staff estimates that an experimental prototype SOFC-GT Hybrid locomotive would cost more than $8 million dollars.

5. Current Status

ARB staff believes the SOFC-GT concept is at the early research phase. The next step is to finalize a conceptual design and then move forward with the building a laboratory scale SOFC-GT for test and demonstration purposes.

6. Key Challenges and Next Steps

The SOFC-GT is a strong candidate system for the freight interstate line haul locomotive application. Further development of the system in terms of optimizing system theoretical design and moving toward demonstration of physical test systems (including SOFC materials that will better able to withstand thermal recycling stresses) will provide further insights into the benefits of the system. Also, there are challenges that may need to be overcome for its eventual physical integration into a current freight interstate line haul locomotive to be able to operate in the North American freight rail system. (Samuelsen and Brouwer, 2008; Martinez et al., 2012a; Martinez et al., 2012b)

The full system integration of SOFC-GT with fuel processor (i.e., reformer) in theory is roughly equivalent to the diesel standard, requiring a slightly larger footprint, but occupying less overall volume, the footprint constraint should be achievable as well.

This page left intentionally blank

VIII. FREIGHT RAILROAD ELECTRIFICATION IN CALIFORNIA

As a historical note, a significant portion of California had both freight and passenger rail electrification for the first half of the twentieth century, especially interurban passenger electrified rail operations. The early use of rail electrification in California was spurred by the availability of excess electricity energy, due primarily to the large number of dams built in the State in early part of the century.

Electrified rail operations and infrastructure were replaced with the increased use of automobiles and trucks in the late 1920's to 1930's, and nearly all of the electric systems were replaced after World War II. After World War II, there was a gradual transition where diesel-electric freight and passenger locomotives replaced all-electrified and steam locomotive rail operations by the 1970's.

ARB staff's interest in freight rail electrification is the potential to eliminate locomotive exhaust emissions at railyards and in line-haul operation. This would address the primary source of the highest exposures to toxic diesel PM and the associated health risks in California. If locomotives operated with zero emissions, California could support mode shift from truck to rail (with its inherently greater efficiencies per ton of cargo moved), without the current concern about worsening localized health risks in railyard communities.

However, there are several significant challenges with freight railroad electrification, which include the following.

- Significant capital costs. Depending on the specific system design, staff estimates that freight railroad electrification in the South Coast Air Basin could cost about $50 million or more per route-mile. With up to 500 miles of major rail routes in and around the South Coast Air Basin, the total capital costs could be up to $25 billion or more.

- A basin-specific rail electrification system has the potential to create delays in rail operations. For example, this could occur with an all-electric operation in the South Coast Air Basin that would need to change locomotives at an exchange point (e.g., BNSF Barstow Railyard) to connect to the North American diesel-electric freight rail system for the rest of the trip (e.g., Barstow to Chicago).

- There will be a need to build a significant electricity-generating system. UP and BNSF currently generate up to 400,000 locomotive MWh or more of electricity in the South Coast Air Basin. By 2050, UP and BNSF rail operations could need up to one million MWh in the South Coast Air Basin. A significant level of electric power infrastructure would be needed to meet the electricity demands of heavy hauling freight rail operations in the South Coast Air Basin, and the rest of the State.

A. Technology Options

Staff assessed two approaches for freight railroad electrification – locomotives that are dual mode (i.e., diesel-electric and all-electric power plants) and all-electric. Dual mode provides the flexibility to operate in both in diesel-electric and all-electric operations. All-electric is limited to only all-electric operation.

1. Dual Mode Freight Interstate Line Haul Locomotives

In this technology approach, a freight interstate line haul locomotive would have two separate power plants, diesel-electric and all-electric, which is referred to as a "dual mode" freight locomotive. In this approach, the locomotive would have the flexibility to operate in diesel-electric operation, without having to be connected to electrified rail lines or catenary, which the traditional diesel-electric freight locomotive operation. The dual mode locomotive would also have a separate all-electric plant, with a pantograph, to be able to connect to electrified rail catenary or lines to be powered only by electricity. See Figure VIII-1 for an example of the New Jersey Transit (NJT) dual mode passenger locomotive, built by Bombardier.

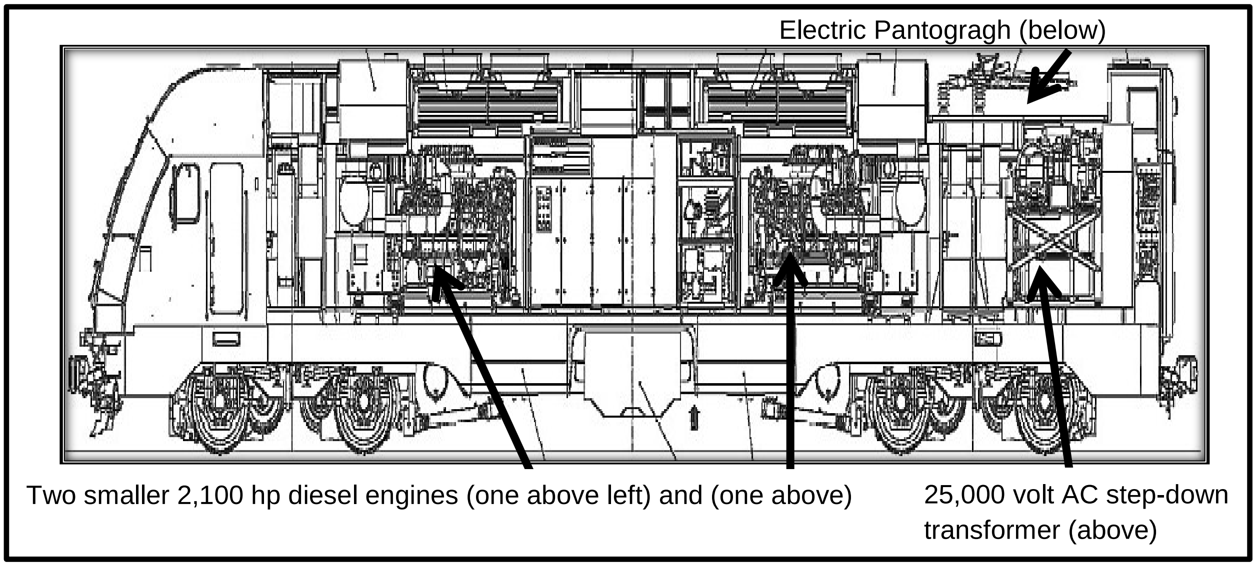


Figure VIII-1:
NJT Dual Mode Passenger Locomotive
(Iden, 2013)

At this time, this approach (dual mode) is simply a concept for use with U.S. freight diesel-electric interstate line haul locomotives. This approach has been used on limited small horsepower locomotives (i.e., comparable or smaller than U.S. switch (yard) locomotives) in other parts of the world, but has not been built or demonstrated in the U.S. However, NJT has been operating a small number of dual mode "passenger" locomotives on a limited basis in the U.S.

2. All Electric Freight Interstate Line Haul Locomotives

An all-electric freight line haul locomotive would be powered solely by electrified catenary. Currently, all-electric freight line haul locomotives operate in other parts of the world (e.g., Europe, China, and Russia). However, these locomotives are typically built for greater speeds, to reduce slowdowns for high speed passenger trains that share the same rail electrification system. Therefore, all-electric freight locomotives have significantly less pulling power (i.e., up to two-thirds less – though they are typically higher horsepower for speed) than U.S. diesel-electric freight interstate line haul locomotives.

Also, all-electric freight locomotives can cost up to two times more than current U.S. diesel-electric freight locomotives (see Figure VIII-2 for example of European electric freight locomotive). As an example, Sweden's iron all-electric locomotive – a special order locomotive built by Bombardier for Sweden, cost about $9 million per unit. (Bombardier, 2007)

Figure VIII-2:
Sweden's Iron Ore and China's All-Electric Freight Locomotive Sets
(Vitins, 2013)

B. Technology Performance: Potential for Emission Reductions and Fuel Efficiency

Locomotive *exhaust* emissions could be zero anytime the locomotive is fully powered by electricity. Of course, exhaust emissions would not account for the indirect electric power plant emissions to provide the electricity to the locomotives. In the diesel-electric mode, emissions would depend on the emission standard that the diesel engine has been designed to meet.

In the South Coast Air Basin, the current ARB locomotive emission inventory estimates that locomotive NOx, PM, and HC emissions combined would be about 12.5 tons per day in 2032. Assuming the locomotive emissions were to remain static for 30 years (i.e., 2033 to 2063), then freight railroad electrification could provide up to 137,000 tons of NOx, PM, and HC emissions reductions over that 30-year period.

C. Operational and Infrastructure Considerations

In this section, staff assesses the potential operational and infrastructure challenges with freight railroad electrification.

1. Operational Considerations

The North American freight railroad system today is a homogeneous rail network of up 160,000 track-miles. The freight intermodal system is also homogeneous, with marine containers a standard 20-foot or 40-foot unit, and domestic containers 53 feet in length. A major operational concern with freight railroad electrification is operating an isolated system that could interrupt the flow of rail goods on the North American freight rail system. Over the past 150 years, freight railroads have continuously looked for system efficiencies so they can compete more effectively with ships and trucks in terms of both price and time.

To become more efficient, North American freight railroads have consolidated from nearly 100 Class I railroads in the 1960's to seven Class I railroads today. As recently as the 1980's, five Class I freight railroads were operating in the State: Sante Fe, Burlington Northern, Western Pacific, Southern Pacific, and Union Pacific railroads. Today, California only has two Class I freight railroads: UP and BNSF.

UP and BNSF currently operate high priority intermodal unit trains that can leave the West Coast and make the trip to Chicago (>2,000 track-miles) in 48 to 72 hours. Freight interstate line haul locomotives, with about 5,000 gallon fuel tanks, have a refueling range of about 1,000 miles. On the trip from Chicago to Los Angeles, a typical freight train will refuel twice: once in Kansas City, Kansas and then either at Belen, New Mexico or Santa Teresa, New Mexico and then to California.

An isolated freight electrification system in California could create a number of challenges for UP and BNSF operations on the North American freight rail system including:

- Maintenance of two separate types of locomotive technologies – all-electric in California and diesel-electric for the rest of North American freight rail system; and

- Delays in operations by having to stop freight trains at an exchange point, just outside the South Coast Air Basin or California border, to switch all-electric to diesel-electric operations (these delays could take anywhere from 2 to 6 hours, depending on the configurations of the trains, and based on price and time, could potentially lead to a mode shift to trucks or ships).

2. Considerations in Designing a Freight Railroad Electrification System for the South Coast Air Basin and California

In 1999, Bharat Bhargava, who worked at the time for Southern California Edison (SCE), wrote a paper on Railway Electrification Systems and Configurations. This paper estimated the electrical power demands for different types of railroad trains, as summarized below in Table VIII-1.

Table VIII-1:
Electric Power Demands for Different Types of Railroad Systems

Rail System	Power Demand	Type
Light Rail	Less than 1 MW	Low
Commuter Trains	About 3 to 4 MW	Medium
High Speed Inter-City Rails	About 4 to 6 MW	Medium
Very Fast Commuter Trains (e.g., TGV in France)	About 8 to 10 MW	High
Freight Trains in Europe	About 6 to10 MW	High
Freight Trains in U.S.	18 to 24 MW	Very High

Note: One MW equals 1 million watts of electrical energy. The current U.S. freight interstate line haul locomotives, in the highest power setting or Notch 8, can generate up to 3.25 MW.

The power demand for the freight railroads in the U.S. is the highest and, therefore poses the maximum challenges for the railroads and the electric power companies. Basically, U.S. freight railroad electrification requires power levels ranging between 18 to 24 MW for per freight train, compared to 6 to 10 MW for freight trains in Europe (see Table VIII-1 above). The U.S. freight train power level is much higher and will require strong utility networks, traction substations, and catenaries.

The major differences in freight rail electrification in Europe and other countries are the power needs and system design. In most cases around the world, railroad electrification has been built for speed, to support high speed passenger trains. In other parts of the world, all-electric freight locomotives are typically built for speed (i.e., with high horsepower) to reduce congestion and delays for the high speed passenger trains sharing the same electric rail system. This is typically at the expense of pulling power.

For comparison, European all-electric freight trains typically pull about ten times less tonnage (i.e., about 1,000 to 2,000 tons) than U.S. diesel-electric freight trains (i.e., 10,000 to 20,000 tons).

A typical European all-electric freight locomotive has about 70,000 pounds of force of pulling power or tractive effort, whereas U.S. diesel-electric freight locomotives can approach 200,000 pounds of force of tractive effort. (See Table III-1 on the U.S. freight diesel-electric interstate line haul locomotive tractive effort levels.)

Greater catenary heights and clearances to allow for double stack containers carried by U.S. freight trains may create clearance issues, especially under bridges and tunnels. In the U.S., the railway electrification systems would require higher catenary clearances (23.5 feet) from rails, and could necessitate lowering tracks or raising bridges to provide adequate clearances.

<u>Higher Voltage Needs for Freight Electrification in North America (50 kilovolt to 100 kilovolt?)</u>

The higher power loads for U.S. freight trains would require higher current, necessitating a heavy-duty catenary system. This could mean electric power systems with higher short circuit duty design consideration and system voltages of at least 230 kilovolt (kV). Auto transformer feeder system or higher (50 kV) catenary voltage catenary would be required to deliver this power to the locomotive, if 60 hertz (Hz) industrial frequency is used.

A U.S. freight railroad electrification system could result in larger conductor sizes, taller catenary supports, and higher catenary losses, which adds to the expense of catenary systems (Bhargava, 1999). Based on the above, the designers of a freight railroad electrification system for the South Coast Air Basin would need to consider:

- The current and future power demands of freight interstate line haul locomotives (e.g., 50 kV today vs. 100 kV in the future?);
- The need for clearances with double-stack trains, bridges, and tunnels; and
- The need for electric power plant and substation infrastructure within the air basin to support a freight railroad electrification system.

For perspective, from 2010 to 2014, UP and BNSF generated an average of about 412,000 MWh of electricity from line haul and switch locomotives operating within the South Coast Air Basin. Assuming an annual rate of growth 2.56 percent compounded annually from 2015 to 2050, based on the annual growth rates projected in the updated ARB locomotive emission inventory, the UP and BNSF locomotive megawatt-hours would increase in the South Coast Air Basin to about one million MWh by 2050.

Power Plant Needs and System Efficiency in the South Coast Air Basin

To meet future freight electrification power demands in the South Coast Air Basin of up to one million MWh by 2050, five 50 MW power plants would be required (assuming those plants operate at 50 percent of capacity on an annual basis).

Finally, it would be critical to build the electricity generating power plants as close to the freight rail operations as possible. The further away the electricity is generated from the rail operations, significant electricity transmission losses can occur, reducing the overall efficiency of the system. Therefore, with transmission losses from electricity generated from power plants outside the South Coast Air Basin or California, more power plants may need to be built.

Current freight diesel-electric freight locomotives can achieve efficiency levels about 40 percent or more. Significant electrical transmission losses, and the use of non-renewable power sources like coal, could reduce the overall efficiency of the rail electrification system to less than 30 percent. This loss in efficiency could potentially offset any gains from fuel savings.

Dual Mode vs. All-Electric Locomotives

Dual mode (diesel-electric and all-electric) provides the flexibility to operate in the diesel mode when electrified catenary is unavailable (e.g., on low volume branch rail lines and within railyards). However, for freight interstate line haul locomotives operating across the North American freight rail system, the all-electric operation would only be employed for about three percent of annual operations while in the South Coast Air Basin or California.

The dual mode technology would create a significant inefficiency, carrying a large non-used power source on the critically limited space available on a freight locomotive, for up to 97 percent of annual rail operations. Further, while the locomotive was in all-electric operation, there would be an inefficiency of having a large diesel plant unavailable as a power source. Dual mode freight interstate line haul locomotives could also be expensive, possibly up to $10 million or more per locomotive.

All-electric freight locomotives could be very efficient while operating in the electrified rail system. However, these locomotives could be up to twice the cost of a diesel-electric freight locomotive and be limited to use only within only the electrified freight rail system.

D. Capital Costs: Locomotives and Infrastructure

This section provides some capital cost estimates for rail electrification infrastructure and dual mode and all-electric locomotive combined, with the combined costs distributed over a rail system's "route-miles".

Staff has no capital cost information for freight rail electrification in the U.S. We have looked at prior studies that attempted to estimate costs for freight rail electrification in the South Coast Air Basin. Staff has also looked at passenger electrification costs in the U.S. to gain some insights on the order of magnitude of potential costs for freight rail electrification. Finally, staff does not have access to detailed operational and maintenance costs for U.S. diesel-electric or other countries all-electric freight locomotives. Similarly, we do not have access to that information for all-electric rail infrastructure.

1. Dual Mode Freight Interstate Line Haul Locomotive Capital Costs

In September 2008, the NJT Board awarded a contract to Bombardier Transit Corporation for the purchase of 26 dual-powered locomotives — which can operate in both electrified and non-electrified territory — at a total cost of approximately $310 million. The cost distributed over each of the 26 locomotives is about $12 million per unit. (NJ Transit, 2011) The total capital costs included: design, engineering, manufacturing, training and spare parts, with the option to purchase additional locomotives in the future. (NJ Transit, 2011; Vantuono, 2008; Pernička, 2008; Gormick, 2009)

In 2010, NJT ordered an additional nine units for a total cost of about $79 million, or about $9 million per unit. (Railway Gazette, 2010) At that time, U.S. EPA Tier 2 emission standards were in effect. Based on the cost differences between Tier 2 and Tier 4 freight diesel-electric line haul locomotives (i.e., $2 to $3 million, about a one-third cost increase), staff estimates that a Tier 4 dual mode passenger locomotive in 2015 could cost about $12 million. Based on the historical ratio between passenger and freight locomotive capital costs, about two to one, staff estimates that a freight dual mode interstate line haul locomotive would cost about $6 million per unit. These costs are summarized in Table VIII-2 below.

Table VIII-2:
Estimate of Dual Mode Freight Interstate Line Haul Locomotive Capital Costs

Type of Operation	Tier 2 Dual Mode	Tier 4 Diesel-Electric	Estimated Tier 4 Dual Mode
Passenger	about $9 million	$6 million	$12 million
Freight	N/A	$3 million	$6 million

2. All Electric Freight Interstate Line Haul Locomotive Capital Costs

Staff has had a number of conversations with U.S. and European diesel-electric and all-electric freight locomotive manufacturers. Based on those conversations, staff estimates that an all-electric freight interstate line haul locomotive, compatible with U.S. freight locomotive pulling power or tractive effort specification of up to 200,000 pounds of force, would cost about $5 million per locomotive.

3. Freight Railroad Electrification Infrastructure and Locomotive Costs

Railroad electrification costs vary widely depending on the type of electric rail system, land and electrical power costs, and the desired speed of the locomotives (e.g., high speed rail (over 125 mph) as compared to traditional speeds with diesel-electric railroad systems (70 to 125 mph).

<u>“Route-Mile” Used to Compare Railroad Electrification Systems</u>

A key metric ARB has used to estimate capital costs (i.e., both infrastructure and locomotives) is in terms of cost per “route-mile”. “Route-miles” is simply the distance from one point of the project to the other end of the project. For example, the route-miles for Amtrak’s Northeast Corridor traveling from Washington D.C. to Boston is 430 miles. “Route-miles” does not account for double-tracking or rail sidings, which would be unique to each project. The purpose of the route-mile estimates is simply to provide an order of magnitude cost comparison, rather than precisely determine each project’s cost per specific miles of electric infrastructure.

Route-miles is typically the metric used in railroad electrification project cost studies, and is therefore the metric ARB staff chose to use in this analysis. ARB staff also include the costs of railroad electrification infrastructure and all-electric locomotives averaged over the route-miles.

**Table VIII-3:
Summary of Costs for a California Conventional All-Electric Passenger Rail and Diesel-Electric Freight Hybrid System**

Study	Route-Miles	Infrastructure (billions)	Rolling Stock	Cost per locomotive	Cost per Route-Mile (millions)
Caltrain 2020 (Conventional: Hybrid Electric and Diesel)	51	$1.5	-	-	$30

Source: *Caltrain 2020 Modernization* (Caltrain, 2016)

Why Did ARB Focus on Caltrain as a Basis to Estimate Freight Railroad Electrification Costs in California?

There were prior Southern California Association of Governments (SCAG) and railroad studies that estimated freight railroad electrification costs in the South Coast Air Basin. All of these studies were dated (SCRRA, 1992; AAR et al., 2008; and SCAG, 2008) and key cost information needed to be updated and made with more relatable experiences to estimate capital costs for freight railroad electrification in California.

Caltrain is currently in the process of actually building a conventional passenger all-electric passenger rail system from San Francisco to San Jose, California or 51 route-miles. Caltrain plans to begin operations as early as 2020.

The Caltrain electric passenger system is designed roughly as 75 percent all-electric and 25 percent diesel-electric. The latter represents the activities of Caltrain's older diesel-electric passenger locomotives, which will be gradually phased out. Also, it is important to note that UP's diesel-electric freight trains will continue to operate along the corridor.

The estimated capital costs for Caltrain's electric infrastructure, and smaller electric passenger locomotives, referred to as electrical multiple units (EMUs), are about $1.5 billion, or about $30 million per route-mile.

ARB staff believes the Caltrain electric passenger system represents the low end of the spectrum with respect to freight railroad electrification capital costs in California for the following reasons:

- Caltrain is designed with a 25 kV catenary electrification system. Freight railroad electrification in the South Coast Air Basin would at a minimum require a 50 kV system, and projecting for future increases in rail activities in 30 to 50 years, may require up to a 75 kV or 100 kV system.

- o Higher voltage systems would likely require higher heights for catenary and result in significant costs for modifications to bridges, tunnels, etc. in the South Coast Air Basin.

- A South Coast Air Basin freight railroad electrification system likely would take up to 30 years or more (based on other electrification experiences) to approve funding, design, permitting, and construction. As a result, capital costs would likely increase over that time.

- ARB staff estimates that all-electric freight locomotives for the South Coast Air Basin would likely cost about 25 percent more ($5 million per freight locomotive) than the all-electric smaller passenger locomotives ($4 million per EMU) that will be procured by Caltrain.

- Based on the above reasons, and a number of other considerations, ARB staff estimated that freight railroad electrification capital costs (i.e., infrastructure and all-electric freight locomotives) for the South Coast Air Basin would be about $50 million per route-mile.

- ARB staff estimates that UP and BNSF operate about 500 freight-track route-miles in and around the South Coast Air Basin (i.e., out to natural exchange points outside the South Coast Air Basin). As a result, ARB staff estimates total freight railroad electrification costs would be about $25 billion.

E. Current Status

At this time, there is limited use of electrification in the U.S. Amtrak operates passenger electrified sections of the Northeast Rail Corridor (i.e., Boston to Washington D.C.). Additionally, there are three all-electric freight rail operations in the U.S. Two of the larger operations are designed with 35 to 78 miles of rail track to move coal to dedicated electric power plants, and that do not interchange with the North American freight rail system. Both of these isolated all-electric freight rail systems are supported by a 50 kV 60 Hz electrified catenary system.

Below is an update and comparison of dual mode and all-electric freight locomotives from other parts of the world with U.S. diesel-electric freight locomotives.

1. Dual Mode Freight Locomotives

In 2008, a Swedish study performed a literature search of existing freight dual-mode locomotives. The examples include: 1) the South African Class 38 (Siemens), of which 50 were built between 1992 and 1994, and 2) British Rail which acquired 49 dual-mode locomotives between 1962 and 1965. Both of these types of dual-mode freight locomotives were relatively small switch locomotives, with diesel engines ranging between 600 and 1,050 hp. For comparison, U.S. freight switch (yard) locomotives average about 2,000 hp. U.S. freight interstate line haul locomotives are about 4,400 hp.

In a more recent example, European freight operator Direct Rail Services had ordered ten Vossloh Class 88 dual mode locomotives with a 4 MW electric power plant. This electric power plant generated about 0.7 MW (i.e., about 500 hp) with a Tier 3 compliant diesel engine for hoteling operations. (Railcolor, 2013) A diesel engine of this size would be used in the U.S. as hotel or auxiliary power to provide electricity for air conditioning and lighting on passenger railcars.

The Vossloh dual-mode locomotives can achieve speeds of up to 100 miles per hour, allowing them to serve in both freight and passenger operations. The tractive effort for these dual-mode freight locomotives is about 71,000 pounds of force (Modern Railways, 2013), nearly equivalent to U.S. passenger or freight switch locomotives, with about one-third the pulling power of a U.S. freight interstate line haul locomotive.

The first of the Class 88's were scheduled to arrive for service in 2015. In the Vossloh configuration, the electric system is the dominant power plant (about 5,400 hp), with a relatively small diesel engine (about 500 hp) providing the flexibility to operate in those areas (e.g., railyards) without electric infrastructure. (Railcolor, 2013; Modern Railways, 2013)

2. All Electric Freight Locomotives in the U.S.

ARB staff obtained information on three currently operating freight all-electric railroads in the U.S. These operations include: Black Mesa and Lake Powell Railroad (BM&LP), Deseret Power Railroad (DPR), and the Iowa Traction Railway (IATR). The IATR is a small railroad (about ten miles in length) that serves a small community in Iowa, but does have the capability to interchange with a Class I railroad. The other two are larger U.S. all-electric freight railroads which are isolated and do not interchange with the North American freight rail system. These two larger all-electric freight operations were built in the 1970's to 1980's and are about 35 to 78 miles in length. Both of these all-electric railroads are dedicated operations that are limited to providing coal from a coal mine to an individual electric power plant. The electric power plants also power the all-electric freight locomotives that support these operations.

The two larger operations (BM&LP and DPR) each have about ten all-electric freight line haul locomotives originally built by GE in the 1970's. This GE all-electric freight locomotive modified the dominant diesel-electric line haul locomotive model of the 1970's, which was an EMD SD40 of about 3,000 hp. The resultant model (GE E60) provided about 70,000 pounds of force for pulling power, which is about one-third the pulling power of the new U.S. diesel-electric freight interstate line haul locomotives.

F. Key Challenges and Next Steps

Freight railroad electrification has successfully operated in the past in the U.S. and is being used in other parts of the world today. Freight railroad electrification in the U.S. will require significant capital costs, but could potentially have lower operating (e.g., electricity vs. diesel fuel savings – the latter could offset electrification capital costs, over 30 years, by up to ten percent. This assumes about 30 million gallons/annually saved in the South Coast Air Basin x 30 years x at $3 per gallon) costs.

This type of information may be provided by the ARB-funded University of Illinois study of California rail operations and economics. Freight railroad electrification in the South Coast Air Basin, or the rest of California, will require large amounts of electrical power. The current key challenges with freight railroad electrification in California include:

- Significant capital costs to build electric rail infrastructure and electric locomotives;

- Locomotive manufacturers being able to build and demonstrate all-electric freight locomotives that meet the current tractive effort capabilities of existing U.S. freight diesel-electric interstate line haul locomotives; and

- Limiting potential delays and other operational impacts on North American freight railroad operations.

This page left intentionally blank

IX. LOCOMOTIVE EMISSIONS CAPTURE AND CONTROL SYSTEMS

Emissions capture and control systems are a technology that could be developed and deployed to control exhaust emissions from stationary locomotive engines while operating within specific areas of railyards (e.g., during locomotive maintenance, diagnostics, and refueling events).

A. Technology

In 2006, Advanced Cleanup Technologies, Incorporated (ACTI) developed the Advanced Locomotive Emission Control System (ALECS). This system includes a set of stationary emissions control equipment with ducting to an articulated bonnet or hood that can connect to a locomotive exhaust stack(s). The hood is designed to capture or extract air pollutants from locomotive exhaust stack(s) and deliver the pollutants to a ground-based emission control system via ducting. (ARB, 2009). See Figure IX-1 below.

Figure IX-1: Advanced Locomotive Emission Control System
(TIAX, 2007)

The hood remains attached via ducting to the stationary control system, but has the flexibility to stay connected to the locomotive exhaust stack, even while the locomotive may move slowly over very short distances. (TIAX, 2007) Based on prior discussions with ACTI, staff's understanding is the hood movements are limited by the length of the full system ducting, or about 400 to 1,200 feet in length, depending on the particular system configuration.

In the summer of 2007, the emissions capture system (ECS) portion of ALECS was initially tested on a limited basis, with a small number of locomotives on an isolated and separate track, as part of a pilot program at the UP Roseville Railyard. TIAX prepared a detailed report with the results of the testing, including information on the prototype system design and components, emissions control, and energy consumption. (TIAX, 2007)

The ALECS prototype was subsequently moved to the Port of Long Beach and adapted to perform the same function on the exhaust stack of ocean going vessels at berth.

In 2015, ARB approved the use of two barge-based emissions capture and control technologies (made by two competing companies) as alternatives to shore power for container vessels at berth, based on the results of prototype performance and durability testing. These approvals allow vessel fleets to use the technologies for compliance with Section 93118.3, Title 17, Chapter 1, Subchapter 7.5, of California Code of Regulations (CCR): Airborne Toxic Control Measure for Auxiliary Diesel Engines Operated on Ocean-Going Vessels At-Berth in a California Port. The ARB Executive Orders approving the performance of these marine versions of an emissions capture and control system are available at: http://www.arb.ca.gov/ports/shorepower/shorepower.htm. As those systems transition from single prototypes to production of commercial units, there will be more data on long-term performance and costs that would be helpful in considering the possible railyard applications.

B. Key Challenges and Next Steps

There is potential for a locomotive emissions capture and control system to reduce railyard diesel PM and the associated health effects in nearby communities. ARB and its partner air districts have offered funding from the Proposition 1B: Goods Movement Emission Reduction Program for such a system, but no railroad has expressed interest in the incentives offered to date.

The next step would be to test a locomotive emissions capture and control system on a larger scale to demonstrate its effectiveness and durability in full scale railyard operations. Such a system would need this full-scale railyard demonstration to determine the potential utilization rates (e.g., hours per day and number of locomotives that can be attached to the system at one time) and amount of potential emissions reductions within actual railyard operations.

Staff believes the most effective application of a locomotive emissions capture and control system would be in areas of a railyard where the utilization rate (emission capture) can be maximized with locomotives that are typically stationary or which may move over very short distances. This could potentially include: railyard maintenance, service, and refueling locations. The potential emission reductions would be highly dependent on the specific operations conducted at a particular location within individual railyards. The greatest potential to capture and control railyard emissions is with locomotives that are idling or in operating within maintenance areas where personnel perform engine diagnostics for extended periods of times

Major classification railyards like UP Roseville, BNSF Barstow, and UP Colton have major locomotive maintenance operations and offer the greatest potential to control stationary locomotive emissions.

This page left intentionally blank

X. POTENTIAL STEPS TO DEVELOP AND DEMONSTRATE ZERO-EMISSION TRACK-MILE AND ZERO-EMISSION LOCOMOTIVES

ARB staff believes that advanced locomotive technologies, such as batteries and fuel cells and freight railroad electrification, could be developed to play a critical role in providing California with locomotives capable of zero-emission track-miles for local and regional operation. These are technologies that could potentially provide further emissions and diesel fuel reductions beyond Tier 4 and Tier 4 with aftertreatment and on-board batteries.

A. Technology Options

The technology possibilities include the use of a current hybrid diesel-electric (or natural gas-electric) locomotive engine modified to switch from the diesel engine to another source of electricity. This source may be a bank of batteries or fuel cells within the locomotive or located on the subsequent rail car (a “tender”) or an external power supply (like overhead electric catenary or in-ground wayside power). While running in zero-emission mode, the diesel engine would not be operating.

In addition, battery and fuel cell technologies may be able to meet the energy demands of switch locomotives that are limited to railyard operations, and some MHP locomotives that are limited to operations within specified localities or regions.

Freight railroad electrification has been proven to be technically feasible to operate with freight line haul locomotives. However, local and regional catenary electrification could have potentially significant impacts on freight rail operations, and require significant levels of capital costs and electric power infrastructure.

The concept of an SOFC-GT may have the potential to achieve zero (or near-zero) emissions with sufficient thermal energy (heat) on-board the locomotive to power it across the entire North American freight rail system. This type of technology would not need to be limited to specific localities or regions, and could potentially achieve an efficiency level of up 70 percent. However, there are significant engineering and safety challenges that need to be addressed, including the use of a gas turbine to operate a line haul locomotive in both steady and transient states.

B. Technology Performance: Potential for Emissions Reductions and Fuel Efficiency

As defined here, “zero-emission track-miles” means locomotives capable of operating with zero exhaust emissions for periods of time on existing railroad tracks, within a railyard or within a geographic region like an impacted community or air basin.

ARB staff defines “zero-emission locomotive technologies” as those technologies that could potentially provide zero exhaust emissions for freight interstate line haul locomotives over the entirety of the North American freight rail system (i.e., up to 140,000 or more track-miles or more) on an annual basis.

Advanced zero-emission track-mile and freight railroad electrification could potentially significantly reduce freight railroad diesel fuel consumption. The diesel fuel reductions could provide some level of fuel savings to the freight railroads. ARB has contracted with the University of Illinois to provide an assessment of the potential operating costs and savings from advanced locomotive technologies.

C. Operational and Infrastructure Considerations

At this time, it is challenging to assess what the operational and infrastructure considerations would be for advanced locomotive technologies like battery and fuel cell tenders and freight railroad electrification. The key considerations include the installation of stationary electric charging infrastructure and the need to exchange locomotive technology at the edge of the geographic area before the train could continue the rest of its interstate journey.

ARB staff contracted with the University of Illinois to evaluate the operational and economic impacts of such exchange points on the national freight rail system. This evaluation was published in June 2016, and is available on ARB’s website.

D. Costs

Table X-1 below summarizes potential advanced locomotive technologies and preliminary estimates of the capital costs. For the national fleet options, the capital costs and benefits would be shared across the country. About seven percent of the total annual interstate line haul locomotive activity by UP and BNSF occurs in California, so the table includes pro-rated “California share” costs as well.

Table X-1:
Estimated Capital Costs of Advanced Locomotive Technologies

Technology Type	Scope and Number of Units	Technology		
		Capital Cost/Unit (M)illions	Capital Cost (M)illions or (B)illions	Life (Yrs)
U.S. Freight Locomotives in National Fleet				
Fuel Cell (SOFC-GT) Line Haul Locomotive	National 17,500 locomotives[1]	$2-5M/locomotive (above Tier 4)	Nationwide: $35-87.5B CA share: $1.4-3.5B	15
UP and BNSF Freight Locomotives Operating with Zero-Emission Track-Miles in the South Coast Air Basin				
Battery/Fuel Cell Tender	South Coast 130 trains/day 4 locomotives/train 3 tenders/locomotive	$5M/tender and integration hardware + $15M total for 5 battery replacements/tender	South Coast Air Basin only: $39B	30
Freight Railroad Electrification	South Coast 500 route-miles	$50M/route-mile, including infrastructure and rolling stock	South Coast Air Basin only: $25B	30

1. Natural turnover of the national fleet to newly manufactured, advanced technology locomotives based on Tier 4 with aftertreatment and on-board batteries, and to remanufactured locomotives based on Tier 4 with aftertreatment, would occur over roughly two decades.

E. Other Cost Considerations for Batteries and Fuel Cells

Based on data from a variety of sources, and economies of scale, the cost differential between conventional diesel locomotives and near-zero or zero-emission technologies is expected to diminish over the next ten to 20 years.

Near-zero and zero-emission technologies from the light duty sector readily transfer to the medium duty and heavy duty vehicle sectors. Transferring near-zero and zero-emission technologies to locomotives will also occur, but will require additional research and development to satisfy the high power requirements needed (e.g., about 3.3 MW or 4,400 hp).

Diesel engine costs will rise due to tightening exhaust emission standards. Table X-2 below shows a percent increase for diesel engines in dollars per kilowatt by 2030.

- Fuel cells costs in dollars per kilowatt are expected to drop by a factor of 13.
- Battery costs are expected to decrease by a factor of three.
- Operating and maintenance costs are largely unknown at this time.
- Major infrastructure investments will be needed to ensure the success of near-zero and zero-emission technologies and will vary by application and operational needs.

These general economic factors are summarized below in Table X-2.

Table X-2:
General Economic Factors

Category	Cost Forecast	Dollars Per Kilowatt in	
		2012	2030
Diesel engine	↑	70	90
Fuel Cell	↓	1,300	100
Battery	↓	600	200
Operating and Maintenance	**?**	variable / unknown	variable / unknown
Infrastructure	↑	variable / major	variable / major

F. Current Status and Key Challenges

Currently, freight railroad electrification has been demonstrated to be technically feasible, but potentially has significant North American freight railroad operational and capital cost impacts.

There are a number of other key challenges to develop battery and fuel cell locomotive technologies as discussed below.

The Power and Energy Demands of a Freight Locomotive

A North American diesel-electric freight locomotive generates up to 3.3 MW of electricity in Notch 8 (the highest power setting). Maintaining this power output over one hour would be equivalent to 3.3 MWh.

This would be equivalent to the electricity generated by a small electric power plant. For perspective, the average freight interstate line haul locomotive pulling a train across the South Coast Air Basin generates about 7.5 MWh.

Locomotives have little available space within the locomotive platform for the retrofit of additional batteries or fuel cells. Due to current technology limits for power and energy density of batteries and fuel cells, multiple battery and/or fuel cell tenders or rail cars may be needed to meet the demands of a single freight interstate line haul locomotive (see discussion of battery tenders in Chapter VI).

There are a number of energy and cost considerations that need to be addressed with both battery and fuel cell technologies to deploy them with freight interstate line haul locomotives.

Relative Energy Density of Batteries and Liquid Fuels

Figure X-1 (see next page) illustrates the challenges with the current levels of energy density of available battery technologies compared to diesel and other fuels to be able to power freight interstate line haul locomotives. There are potential technology breakthroughs (e.g., lithium oxide) that could occur and be commercialized to address some of these concerns. However, for the foreseeable future, the current and forecasted battery technologies, and similar PEMFC applications, will limit their commercial viability to lower horsepower switch (yard) locomotives.

With future improvements, these technologies could potentially power freight interstate line haul locomotives for local and regional distances.

As shown in Figures X-1 and X-2, SOFC have some of the highest volumetric (watt-hour/L) and gravimetric energy or specific energy (watt-hour/kg) densities of any generation technology. In addition SOFC have high specific power (watt/kg) and power density watt/cm^3). This allows them to be small and light.

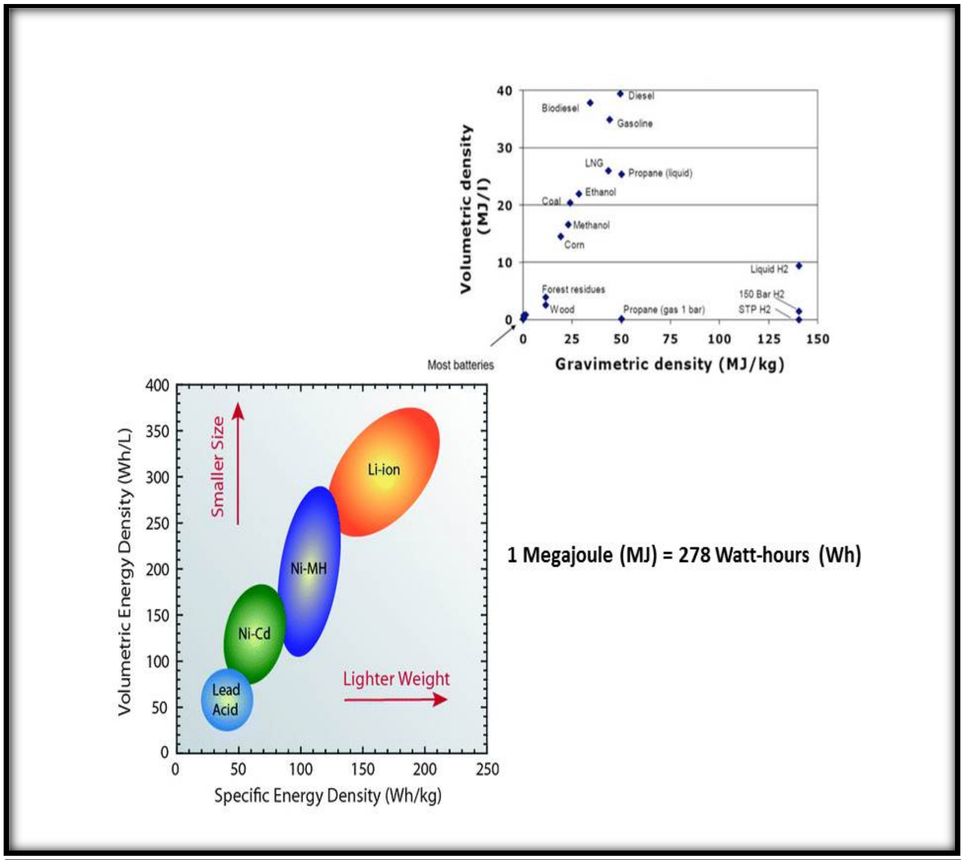


Figure X-1:
Relative Energy Density of Liquid Fuels and Various Battery Chemistries

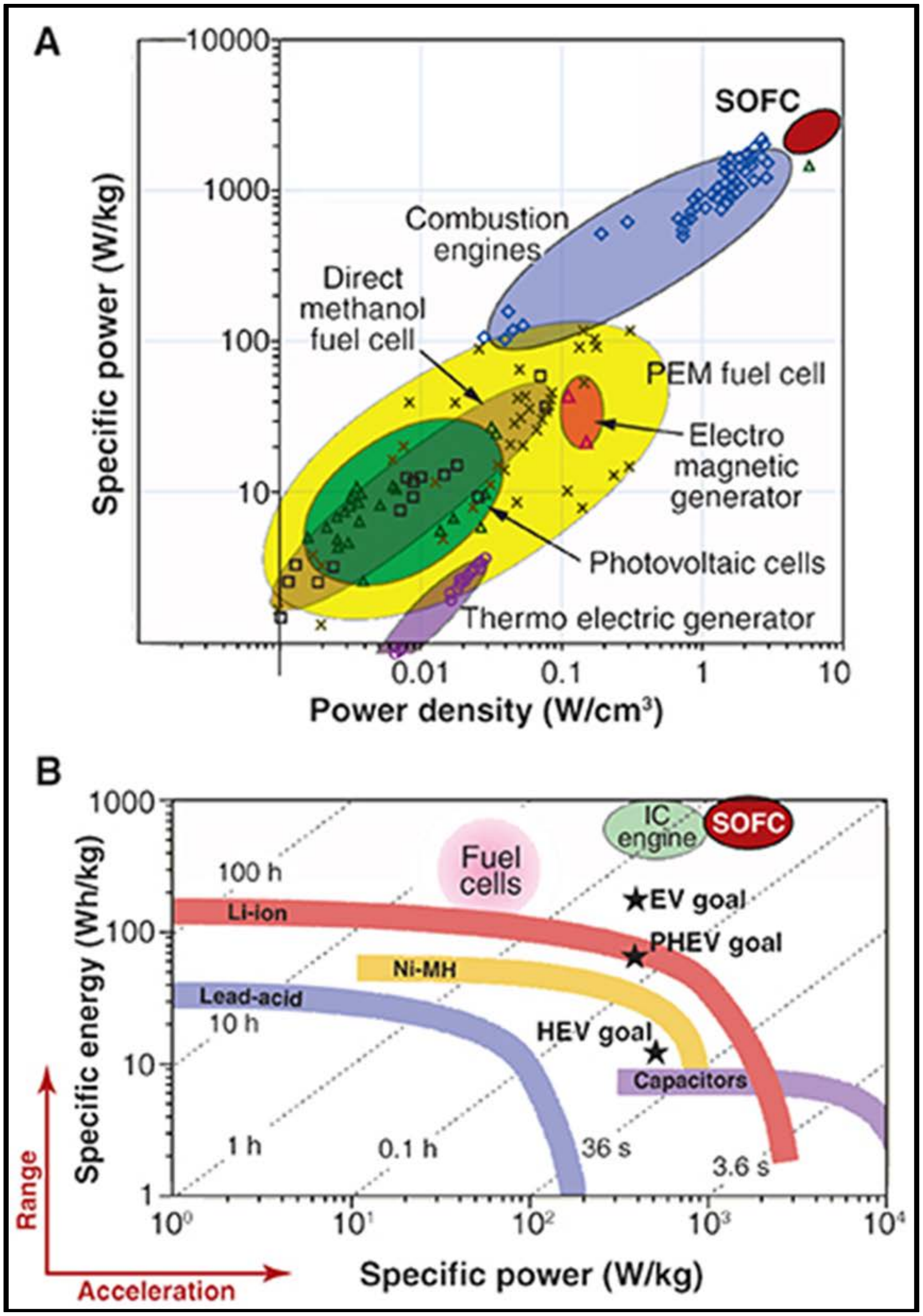


Figure X-2:
Power Density and Specific Power of
Various Battery Chemistries

G. Next Steps

Table X-3 provides suggested pathways to achieve zero-emission track-miles. Several technology options are presented with estimated timeframes for commercial production. Several options build upon existing prototypes while more advanced approaches will require research and development.

The pathway options include the following steps:

- Key research and development;
- Estimated timelines; and
- Estimated costs.

These technology options are based on a number of discussions with key locomotive manufacturers and researchers, all of whom have participated to some degree in the early research, design, and in some cases have built prototypes of zero-emission track-mile locomotive technologies.

Based on the varied experiences and expertise of those contacted, staff asked what further development steps might be needed and the potential costs, in order to develop these technologies to be potentially viable for commercial production. Specifically, commercially viable as some or all of the following freight locomotive applications: switcher, MHP, or interstate line haul.

Table X-3 has been designed to be generic, rather than represent specific locomotive manufacturers, researchers, and their projects – but is based to some degree on the input we received from each of them. This matrix is based to a large degree on the developmental steps and timelines GE and EMD, the two U.S. freight line haul locomotive manufacturers, used to research, design, and demonstrate Tier 2 and Tier 4 freight interstate line haul locomotives.

Table X-3:
Pathways to Potentially Develop and Demonstrate
Zero-Emission Track-Mile and Zero-Emission Freight Locomotives

Advanced Locomotive Technology	**Research and Design (2-3 years)**	**Build and Test Prototype (1-2 Years)**	**Build and Field Test Small Scale Demo (3-5 units) (2-3 years)**	**Full Scale Demo (10-20 units) (3-4 years)**	**Commercial Production**
Focus on Switch (Yard) Locomotives (1,006 – 2,300 hp) – Then Transition to MHP and Ultimately to Interstate Line Haul Locomotives[1]					
All-Battery Switcher (e.g., NS 999) – Lithium Ion			2017-2019 (up to $15M @$3M per Battery Switcher)	2020-2024 (up to $60M @$3M per Battery Switcher)	2025 <u>Total Dev. Costs</u>: (up to $75M)
Fuel Cell/Battery Switcher (e.g., BNSF 1205 – PEMFC)			2017-2019 (up to $20M @$4m per Fuel Cell Battery Switcher)	2020-2024 (up to $80M @$4M per Fuel Cell Battery Switcher)	2025 <u>Total Costs</u>: (up to $100M)
Switcher Battery Tender* (no current prototype)	2016-2018 ($2M-design)	2018-2020 ($3M)	2021-2023 (up to $15M @$3m per Battery Tender)	2024-2028 (up to $60M @$3M per Battery Tender)	2029 <u>Total Dev. Costs</u>: (up to $80M)
SOFC-GT Switch to Line Haul Locomotive (no current prototype)	2016-2020 (up to $8M) (includes lab engine testing)	2021-2022 (up to $7M)	2023-2025 (up to $20M @ about $4M per unit)	2026-2028 (up to $45M)	2029 <u>Total Dev. Costs</u>: (up to $80M)
Line Haul Battery Tender (no current prototype)	2016-2018 ($2M)	2019-2020 ($5-6M)	2021-2023 (up to $25M@$5M per Battery Tender)	2024-2026 (up to $100M@$5M per Battery Tender)	2027 <u>Total Dev. Costs</u>: (up to about $135M)

1. Switch locomotive technologies may be able to be transition to MHP and interstate line haul locomotives.

Note: The dark grey cells are steps that have already been implemented to some degree by either locomotive manufacturers or researchers.

Note: One manufacturer has built a commercially available smaller scale zero-emission track-mile locomotive technology in the form of a local people mover. This technology would need to be scaled-up for freight switcher (yard) applications.

H. Approaches to Develop Zero-Emission Track-Mile Locomotive Technologies

In order to develop zero-emission track-mile freight locomotive technologies, ARB staff recommends that California pursue a series of steps that include research, development, and demonstration between 2016 and 2030 or longer:

California's Participation in a National Research and Development Program

Staff recommends that California provide even greater support for national research and development efforts for battery and fuel cell technologies applicable to locomotive and marine sectors. This increased support could help to accelerate efforts to advanced battery and fuel cell technologies.

Development efforts associated with locomotives could potentially benefit all transportation sectors, especially if there were battery and fuel cell technologies developed to meet the power and energy demands of freight locomotives, with peak power demands of up to 3.3 MW.

California could play a greater role in participating in national research and development efforts for battery and fuel cell technologies through the Department of Energy (DOE), Department of Transportation (DOT) – including the Federal Railroad Administration (FRA), and other appropriate federal agencies.

California's Efforts to Demonstrate Current Zero-Emission Locomotive Technologies

California could lead the country in participating in the research, development, and demonstration of currently available battery and fuel cell technologies for use with freight and passenger locomotives.

This would allow locomotive manufacturers and researchers to identify potential design and operational issues with currently available advanced technologies, especially in real world railroad applications, and identify potential solutions to overcome those limitations. This information could be used to also support and advance the national research and development battery and fuel cell programs.

Summary of Possible ARB Actions to Support Zero-Emission Track-Mile Technologies

Based on all of the above, staff recommends that ARB support:

- National efforts to research and develop battery and fuel cell technologies with greater power and energy density that are less costly, and

- California's efforts to develop and demonstrate currently available battery and fuel cell locomotive technologies to identify and improve on the limitations of these technologies to power freight locomotives for zero-emission track-miles.

Appendix A: References

Executive Summary

(AAR, 2014): American Association of Railroads, *Class I Railroad Statistics*, July 2014. Archived by ARB staff, April 19, 2016.

(AAR, 2015): American Association of Railroads, *Class I Railroad Statistics*, May 2015. Archived by ARB staff, August 17, 2015.

(AAR, 2016): American Association of Railroads, *Class I Railroad Statistics*, January 2016. Archived by ARB staff, April 19, 2016.

(ARB, 1998a): Air Resources Board, *1998 Locomotive NOx Fleet Average Agreement*. http://www.arb.ca.gov/railyard/1998agree/1998agree.htm. Accessed February 9, 2016.

(ARB, 2005): Air Resources Board, ARB/Railroad Statewide Agreement, *Particulate Emissions Reduction Program at California Rail Yards*, June 2005: http://www.arb.ca.gov/railyard/ryagreement/080805fs.pdf. Accessed February 9, 2016.

(GE, 2005): General Electric, *Hybrid Locomotive: A Product of GE Ecomagination* Product Information Sheet. Archived by ARB staff, September 13, 2011.

(GE, 2016): General Electric, *Comments of GE Transportation on California Air Resources Board's Draft Technology Assessment for Freight Locomotives*, June 15, 2016. Archived by ARB staff, June 16, 2016.

(Progressive Railroading, 2014): Progressive Railroading, *Fleet Stats 2014*, July 2014. http://www.progressiverailroading.com/pr/graphics/14/07/pr0714.pdf . Accessed April 19, 2016.

(Railway Gazette, 2007): Railway Gazette, *GE Unveils Hybrid Locomotive*, Railway Gazette, July 2, 2007. http://www.railwaygazette.com/news/single-view/view/ge-unveils-hybrid-locomotive.html. Accessed February 11, 2016.

(The Diesel Shop, 2016): The Diesel Shop, *Class I Railroads*, February 2016. http://www.thedieselshop.us/INDEXCLSS.html. Accessed March 17, 2016.

(U.S. DOT, 2015): United States Department of Transportation, *National Transportation Statistics: Amtrak Fuel Consumption and Travel* , January 2016. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_18_m.html. Accessed April 19, 2016.

(U.S. EPA, 1998): United States Environmental Protection Agency, *Locomotive Emissions Standards – Regulatory Support Document*, EPA-420-R-98-101, April 1998. http://www.epa.gov/otaq/documents/420r98101.pdf. Accessed February 9, 2016.

(U.S. EPA, 2009): United States Environmental Protection Agency, *Emission Factors for Locomotives*, EPA-420-F-09-025, April 2009. http://www.epa.gov/nonroad/locomotv/420f09025.pdf. Accessed February 9, 2016.

(40 CFR Part 1033.101a): Title 40 Code of Federal Regulations Part 1033.101(a).

(40 CFR Part 1033.901): Title 40 Code of Federal Regulations Part 1033.901.

Chapter I: North American and California Railroad Operations

(AAR, 2015): American Association of Railroads, *Class I Railroad Statistics*, May 2015. Archived by ARB staff, August 17, 2015.

(Annual Energy Outlook, 2014): *Annual Energy Outlook, 2014, With Projections to 2040*. DOE/EIA-0383(2014), April 2014. http://www.eia.gov/forecasts/archive/aeo14/pdf/0383(2014).pdf. Accessed February 9, 2016.

(ARB, 1998a): Air Resources Board, *1998 Locomotive NOx Fleet Average Agreement*. http://www.arb.ca.gov/railyard/1998agree/1998agree.htm. Accessed February 9, 2016.

(ARB, 2011a): Air Resources Board, *UP 9900*, November 2011. http://www.arb.ca.gov/railyard/docs/up%209900%20nov-9-2011.jpg. Accessed February 9, 2016.

(ARB, 2015a): Air Resources Board, Train data compiled by ARB staff (number of trains per day, distributed power units), 2015.

(Bachand, 2007a): Bachand, J., *General Electric ES44AC*, October 27, 2007. http://www.thedieselshop.us/Data%20ES44AC.HTML. Accessed February 9, 2016.

(Bachand, 2007b): Bachand, J., *General Electric ES44DC*, October 27, 2007. http://www.thedieselshop.us/Data%20ES44DC.HTML. Accessed February 9, 2016.

(BNSF, 2013): BNSF Railway, *BNSF Corporation Form 10-K Filing, United States Securities Exchange Commission, for the Fiscal Year Ended December 31, 2013*. http://www.bnsf.com/about-bnsf/financial-information/form-10-k-filings/pdf/10k-railway-2013.pdf. Accessed February 9, 2016.[*]

(Cotey, 2009): Cotey, A., *Locomotive Manufacturers Offer Information on their Fuel-Saving Models*, Progressive Railroading, August 2009. http://www.progressiverailroading.com/mechanical/article/Locomotive-Manufacturers-Offer-Information-on-their-FuelSaving-Models--21139. Accessed February 9, 2016.

[*] 7,000 locomotives in 2013.

(Davis et al., 2014): Davis, S., Diegel, S., and Boundy, R., *Transportation Energy Data Book: Edition 33, ORNL-6990*, Oak Ridge National Laboratory, Oak Ridge, TN, July 2014. Archived by ARB staff, August 6, 2015.

(FRA, 2015): Federal Railroad Administration, *Freight Rail Today*. https://www.fra.dot.gov/Page/P0362. Accessed February 9, 2016.

(Metrolink News, 2016): Metrolink News, *First Metrolink Tier 4 Locomotive Completed*, January 29, 2016. http://www.metrolinktrains.com/news/news_item/news_id/1051.html. Accessed February 9, 2016.

(RR Picture Archives, 2009): RR Picture Archives, Photo contributed by Christopher Palmieri, November 2009. http://www.rrpicturearchives.net/showPicture.aspx?id=1870846. Accessed February 9, 2016.

(RR Picture Archives, 2014a): RR Picture Archives, Photo contributed by Noel Stoutenburg, May 2014. http://www.rrpicturearchives.net/showPicture.aspx?id=3846817. Accessed February 9, 2016.

(UP, 2013a): *Union Pacific Corporation Factbooks*, 2013 http://www.up.com/investor/factbooks/index.htm. Accessed February 9, 2016.

(UP and BNSF, 2010): Union Pacific and BNSF Railway, Company confidential annual locomotive diesel fuel consumption information provided to ARB staff through 2010**.**

(Winters, 2015): Winters, E., *Railroad 101 and the Port and Railroad Relationship*, Presentation to Association of Pacific Ports, January 2015. http://static1.squarespace.com/static/5228f3e5e4b00447185d4ee0/t/54c81d77e4b0297eaee98b09/1422400887994/Eric+Winters%2C+TY+Lin+International.pdf. Accessed February 18, 2016.

(40 CFR Part 1033.901): Title 40 Code of Federal Regulations Part 1033.901.

Chapter II: Programs That Reduce Locomotive Emissions in California

(ARB, 1998a): Air Resources Board, *1998 Locomotive NOx Fleet Average Agreement*. http://www.arb.ca.gov/railyard/1998agree/1998agree.htm. Accessed February 9, 2016.

(ARB, 1998b): Air Resources Board, *1998 Locomotive NOx Fleet Average Agreement Archives*. http://www.arb.ca.gov/railyard/1998agree/1998arch.htm. Archived by ARB staff, August 9, 2015.

(ARB, 2004): Air Resources Board, Staff Report: *Initial Statement of Reasons for Proposed Rulemaking - Proposed Regulatory Amendments Extending the California Standards for Motor Vehicle Diesel Fuel to Diesel Fuel Used in Harborcraft and Intrastate Locomotives*, October 1, 2004. http://www.arb.ca.gov/regact/carblohc/isor.pdf. Accessed February 9, 2016.

(ARB, 2004-2008): Air Resources Board, *Railyard Heath Risk Assessments and Mitigation Measures*, 2004-2008, http://www.arb.ca.gov/railyard/hra/hra.htm. Accessed February 9, 2016

(ARB, 2005): Air Resources Board, ARB/Railroad Statewide Agreement, *Particulate Emissions Reduction Program at California Rail Yards*, June 2005: http://www.arb.ca.gov/railyard/ryagreement/080805fs.pdf. Accessed February 9, 2016.

(ARB, 2011b): Air Resources Board, *Supplement to the June 2010 Staff Report on Proposed Actions to Further Reduce Diesel Particulate Matter at High-Priority California Railyards*, July 2011. http://www.arb.ca.gov/railyard/commitments/suppcomceqa070511.pdf. Accessed February 9, 2016.

(ARB, 2013): Air Resources Board, ARB Almanac Emission Projection Data: *2012 Estimated Annual Average Emissions*. http://www.arb.ca.gov/app/emsinv/2013/emseic_query.php?F_YR=2012&F_DIV=-4&F_SEASON=A&SP=2013&SPN=2013_Almanac&F_AREA=CA&F_EICSUM=820. Accessed February 9, 2016

(UP and BNSF, 2014): Union Pacific and BNSF Railway, Company confidential diesel fuel dispensed within California in 2012 and 2014.

(U.S. EPA, 1998): United States Environmental Protection Agency, *Locomotive Emissions Standards – Regulatory Support Document*, EPA-420-R-98-101, April 1998. http://www.epa.gov/otaq/documents/420r98101.pdf. Accessed February 9, 2016.

(U.S. EPA, 2009): United States Environmental Protection Agency, *Emission Factors for Locomotives*, EPA-420-F-09-025, April 2009. http://www.epa.gov/nonroad/locomotv/420f09025.pdf. Accessed February 9, 2016.

(40 CFR Part 1033.101a): Title 40 Code of Federal Regulations Part 1033.101(a).

Chapter III: Framework for Technology Assessment: Key Performance, Operational, and Economic Considerations

(AAR, 2008): American Association of Railroads, *Manual of Standards and Recommended Practices Section M*, 2008.

(ARB, 2014a): Air Resources Board, ARB Air Quality Planning and Science, *Locomotive Inventory Update: Line Haul Activity*, November 7, 2014. http://www.arb.ca.gov/msei/goods_movement_emission_inventory_line_haul_octworkshop_v3.pdf. Accessed February 9, 2016.

(Bachand, 2006a): Bachand, J., *EMD GP38-2*, June 21, 2006. http://www.thedieselshop.us/Data%20EMD%20GP38-2.HTML. Accessed February 9, 2016.

(Bachand, 2006b): Bachand, J., *EMD SD40 and SD40A*, September 1, 2006. http://www.thedieselshop.us/Data%20EMD%20SD40.HTML. Accessed February 9, 2016.

(Bachand, 2006c): Bachand, J., *EMD SD60 / GMDD SD60F*, October 5, 2006. http://www.thedieselshop.us/Data%20EMD%20SD60.HTML. Accessed February 9, 2016.

(Bachand, 2007a): Bachand, J., *General Electric ES44AC*, October 27, 2007. http://www.thedieselshop.us/Data%20ES44AC.HTML. Accessed February 9, 2016.

(Craig, 2006): Craig, R., *EMD SD70ACe*, September 11, 2006. http://www.thedieselshop.us/Data%20EMD%20SD70ACe.HTML. Accessed February 9, 2016.

(GE, 2016): General Electric, *Comments of GE Transportation on California Air Resources Board's Draft Technology Assessment for Freight Locomotives*, June 15, 2016. Archived by ARB staff, June 16, 2016.

(ICF, 2008), ICF International, *Analysis of Goods Movement Emission Reduction Strategies, Task 1 Final Report*, Prepared for SCAG, January 2008. http://s3.amazonaws.com/zanran_storage/www.scag.ca.gov/ContentPages/509500638.pdf. Accessed February 9, 2016.

(NRE, 2016a): National Railway Equipment, *N-ViroMotive 3GS-21B ULEL Switcher*. http://www.nationalrailway.com/locomotives/new-locomotives/3gs-21b_n-viromotive-3gs-21b-ulel-switcher. Accessed February 22, 2016.

(NRE, 2016b): National Railway Equipment, *N-ViroMotive 3GS-21C ULEL Unit*. http://www.nationalrailway.com/locomotive/n-viromotive-3gs-21c-ulel-unit. Accessed February 22, 2016.

(Tita and Hagerty, 2014): Tita, B. and Hagerty, J., *Caterpillar Falls Behind GE in Locomotives Race*, The Wall Street Journal, July 13, 2014. http://www.wsj.com/articles/caterpillar-falls-behind-ge-in-locomotives-race-1405291739. Accessed February 9, 2016.

(Trainweb, 2002): Trainweb, *D&RGW Modeling: GE Locomotive Lengths*. http://www.trainweb.org/utahrails/drgw/locolengthg.html. Accessed February 22, 2016.

(Trainweb, 2003): Trainweb, *D&RGW Modeling: EMD Locomotive Lengths*. http://www.trainweb.org/utahrails/drgw/locolength.html. Accessed February 9, 2016.

(UP, 2009): Courtesy of Union Pacific Railroad.

(U.S. EPA, 1998): United States Environmental Protection Agency, *Locomotive Emissions Standards – Regulatory Support Document*, EPA-420-R-98-101, April 1998. http://www.epa.gov/otaq/documents/420r98101.pdf. Accessed February 9, 2016.

(Worden et al., 2013): Worden, B., Kumar, A., Malone, M., Coyne, J., Tambe, N., Garule, M., Kumar A., Tractive Effort System and Method, U.S. Patent Application Publication, Pub. No. US2013/0202862 A1, Aug. 15, 2013. http://www.google.com/patents/US20130206862. Accessed February 9, 2016.

(40 CFR Part 1033.101g): Title 40 Code of Federal Regulations Part 1033.101(g).

(40 CFR Part 1033.530): Title 40 Code of Federal Regulations Part 1033.530.

Chapter IV: Development Timelines and Technologies to Meet Current National Locomotive Emisssion Standards

(AAR, 2013): American Association of Railroads, *Total Annual Spending: 2013 Data*, https://www.aar.org/Fact%20Sheets/Safety/2013-AAR_spending-graphic-fact-sheet.pdf. Accessed February 9, 2016.

(Annual Energy Outlook 2014): Annual Energy Outlook, 2014, With Projections to 2040. DOE/EIA-0383(2014), April 2014. http://www.eia.gov/forecasts/archive/aeo14/pdf/0383(2014).pdf. Accessed February 9, 2016.

(ARB, 2006a): Air Resources Board, *Driving Toward Low Emissions*. GE presentation at Semi-Annual Public Meeting to Discuss Future Locomotive Emission Control Measures, July 13, 2006. http://www.arb.ca.gov/railyard/ryagreement/071306lawson.pdf. Accessed February 10, 2016.

(ARB, 2014b): Air Resources Board, Personal communications of ARB staff with manufacturers.

(ARB, 2015b): Air Resources Board, Personal communications of ARB staff with manufacturers.

(ARB, 2015c): Air Resources Board, Personal communications of ARB staff with manufacturers.

(Black and Clough, 2014): Black, T. and Clough, R., *Well-Timed Bet Has GE Ahead of Caterpillar in Locomotives*, September 29, 2014. http://www.newsmax.com/Finance/Companies/GE-Caterpillar-Locomotives-bet/2014/09/29/id/597572/. Accessed February 10, 2016.

(Carvalhaes, 2013): Carvalhaes, B., *Use of Natural Gas in Dash9 (3,000 kW) Locomotives,* in Proceedings of the 10th International Heavy Haul Association Conference, New Delhi, India, February 2013.

(CN, 2012): Canadian National, *CN Tests Natural Gas/Diesel Fuel Powered Locomotives Between Edmonton and Fort McMurray, Alta*., September 27, 2012. http://www.cn.ca/en/news/2012/09/media_news_cn_tests_natural_gas_locomotives_20120927. Accessed February 10, 2016.

(Cotey, 2014): Cotey, A., *Locomotive Engine Upgrades Reflect Pending Emission Regulations, Evolving Fuel Trends*, Progressive Railroading, June 2014. http://www.progressiverailroading.com/rail_industry_trends/article/Locomotive-engine-upgrades-reflect-pending-emission-regulations-evolving-fuel-trends--40689. Accessed February 10, 2016.

(Craig, 2015a): Craig, R., *Burlington Northern Santa Fe Motive Power Fleet*, December 15, 2015. http://www.thedieselshop.us/BNSF.HTML. Accessed February 22, 2016.

(Craig, 2015b): Craig, R., *Norfolk Southern Motive Power*, December 23, 2015. http://www.thedieselshop.us/NS.HTML. Accessed February 22, 2016.

(Craig, 2016a): Craig, R., C*SX Motive Power Summary*, February 8, 2016. http://www.thedieselshop.us/CSX.HTML). Accessed February 22, 2016.

(Craig, 2016b): Craig, R., *Union Pacific Motive Power*, February 8, 2016. http://www.thedieselshop.us/UP.HTML. Accessed February 22, 2016.

(Ditmeyer, 2013): Ditmeyer, S., , *Natural Gas Locomotives.* Presentation by Steve Ditmeyer, Transportation Research Board Mid-Year Meeting: Session on Natural Gas as a Fuel for Freight Transport, July 18, 2013. http://www.slideshare.net/scamay/130718-ditmeyer-natural-gas-locomotives-trb. Accessed February 10, 2016.

(GE, 2009): General Electric, *GE's Evolution Series Locomotive Delivers 6% Fuel Advantage over Competitor*, July 8, 2009. http://www.genewsroom.com/press-releases/ges-evolution-series-locomotive-delivers-6-fuel-advantage-over-competitor-244399. Accessed February 17, 2016.[*]

[*] Over $400 million over 8 years to develop Tier 2.

(GE, 2014): General Electric, *NextFuel™ Natural Gas* (GE Proprietary), September 3, 2014. Archived by ARB staff, October 20, 2014.

(Hitachi, 2005): Hitachi, *Hitachi Construction Machinery, Common Rail Type Fuel Injection System*. http://www.hitachi-c-m.com/asia/products/excavator/medium/zx225usr-3/feature_1.html. Accessed February 10, 2016.

(Indiana Harbor Belt, 2014): Indiana Harbor Belt, *Indiana Harbor Belt Railroad Announces Qualified Potential Vendors eligible to bid on future Request for Proposals of 31 Locomotives to Natural Gas*, February 10, 2016. http://www.ihbrr.com/IHB%20Qualification%20Announcement.pdf.

(Indiana Harbor Belt, 2015): Indiana Harbor Belt, *About the Indiana Harbor Belt Railroad*, http://www.ihbrr.com/. Accessed February 10, 2016.

(Locomotive Wiki, 2015): Locomotive Wiki, *GE ES44AC*, 2015. http://locomotive.wikia.com/wiki/GE_ES44AC. Accessed February 10, 2016.

(Myers, 2014a): Myers, L., *Juniata Diesel Conversions GP50 to RP-E4C CNG Slug/Tender for Norfolk Southern*, 2014. http://www.altoonaworks.info/rebuilds/ns_cngslugtender.html. Accessed February 10, 2016.

(Office of the Federal Coordinator, 2013): Office of the Federal Coordinator, Alaska Natural Gas Transportation Projects, *Liquefaction Plant Single Largest Cost for Alaska LNG Project*, June 4, 2013. http://www.arcticgas.gov/liquefaction-plant-single-largest-cost-alaska-lng-project. Accessed February 10, 2016.

(Piellisch, 2013a): Piellisch, R., *CN Orders Westport LNG Tenders*, June 5, 2013. http://hhpinsight.com/rail/2013/06/cn-orders-lng-tenders-from-westport/. Accessed February 10, 2016.

(Piellisch, 2013b): Piellisch, R., *31 Chicago-Area Locomotives on CNG*, October 28, 2013. http://hhpinsight.com/rail/2013/10/31-locomotives-on-cng/. Accessed February 10, 2016.

(Piellisch, 2013c): Piellisch, R., *Vintage Train Saving More with CNG*, July 22, 2013. http://hhpinsight.com/rail/2013/07/vintage-train-saving-more-with-cng/. Accessed February 10, 2016.

(Piellisch, 2015): Piellisch, R., *Westport Innovations: Westport Throttles Back on LNG Tenders*, March 11, 2015. http://hhpinsight.com/tag/westport-innovations. Accessed February 10, 2016.

(Railway Strategies, 2008): Railway Strategies, *New MTU Series 400 Rail Diesel Engine: Cleaner and Even More Powerful*, April-May 2008. http://www.railwaystrategies.co.uk/article-page.php?contentid=5294&issueid=200. Accessed February 10, 2016.

(RR Picture Archives, 2005): RR Picture Archives, *BNSF 5815*. http://www.rrpicturearchives.net/Locopicture.aspx?id=49231. Accessed February 10, 2016.

(RR Picture Archives, 2010a): RR Picture Archives, *NVRR 73*. Photo contributed by Stephie Kolata, August 7, 2010. http://www.rrpicturearchives.net/locopicture.aspx?id=55299. Accessed February 10, 2016.

(RR Picture Archives, 2014b): RR Picture Archives, *BNSF 933501 (Tank Car)*. Photo contributed by Jeff Carlson, February 2014. http://www.rrpicturearchives.net/showPicture.aspx?id=3753327. Accessed February 10, 2016.

(RR Picture Archives, 2015): RR Picture Archives, *EMD Order 20026404 Details*, http://www.rrpicturearchives.net/orderList.aspx?order=20026404&mfg=EMD. Accessed February 10, 2016.

(RR Picture Archives, 2016a): RR Picture Archives, Build information for BNSF 9130. http://www.rrpicturearchives.net/Locopicture.aspx?id=94748. Accessed February 12, 2016.

(RR Picture Archives, 2016b): RR Picture Archives, Build information for BNSF 9131. http://www.rrpicturearchives.net/locoPicture.aspx?id=93615. Accessed February 10, 2016.

(Smith, 2014): Smith, Kevin, *Westport Delivers First LNG Tender to EMD*, Railway Age, April 11, 2014. http://www.railwayage.com/index.php/mechanical/locomotives/westport-delivers-first-lng-tender-to-emd.html. Accessed February 16, 2016.

(Stagl, 2014a): Stagl, J., *Indiana Harbor Belt Railroad Adopts Compressed Natural Gas as a Locomotive Fuel Alternative*, Progressive Railroading, February, 2014 http://www.progressiverailroading.com/mechanical/article/Indiana-Harbor-Belt-Railroad-adopts-compressed-natural-gas-as-a-locomotive-fuel-alternative--39401. Accessed February 10, 2016.

(SwRI, 2008): Southwest Research Institute, *Locomotive Exhaust Emissions Test Report: MK1200G*, January 2008. Archived by ARB staff, June 5, 2014.

(The Diesel Shop, 2015): The Diesel Shop, *GE Demonstrators, Proto-types & Test Beds*, March 27, 2015. http://www.thedieselshop.us/GEdemo2.HTML. Accessed February 10, 2016.

(Trainorders, 2013): Trainorders, *GE Test Train (GECX 2021 and 2022)*, August 6, 2013. http://www.trainorders.com/discussion/read.php?2,3148195,3148195#msg-3148195. Accessed February 22, 2016.
(Trainorders, 2014a): Trainorders, *CSX Q 357 New GECX 2023-2024 Tier 4 Test Units Willard,* March 7, 2014. http://www.trainorders.com/discussion/read.php?2,3345315,3345315#msg-3345315. Accessed February 22, 2016.

(Trainorders, 2014b): Trainorders, *BNSF & GE Gas Test Units BNSF 5815 – NextFuel GE 3000*, April 24, 2014. http://www.trainorders.com/discussion/read.php?2,3390862,3390862. Accessed February 10, 2016.

(Trainorders, 2015): Trainorders, *GE Tier 4 Status Questions*, June 19, 2015. http://www.trainorders.com/discussion/read.php?2,3772933,3773551#msg-3773551. Accessed February 22, 2016.

(Trains, 2015): Trains, *New Locomotive Deliveries Begin in 2015 with 'Credit User' Provision*, January 30, 2015. http://trn.trains.com/news/news-wire/2015/01/new-locomotive-deliveries-begin-in-2015-with-credit-user-provision. Accessed February 10, 2016.

(UP, 2013b): Union Pacific, *LNG as Railroad Fuel*. Presentation by Mike Iden, High Horsepower Conference, Chicago, September 2013.

(UP, 2016): Union Pacific, *Union Pacific and Liquefied Natural Gas (LNG)*. https://www.up.com/cs/groups/public/@uprr/documents/up_pdf_nativedocs/pdf_up_emg_lng_facts.pdf. Accessed March 30, 2016.

(U.S. EPA, 1998): United States Environmental Protection Agency, *Locomotive Emissions Standards – Regulatory Support Document*, EPA-420-R-98-101, April 1998. http://www.epa.gov/otaq/documents/420r98101.pdf. Accessed February 9, 2016.

(U.S. EPA, 2007): United States Environmental Protection Agency, *Draft Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression-Ignition Engines Less than 30 Liters per Cylinder*, EPA420-D-07-001, March 2007, pp. 4-11 and 4-12. http://www.epa.gov/nonroad/420d07001chp4.pdf. Accessed February 10, 2016.

(U.S. EPA, 2008): United States Environmental Protection Agency, *Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less than 30 Liters Per Cylinder*, EPA420-R-08-001a, May 2008, pp. 1-50 and 1-51. http://permanent.access.gpo.gov/gpo48262/ZyPDF.pdf. Accessed February 10, 2016.[*]

(Vantuono, 2013): Vantuono, W., *A Closer Look at LNG*, Railway Age, November 8, 2013. http://www.railwayage.com/index.php/mechanical/locomotives/a-closer-look-at-lng.html. Accessed February 10, 2016.

(Vantuono, 2014): Vantuono, W., *Four Paths to Natural Gas*, Railway Age, November 12, 2014. http://www.railwayage.com/index.php/mechanical/locomotives/four-paths-to-natural-gas.html. Accessed February 10, 2016.

Chapter V: Basis for Tighter National Locomotive Emission Standards

(AAR, 2008): American Association of Railroads, *Manual of Standards and Recommended Practices Section M*, 2008.

(ARB, 2008): Air Resources Board, *Update on the Implementation of the 2005 ARB/Railroad Statewide Agreement*, April 11, 2008. http://www.arb.ca.gov/railyard/ryagreement/041108rpt.pdf. Accessed February 10, 2016.

(ARB, 2011c): Air Resources Board, Verification Letter for PR30C Locomotive Emission Test Data, September 14, 2011.

(ARB, 2015d): Air Resources Board, *Locomotive Technology Demonstrations and Emissions Verifications*, April 8, 2015. http://www.arb.ca.gov/railyard/demover/locotech.htm. Accessed February 10, 2016.

(Businesswire, 2007): Businesswire, *ESW Canada Selected as Consortium Member for GE Locomotive Retrofit Program*, November 9, 2007. http://www.businesswire.com/news/home/20071109005062/en/ESW-Canada-Selected-Consortium-Member-GE-Locomotive#.VIdnxha0KBU. Accessed February 10, 2016.

[*] The cost of a locomotive can vary between $1.5 million to $2.2 million, depending on the configuration and options installed. Figure 1-1-7 on p. I-51 shows data from the AAR's Railroad Ten-Year Trends 1995-2004 publication. Some of the variation from year to year can be attributed to differences in features, but it appears the overall trend in the price of AC locomotives is downward, while DC locomotive pricing remains steady. ARB staff estimates that new Tier 2 line haul locomotives from model-years 2005-2011, especially DC were slighting higher due to new equipment such as electronic fuel injection, enhanced cooling, and systems integration costs.

(Craig, 2012): Craig, R., *PR30C Production List & Technical Data*, December 18, 2012. http://www.thedieselshop.us/PR30C%20data.HTML. Accessed February 10, 2016.

(EF&EE, 2010a): Engine, Fuel, and Emissions Engineering, Inc., *Demonstration of Compact SCR™ in a Passenger Locomotive*, Final Report to SCAQMD and TERC, December 7, 2010. http://files.harc.edu/Sites/TERC/NTRD/Projects/N011FinalReport.pdf. Accessed February 10, 2016.

(EF&EE, 2010b): Engine, Fuel, and Emissions Engineering, Inc., *Demonstration of Selective Catalytic Reduction with Diesel Particulate Filters on a Passenger Ferry*. Presentation to ARB for Chair's Seminar Series, July 7, 2010. http://www.arb.ca.gov/research/seminars/weaver/weaver.pdf. Accessed February 10, 2016.

(EV World, 2010): EV World, *Hybrid Locomotives Have Bright Future*, October 28, 2010. http://evworld.com/news.cfm?newsid=24252. Accessed February 22, 2016.

(GE, 2005): General Electric, *Hybrid Locomotive: A Product of GE Ecomagination* Product Information Sheet. Archived by ARB staff, September 13, 2011.

(GE, 2016): General Electric, *Comments of GE Transportation on California Air Resources Board's Draft Technology Assessment for Freight Locomotives*, June 15, 2016. Archived by ARB staff, June 16, 2016.

(GE Global Research, 2014): General Electric Global Research, Tier 4 Locomotive Achieves Stringent Emission Standards, 2014. http://www.geglobalresearch.com/innovation/tier-4-locomotive-achieves-stringent-emission-standards. Access February 10, 2016.

(LMOA, 2013): Locomotive Maintenance Officers Association, Proceedings of the 75th Annual Meeting, September 30 – October 1, 2013, Indianapolis, IN. http://www.lmoarail.com/wp-content/uploads/2014/10/LMOA2013-Book-WEB-Final.pdf. Accessed February 10, 2016.

(Progressive Railroading, 2012): Progressive Railroading, *April 24: Updates from Progress Rail, IAS, Cubic and Auto Truck*, April 24, 2012. http://www.progressiverailroading.com/prdailynews/news.asp?id=30772. Accessed February 10, 2016.

(Railway Gazette, 2007): Railway Gazette, *GE Unveils Hybrid Locomotive*, Railway Gazette, July 2, 2007. http://www.railwaygazette.com/news/single-view/view/ge-unveils-hybrid-locomotive.html. Accessed February 11, 2016.

(SDTC, 2015): Sustainable Development Technology Canada, *Clean Diesel Locomotive Program*, 2015. https://www.sdtc.ca/en/portfolio/projects/clean-diesel-locomotive-program. Accessed February 10, 2016.

(SMAQMD et al., 2012): Sacramento Metropolitan Air Quality Management District, Electro-Motive Diesel Inc., and Union Pacific, *EMD Tier 4 (PM) Aftertreatment Upgrade on a Line Haul Locomotive*, Final Report, August 31, 2012. http://www.arb.ca.gov/railyard/docs/final_report_emd_tier_4_pm_aftertreatment_upgrade_83112_final_v1.pdf. Accessed February 10, 2016.

(SwRI, 2007): Southwest Research Institute, *ARB Locomotive Project: Selective Catalytic Reduction (SCR) efforts with EMD 710 Engine*, November 28, 2007. (http://www.arb.ca.gov/railyard/ryagreement/112807fritz.pdf). Accessed February 10, 2016.

(Trainorders, 2007), Trainorders, *GECX 2010...The Evolution Series Hybrid is here...*, April 27, 2007. http://www.trainorders.com/discussion/read.php?1,1394157,page=3. Accessed March 31, 2016.

(Trainweb, 2002): Trainweb, *D&RGW Modeling: GE Locomotive Lengths*. http://www.trainweb.org/utahrails/drgw/locolengthg.html. Accessed February 22, 2016.

(Trainweb, 2003): Trainweb, *D&RGW Modeling: EMD Locomotive Lengths*. http://www.trainweb.org/utahrails/drgw/locolength.html. Accessed February 9, 2016.

(U.S. EPA, 2008): United States Environmental Protection Agency, *Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less than 30 Liters Per Cylinder*, EPA420-R-08-001a, May 2008, pp. 1-50 and 1-51. http://permanent.access.gpo.gov/gpo48262/ZyPDF.pdf. Accessed February 10, 2016.

Chapter VI: Battery Technologies to Power Locomotives

(ARB, 2006b): Air Resources Board, Verification Letter for Green Goat GG20, December 13, 2006.

(ARB, 2008): Air Resources Board, *Update on the Implementation of the 2005 ARB/Railroad Statewide Agreement*, April 11, 2008. http://www.arb.ca.gov/railyard/ryagreement/041108rpt.pdf. Accessed February 10, 2016.

(ARB, 2009): Air Resources Board, *Technical Options to Achieve Additional Emissions and Risk Reductions from California Locomotives and Railyards*, August 2009 (Technical Options Document). http://www.arb.ca.gov/railyard/ted/083109tedr.pdf. Accessed February 9, 2016.

(CALSTART, 2013): CALSTART, Inc., *I-710 Project Zero-Emission Truck Commercialization Study Final Report*, Pasadena, CA, November 20, 2013. http://www.calstart.org/Libraries/I-710_Project/I-710_Project_Zero-Emission_Truck_Commercialization_Study_Final_Report.sflb.ashx. Accessed February 10, 2016.

(CE Delft, 2013): CE Delft, *Zero Emission Trucks: An Overview of State-of-the-Art Technologies and Their Potential*, July 2013. http://www.theicct.org/sites/default/files/publications/CE_Delft_4841_Zero_emissions_trucks_Def.pdf. Accessed February 10, 2016.

(EERE, 2005): Office of Energy Efficiency & Renewable Energy, National Idling Reduction Network News, *Nation's First Hybrid Locomotive Gets to Work in California*, April 2005. http://www1.eere.energy.gov/vehiclesandfuels/pdfs/idling_news/apr05_network_news.pdf. Accessed February 10, 2016.

(GE, 2005): General Electric, *Hybrid Locomotive: A Product of GE Ecomagination* Product Information Sheet. Archived by ARB staff, September 13, 2011.

(GE, 2015), General Electric, *GE Energy Storage: Durathon Batteries: Battery Power, Reimagined*, Brochure #20194-A. http://docslide.us/documents/gedurathonbrochure.html. Accessed February 17, 2016.

(Moore, 2008): Moore, J., *Railpower Technologies Corp. Green Goat Hybrid Locomotive Roster*, March 12, 2008. http://www.trainweb.org/greengoats/features/Hybrid_Roster.pdf. Accessed February 22, 2016.

(Myers, 2014b): Myers, L., *Juniata Battery-Powered Yard Locomotive*, 2014. http://www.altoonaworks.info/built/jbs/ns_bp4.html. Accessed February 11, 2016.

(Norfolk Southern, 2009): Norfolk Southern, *BizNS*, Vol. I, Issue 6, Nov-Dec., 2009. http://www.nscorp.com/nscorphtml/bizns/bizNS1-6.pdf. Accessed February 11, 2016.

(Petersen, 2012): Petersen, J., *Axion Power – A Battery Manufacturer Charging Forward*. November 18, 2012. http://www.nasdaq.com/article/axion-power-a-battery-manufacturer-charging-forward2-cm191648. Accessed February 22, 2016.

(Progressive Railroading, 2005): Progressive Railroading, *BNSF to lease five Green Goat switchers from RailPower*, June 16, 2005. http://www.progressiverailroading.com/mechanical/news/BNSF-to-lease-five-Green-Goat-switchers-from-RailPower--8423. Accessed February 11, 2016.

(Railpower, unknown date): Railpower, *Diagram of a Green Goat Switch (Yard) Locomotive*. Archived by ARB staff, June 17, 2009

(Railway Gazette, 2007): Railway Gazette, *GE Unveils Hybrid Locomotive*, Railway Gazette, July 2, 2007. http://www.railwaygazette.com/news/single-view/view/ge-unveils-hybrid-locomotive.html. Accessed February 11, 2016.

(R.J. Corman, 2016): R.J. Corman, *RP Series Product Line*, 2016. http://www.rjcorman.com/railpower/products.html. Accessed February 11, 2016.

(RR Picture Archives, 2007): RR Picture Archives, *UPY 2315*. Photo contributed by Paul S. Highland, January 18, 2007. http://www.rrpicturearchives.net/showPicture.aspx?id=628390. Accessed February 11, 2016.

(Shulock and Pike, 2011): Shulock, C. and Pike, E., *Vehicle Electrification Policy Study, Task 1 Report: Technology Status,* The International Council on Clean Transportation, February 2011. http://www.theicct.org/vehicle-electrification-policy-study-task-1-%E2%80%94-technology-status. Accessed February 11, 2016.

(Trainweb, 2015a): Trainweb, *GG20B "Green Goat Switchers*, 2015. http://www.trainweb.org/greengoats/gg20b.html. Accessed February 11, 2016.

(Trainweb, 2015b): Trainweb, *GK10B "Green Kid" Switchers*, 2015. http://www.trainweb.org/greengoats/gk10b.html. Accessed February 11, 2016.

(Trainweb, 2015c): Trainweb, *GG10B "Green Kid" Switchers*, 2015. http://www.trainweb.org/greengoats/gg10b.html. Accessed February 11, 2016.

(Transpower, 2012): Transpower, *Transpower RailServer – Battery Tender Car*. Archived by ARB staff, April 2, 2012.

(Transpower, 2013): Transpower, *Rail-Saver™: A Battery Fuel Car for Zero Emission Rail Transportation*. Transpower presentation at Transitioning to Zero-Emission Freight Transport Technologies Symposium, April 11, 2013.

(Wong, 2009): Wong, V., *All Aboard the Eco-Express: Rail's Hybrid Energy Solutions*, Scientific American, August 6, 2009. http://www.scientificamerican.com/article/eco-express-hybrid-railroad/. Accessed February 11, 2016.

(4rail, 2015a): 4rail, *Rolling Stock – GE ES44AC, ES44DC and ES44C4*, 2015. http://4rail.net/reference_rollingstock_ge_es44acdc.html. Accessed February 11, 2016.

Chapter VII: Fuel Cell Technologies to Power Locomotives

(Department of Energy, 2016): Department of Energy, Office of Energy Efficiency & Renewable Energy (EERE), *Solid Oxide Fuel Cells*, 2015. http://energy.gov/eere/fuelcells/types-fuel-cells. Accessed February 11, 2016.

(EERE, 2010): Office of Energy Efficiency & Renewable Energy Information Center, Fuel Cell Technologies Program, *Fuel Cell Fact Sheet*, November 2010. http://energy.gov/sites/prod/files/2014/03/f10/fct_h2_fuelcell_factsheet.pdf. Accessed February 11, 2016.

(Fuel Cells 2000, 2015): Fuel Cells 2000, *Types of Fuel Cells*, 2015. http://www.fuelcells.org/base.cgim?template=types_of_fuel_cells. Accessed February 11, 2016.

(FuelCellToday, 2012): FuelCellToday, *Fuel Cell Basics: Technology Types*, May 2012. http://www.fuelcelltoday.com/media/1637138/fc_basics_technology_types.pdf. Accessed February 11, 2016.

(Hess, 2010): Hess, K., *Demonstration of a Hydrogen Fuel Cell Locomotive*, APTA 2010 Rail Conference, Vancouver, June 7, 2010. http://www.apta.com/mc/rail/previous/2010/Presentations/EET-Hess-rail10.pdf. Accessed February 11, 2016.

(Martinez et al., 2012a): Martinez, A., Brower, J., Samuelsen, G., *Feasibility Study for SOFC-GT Hybrid Locomotive Power, Part I – Development of a Dynamic 3.5 MW SOFC-GT FORTRAN Model*. Journal of Power Sources, (213) 203-217, 2012.

(Martinez et al., 2012b): Martinez, A., Brower, J., Samuelsen, G., *Feasibility Study for SOFC-GT Hybrid Locomotive Power, Part II – System Packaging and Operating Route Simulation*. Journal of Power Sources, (213) 358-374, 2012.

(Miller, 2006): Miller, A., *FuelCell Hybrid Switch Locomotive: Project Status as of December 4, 2006*, Vehicle Projects LLC, 2006. Archived by ARB staff, December 18, 2006.

(Miller et al., 2007): Miller, A., Hess, K., Barnes, D., and Erickson, T., *System Design of a Large Fuel Cell Hybrid Locomotive*, Journal of Power Sources, (173) 935-942, 2007. http://www.vehicleprojects.com/docs/System%20design_Manuscript%20_06%20Sep%2007_.pdf. Accessed February 11, 2016.

(RR Picture Archives, 2010b): RR Picture Archives, *BNSF (GG20B)*. Photo contributed by Scott Garcia, February 24, 2010. http://www.rrpicturearchives.net/showPicture.aspx?id=2114946. Accessed February 11, 2016.

(Samuelsen and Brouwer, 2008): Samuelsen, G. and Brouwer, J., *SOFC-GT Systems for Locomotives Associated with Port Operations*, National Fuel Cell Research Center, University of California, Irvine, May 19, 2008.

(Smithsonian Institute, 2015): Smithsonian Institute, The National Museum of American History, *Fuel Cell Basics: What Is a Fuel Cell?*, http://americanhistory.si.edu/fuelcells/basics.htm. Accessed February 11, 2016.

(Trainweb, 2015d): Trainweb, *BNSF Fuel Cell-Hybrid HH20B BNSF 1205*, 2015. http://www.trainweb.org/greengoats/bnsf/1205.html. Accessed February 11, 2016.

(University of Cambridge, 2015): University of Cambridge, *Solid oxide fuel cells (SOFCs)*, 2015. http://www.doitpoms.ac.uk/tlplib/fuel-cells/high_temp_sofc.php. Accessed February 11, 2016.

(Vehicle Projects, 2016): Vehicle Projects, Inc., Our Projects, 2016. http://www.vehicleprojects.com/projects.html. Accessed February 17, 2016.

Chapter VIII: Freight Railroad Electrification in California

(AAR et al., 2008): American Association of Railroads, BNSF Railway, Union Pacific, and Pacific Harbor Lines, *Railroad Letter to Supervisor Gary Ovitt*, February 15, 2008. Archived by ARB staff, October 17, 2008.

(Bhargava, 1999): Bhargava, B., *Railway Electrification Systems and Configurations*, SoCal Edison, Institute of Electrical and Electronics Engineers (IEEE), 1999.

(Bombardier, 2007): Bombardier, *Bombardier is Awarded an Additional Order for One of the World's Most Powerful Electrical Locomotives*, August 23, 2007. http://www.bombardier.com/en/media-centre/newsList/details.1137-bombardier-is-awarded-an-additional-order-for-one-of-the-worlds-most-powerful-electrical-locomotives.bombardiercom.html?filter-bu=transport. Accessed February 10, 2016.

(Caltrain, 2016): Caltrain, *Caltrain 2020 Modernization*, 2016. http://www.caltrain.com/projectsplans/CaltrainModernization/Modernization.html. Accessed February 10, 2016.

(Gormick, 2009): Gormick, G., *A Growth Industry Picks Up Speed*, Railway Age, March 2009. http://www.nxtbook.com/nxtbooks/sb/ra0309/. Accessed February 10, 2016.

(Iden, 2013): Iden, M., *Freight Railroad Energy: Alternatives & Challenges*, William W. Hay Railroad Engineering Seminar, February 15, 2013. http://railtec.illinois.edu/cee/seminars/UP-Iden%20Seminar%202013Feb15.pdf. Accessed February 10, 2016.

(Modern Railways, 2013): Modern Railways, *Beacon Rail and DRS Order Dual-Mode Locos*, Modern Railways, September 12, 2013. http://www.modern-railways.com/view_article.asp?id=6788. Accessed February 10, 2016.

(NJ Transit, 2011): New Jersey Transit, *NJ Transit Unveils First Dual-Powered Locomotive*, May 11, 2011. http://www.njtransit.com/tm/tm_servlet.srv?hdnPageAction=PressReleaseTo&PRESS_RELEASE_ID=2677. Accessed February 10, 2016.

(Pernička, 2008): Pernička, J., *Electro-Diesels for New Jersey and Montreal*, Railvolution, No. 6/10, 2008. https://library.e.abb.com/public/2cb85de0f43836f3c12578260051d829/Railvolution06-10-Traction-transformer.pdf. Accessed February 10, 2016.

(Railcolor, 2013): Railcolor, *Vossloh Try-Outs: News: DRS Is Launching Customer for Vossloh Dual Mode*, September 12, 2013. http://www.railcolor.net/index.php?nav=1409453&lang=1#.VfHGGk3luUl. Accessed Accessed February 10, 2016.

(Railway Gazette, 2010): Railway Gazette, *NJ Transit Approves FY2011 Spending*, Railway Gazette, July 19, 2010. http://www.railwaygazette.com/news/single-view/view/nj-transit-approves-fy2011-spending.html. Accessed February 10, 2016.

(SCAG, 2008): Southern California Association of Governments, *Regional Transportation Plan*, 2008. http://rtpscs.scag.ca.gov/Documents/2008/fGoods_Movement.pdf. Accessed February 17, 2016.

(SCRRA, 1992): Southern California Regional Rail Authority, *Southern California Accelerated Rail Electrification Program*, February 10, 1992. http://libraryarchives.metro.net/DPGTL/Metrolink/1992-ExecSummary-SoCal-Accelerated-Rail-Electrification.pdf. Accessed February 10, 2016.

(Vantuono, 2008): Vantuono, W., *NJT, AMT Ready for Dual-Power Locomotives*, Railway Age, August 2008. http://www.nxtbook.com/nxtbooks/sb/ra0808/#/20. Accessed February 10, 2016.

(Vitins, 2013): Vitins, J., *Dual-mode and all-electric U.S. freight line haul locomotives*, Freight Transport Technologies Symposium, Diamond Bar, California, April 2013. Archived by ARB staff, April 8, 2013.

Chapter IX: Locomotive Emissions Capture and Control Systems

(ARB, 2009): Air Resources Board, *Technical Options to Achieve Additional Emissions and Risk Reductions from California Locomotives and Railyards*, August 2009 (Technical Options Document). http://www.arb.ca.gov/railyard/ted/083109tedr.pdf. Accessed February 9, 2016.

(TIAX, 2007): TIAX LLC, *Evaluation of the Advanced Locomotive Emissions Control System (ALECS)*, Report to Placer County Air Pollution Control District, April 2, 2007. http://www.placer.ca.gov/~/media/apc/documents/UP/2007/April/ALECSFinalReport040507.pdf. Accessed February 9, 2016.

This page left intentionally blank

Appendix B: University of Illinois Report, Executive Summary

The objective of this research, commissioned by the ARB, is to identify and examine the operational changes and economic challenges and opportunities associated with a transition from conventional diesel-electric to zero or near-zero emission line-haul freight rail operations in California.

To accomplish this objective, the research presented in this report assesses and compares the operations and economic impacts of different zero or near-zero emission locomotive technology on line-haul mainline freight railroads. For the purposes of this study, mainline line-haul freight operations are defined as trains operating on Class 1 railroad mainlines directly between origin and destination terminals.

There are two different deployment scenarios analyzed in this report:

- A South Coast Air Basin (SCAB) deployment scenario, with a smaller captive fleet of advanced technology freight locomotives.
- A North American deployment scenario, with a national fleet of advanced technology locomotives.

In the near- to mid-term, the research showed that the North American deployment of Tier 4 diesel-electric locomotives with after-treatment and onboard battery storage technology offers the best economics of any alternatives studied in this report. While this technology is not yet commercialized, prototypes of the various systems exist and have been demonstrated in service.

In the longer-term, the Solid Oxide Fuel Cell (SOFC) gas turbine locomotive with liquefied natural gas (LNG) fuel appears to offer potential for North American deployment within the larger locomotive fleet. However, further research is needed to determine if it is feasible to construct a 4,400 horsepower freight interstate line haul locomotive powered by SOFC-gas turbine technology.

The research also showed that North American deployment of these two locomotive technologies offer improved economics relative to operation with exchange points in the South Coast Air Basin or the state of California. Although North American deployment requires the purchase of more alternative technology locomotives, they realize fuel savings over longer train runs and are not hindered by the capital cost, train delay, and lost revenue associated with locomotive exchange points.

Locomotive Technology

SCAB Deployment Scenario: For the SCAB deployment scenario, this research considered six different locomotive technologies:

- Tier 4 diesel-electric with after-treatment
- Liquefied natural gas with fuel tenders (Diesel-LNG)
- Diesel-electric with battery tenders and onboard battery storage
- Solid-oxide fuel cell (SOFC)
- Electric traction from catenary electric power supply
- Linear synchronous motors (LSM)

This scenario is discussed in Chapters 1-12.

North American Deployment Scenario: For the North American national fleet deployment scenario, two technologies were considered:

- Tier 4 diesel-electric with both after-treatment and onboard batteries, and the
- Solid Oxide Fuel Cell with Gas Turbine (SOFC-GT), which was assessed in both the SCAB captive fleet and North American deployment scenarios.

This scenario is discussed in Chapter 13.

For each locomotive technology, through literature review and consultation with industry experts, the study team examined the potential energy and emissions reductions; economic and operational considerations; and current state of development. Safety of the new locomotive technology is also critical for adoption by the railroads.

It was found that there is no "off the shelf" zero or near-zero emission locomotive technology for North American line-haul freight service. All of the studied locomotive technologies require additional research, development or commercialization before they can be implemented in line-haul service:

- Line-haul Tier 4 diesel-electric locomotives entered production in 2015 but locomotives with additional after-treatment to further reduce emissions are still in experimental stages of development. It is not known how far below Tier 4 levels emissions can be reduced through a combination of further diesel combustion process refinements and additional after-treatment.
- Diesel-LNG locomotives are still in demonstration and test service and the ability of diesel-LNG to achieve additional emissions reductions below Tier 4 levels is not known. Although prototypes exist, standards for LNG tenders are still under development.
- Battery tenders for line-haul freight service are a concept with no working prototypes.
- There are no working SOFC line-haul locomotive prototypes. Other types of fuel cell locomotives have only been demonstrated in switching service.
- Further development is required to design, test and commercialize a modern line-haul electric freight locomotive tailored for operation in the United States.
- Although applied to transit, LSM has not been demonstrated for freight service and it is not known if the technology has the capability to handle the length and weight of typical freight train consists.

It was determined that the most likely implementation scenario for any of the above locomotive technologies within the South Coast is operation of a captive fleet of new technology locomotives within the basin and conventional diesel-electric locomotives outside the basin. Trains entering and exiting the basin must exchange new technology and conventional diesel-electric locomotives at a locomotive exchange point facility near the boundary of the air basin.

Line-Haul Freight Interoperability

The North American Class 1 railroads have continually worked to remove barriers that prevent the seamless movement of freight. Operation with exchange points and a captive fleet in the South Coast reintroduces those barriers. Based on experience with captive fleets and lack of interoperability in Europe, operation with exchange points in the South Coast is likely to result in: increased operating costs, delays and network disruption due to locomotive exchange; decreased locomotive utilization, increased locomotive fleet size and the capital cost of establishing extra regional alternative-technology locomotive maintenance, servicing and fueling facilities. According to the European experience, the net result of these outcomes will likely be a decrease in freight rail market share.

Line-Haul Freight Operations

UP and BNSF operate approximately 130 line-haul freight trains in the South Coast basin each day. At any moment, over 2,000 locomotives from a much larger pool of nearly 10,000 locomotives are allocated to operating trains that originate, terminate or transit the South Coast basin. Based on detailed analysis of STB waybill data, trains originating or terminating in the South Coast basin transport approximately 99 million tons of freight each year. Train data derived from the waybill sample and route data from railroad engineering track charts were used with a train performance calculator to determine the energy consumption of each train operating in the South Coast. Each year line-haul freight train operation in the South Coast consumes approximately 435,000 MWh of energy at the locomotive wheel.

Emissions Benefits

Since this analysis considers local emissions, the three technologies that utilize electricity as an energy source are considered to be zero-emissions, resulting in 100-percent reduction of all criteria pollutants. Over 743 million pounds of CO_2 emissions are potentially eliminated each year within the South Coast basin by any of these three technologies.

Implementation of Tier 4 diesel-electric locomotives with after-treatment does not change CO_2 or CO levels. Although 80 to 90 percent reductions below Tier 2 levels can be achieved, decreases in the emissions of the other criteria pollutants relative to Tier 4 levels will depend on the effectiveness of the exact after-treatment technologies employed.

The diesel-LNG locomotives decrease CO_2 emissions due to the lower carbon content of LNG but increase CO due to decreased fuel efficiency. Approximately 53 million pounds of CO_2 emissions are potentially eliminated each year within the South Coast basin by diesel-LNG technology.

The efficiency of the SOFC-gas turbine with LNG allows this technology to provide the greatest emission benefits of the liquid fuels. The SOFC-gas turbine has the potential to eliminate 423 million pounds of CO_2 emissions each year, representing a 57-percent reduction (Figure S-1 and Figure S-2).

Based on ARB estimates, the Tier 4 diesel with after-treatment would provide an estimated reduction in NOx and PM emissions, beyond the Tier 4 baseline, of up to 75 percent (i.e., Tier 4 NOx = 1.3 to 0.3 g/bhp-hr) for South Coast and North American deployment.

For the North American deployment scenario (Table S.1), a Tier 4 diesel with after-treatment and on-board batteries is assumed to currently be able to reduce fuel consumption by 15 percent. In the future, ARB staff believes by as early as 2025, advances in onboard battery technology could reduce diesel fuel consumption by up to 25 percent. This latter level of fuel reduction could further reduce NOx and PM emissions, beyond the Tier 4 baseline, by up to a total of 85 percent (i.e., Tier 4 NOx = 1.3 to 0.2 g/bhp-hr).

Table S.1: Potential Percent Emissions Reduction Control Levels from Tier 4 Baseline for North American Deployment

Technology	NOx Reductions	PM Reductions
SOFC-GT w/ LNG	50	50
Tier 4 Diesel w/ After-T	75	75
Tier 4 Diesel w/ After-T & Battery	85	85

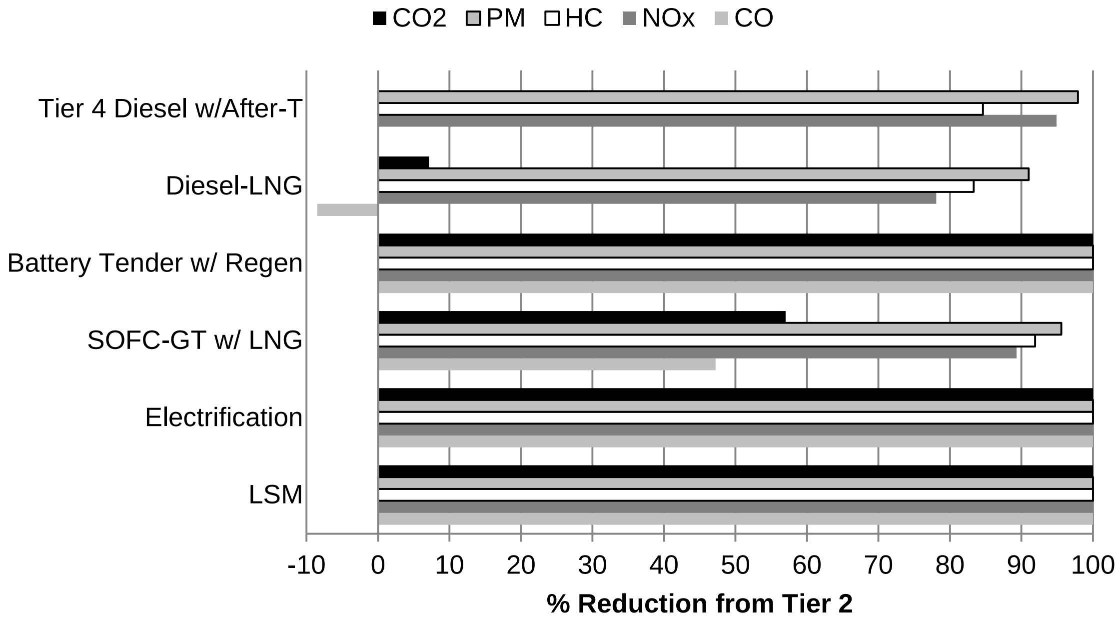


Figure S-1, Potential reduction in South Coast line-haul locomotive emissions from Tier 2 baseline

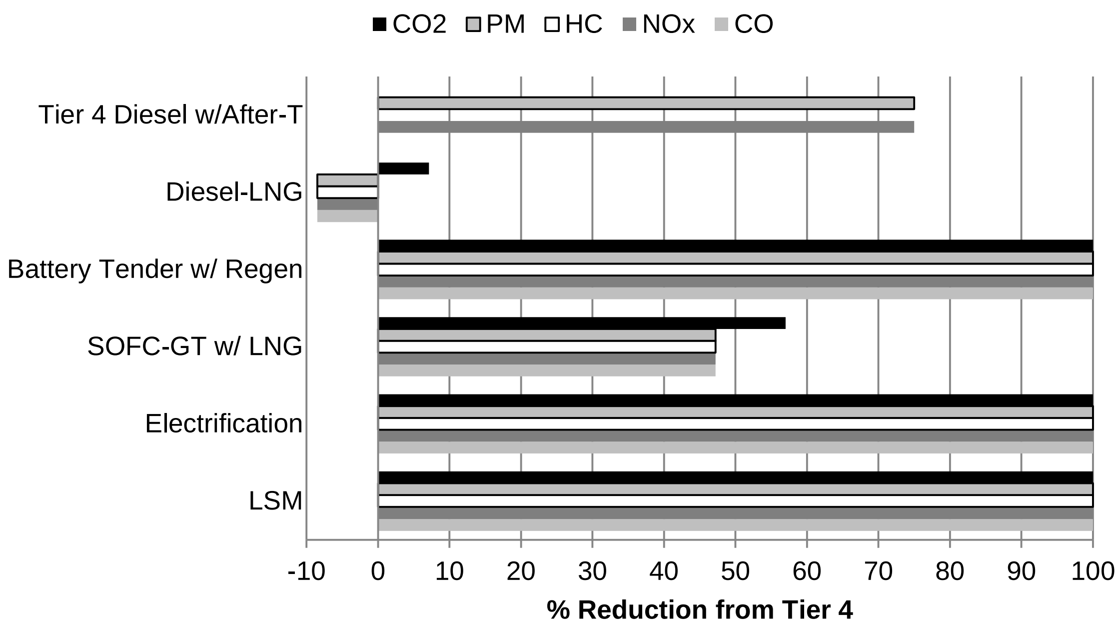


Figure S-2, Potential reduction in South Coast line-haul locomotive emissions from Tier 4 baseline

Locomotive Costs

Operation of a captive locomotive fleet within the South Coast requires 570 new technology locomotives. Depending on the technology, these locomotives are supported by 364 LNG tenders or 1,613 battery tenders. Unit costs of the various locomotive technologies are summarized below (Table S.2).

Table S.2: Assumed Capital Cost of Locomotives and Tenders ($ million/unit) for South Coast Scenarios (and North American Deployment Scenario)

Technology	Locomotive	Tender	Notes
Conventional Tier 4 Diesel	3.0	--	Current Tier 4 baseline cost
Tier 4 Diesel w/After-T	3.5	--	
Diesel-LNG	2.7	1.0	0.64 tenders per locomotive
Battery Tender w/ Regen	3.0*	11.0	2.83 tenders per locomotive
SOFC-GT w/ LNG	5.0	1.0	0.64 tenders per locomotive
Electrification	5.0	--	
LSM	unknown	--	unknown
Tier 4 Diesel w/After-T & Battery	4.0	--	For North American deployment (Section 13)

*Can also retrofit existing locomotives (if available) at a capital cost of $0.2 million per unit.

Purchase cost of new locomotives and tenders, and cost of modifications to conventional locomotives, for the captive new technology locomotive fleet within the South Coast ranges from $1.7 to $19.0 billion depending on the locomotive technology.

The installed cost of the overhead catenary traction power distribution system for electrification is $31.5 billion and LSM infrastructure is $12.6 billion. The study assumes that the capital cost of infrastructure to liquefy LNG is included in the delivered cost of LNG from third-party suppliers.

The construction cost of new locomotive shop facilities for new technology locomotives within the South Coast ranges from $109 to $285 million depending on the locomotive technology.

Annual incremental locomotive maintenance expense relative to the Tier 4 baseline ranges from a decrease of $14 million per year for electrification to an increase of $62 million per year for SOFC locomotives. However, electrification requires an additional $18.9 million per year for catenary maintenance.

Not enough is known about potential freight applications of LSM to develop complete cost data.

Exchange Point Operations and Capital Costs

Based on full-scale field trials, depending on the locomotive configuration, locomotive exchanges are likely to take between 60 and 222 minutes at the locomotive exchange points. The number of tracks at each exchange point is determined from the anticipated dwell time and peak train flow rate. The peak train flow rate is the average train flow rate multiplied by a factor of 2.5.

Construction of six appropriately-sized exchange facilities for the South Coast basin incurs $824 million in capital construction cost, including all sitework, track, support facilities and right-of-way. Depending on the locomotive technology, an additional $39 to $353 million in capital cost is required to establish locomotive and tender servicing and fueling facilities, Crews to operate the exchange points correspond to an annual expense of $61 million.

Exchange Point Delay and Mode Shift

Trains operating through locomotive exchange points are anticipated to experience between 1.59 and 4.29 hours of delay depending on the train type. The annual direct cost of train delay encountered at the South Coast basin locomotive exchange points is $112 million per year. This cost accrues from inefficiencies in crew, railcar and locomotive utilization created by delays at the exchange point.

A mode shift model was used to evaluate the potential for time-sensitive freight in the South Coast to shift to trucks when subject to delay at the exchange points. According to the model, each year, approximately 12.5 million tons of freight would move on trucks that formerly moved on rail. Due to this freight mode shift to truck associated with the delay at the locomotive exchange points, it is estimated that the railroads have the potential lose approximately $1.1 billion in revenue from intermodal and manifest traffic each year.

The shift of freight from rail to truck reduces the emissions benefits of the alternative locomotive technologies relative to Tier 2 (Figure S-3) and Tier 4 baseline levels (Figure S-4). Technologies that showed emissions reductions before mode shift may show increases in emissions (negative reductions) when the induced truck emissions are included in the calculations.

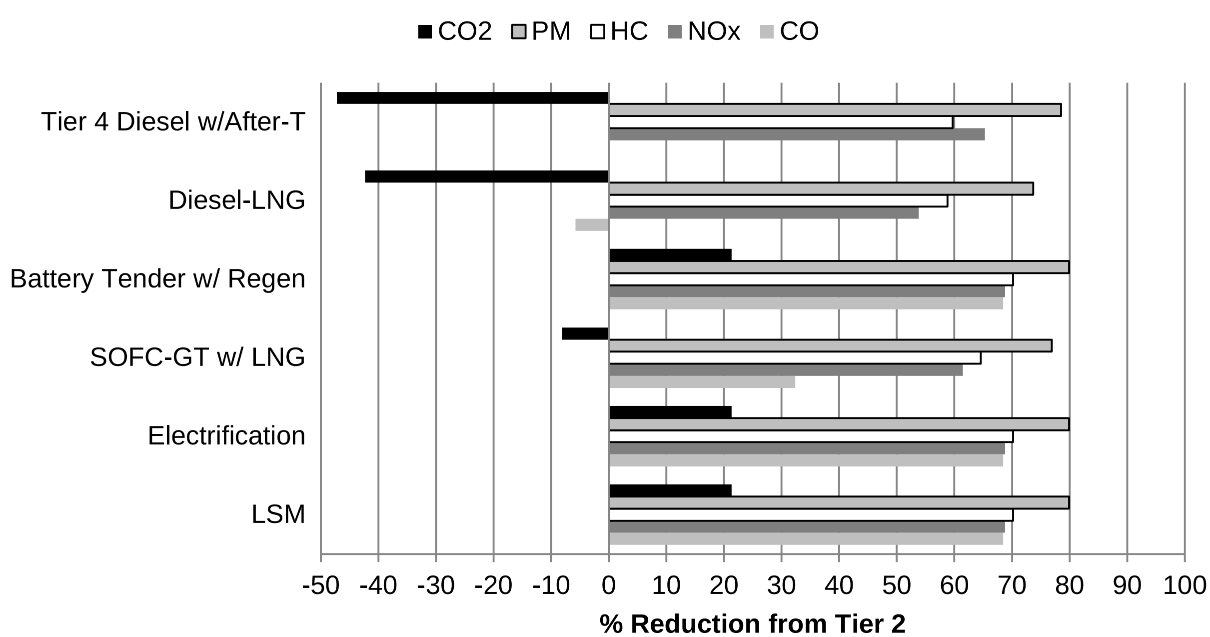


Figure S-3, Potential reduction in South Coast line-haul locomotive emissions from Tier 2 baseline after mode shift to truck

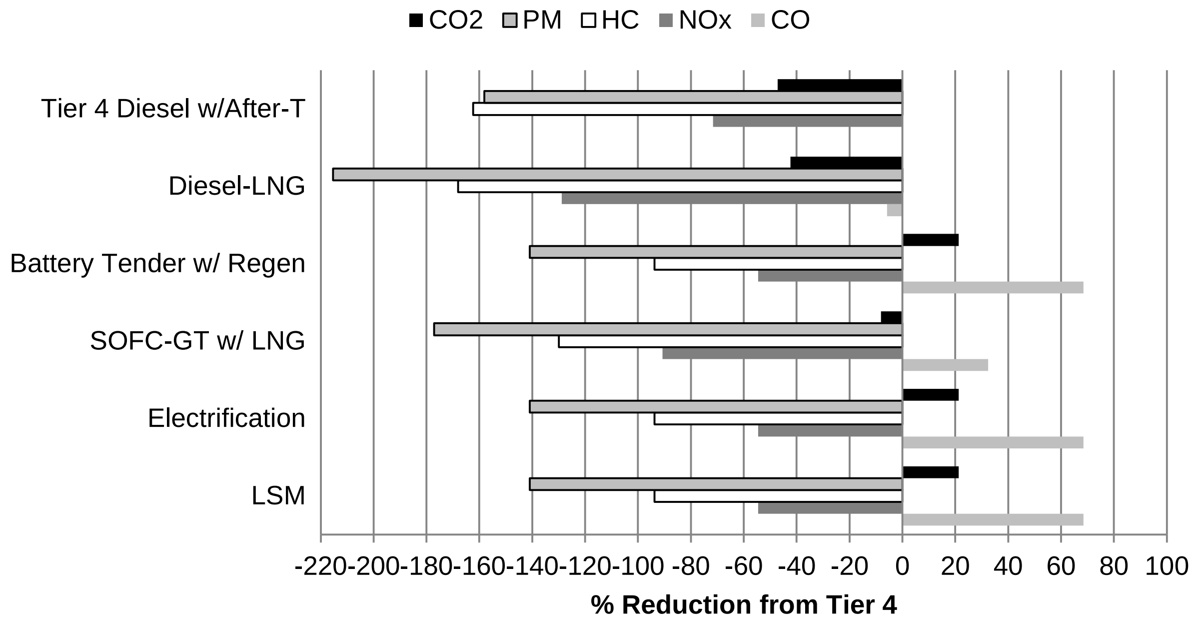


Figure S-4, Potential reduction in South Coast line-haul locomotive emissions from Tier 4 baseline after mode shift to truck

Fuel and Energy Supply Cost Reductions

The alternative locomotive fuel consumption from the train performance simulation was used to calculate the expected energy supply cost of line-haul mainline freight locomotive operations between terminals within the South Coast air basin and the locomotive exchange points (Figure S-5). The Tier 2 and Tier 4 diesel fuel costs serve as baselines for cost reductions. The diesel-LNG locomotive increases fuel cost due to decreased fuel efficiency and the small difference in the price of diesel and LNG. The efficiency of the SOFC-gas turbine with LNG provides the lowest energy supply cost of the liquid fuels, saving $117 million per year. The cost of this operation is nearly comparable to electrification and the LSM.

Unlike electrification and LSM, the limited range of the battery tender locomotive requires it to operate in diesel mode between the air basin boundary and the locomotive exchange point. The diesel fuel consumed during this portion of the trip increases annual energy costs relative to the other electric locomotive technologies. While electrification and LSM reduce energy costs by 52 percent or $116 million per year, the battery tender only exhibits an 18-percent reduction or $41 million per year.

Total Costs

To provide an overall measure of the economic impact of each alternative locomotive technology scenario, a present value cost calculation is performed over the 15-year initial mainline service life of a line-haul freight locomotive (Figure S-6). Electrification has the highest present value cost at $44.3 billion. Due to the cost of battery tenders, the battery tender locomotives have the second-highest present value cost at $30.0 billion. There is insufficient information available on the LSM technology to provide complete cost data.

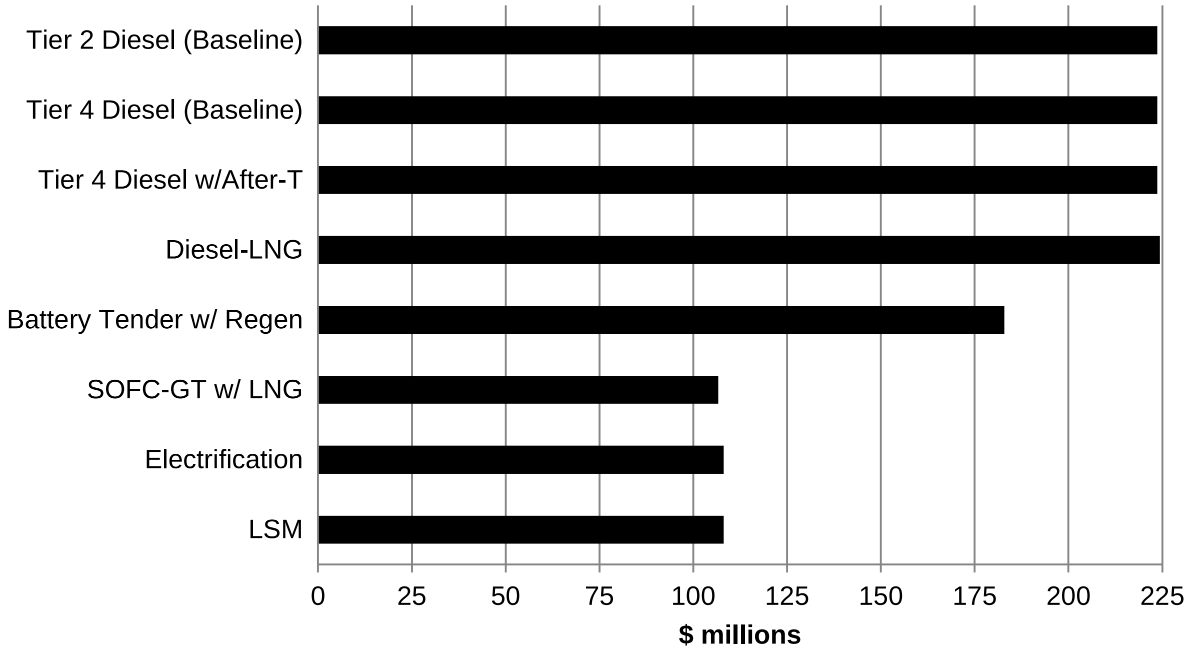


Figure S-5, Annual locomotive energy/fuel cost to South Coast exchange points

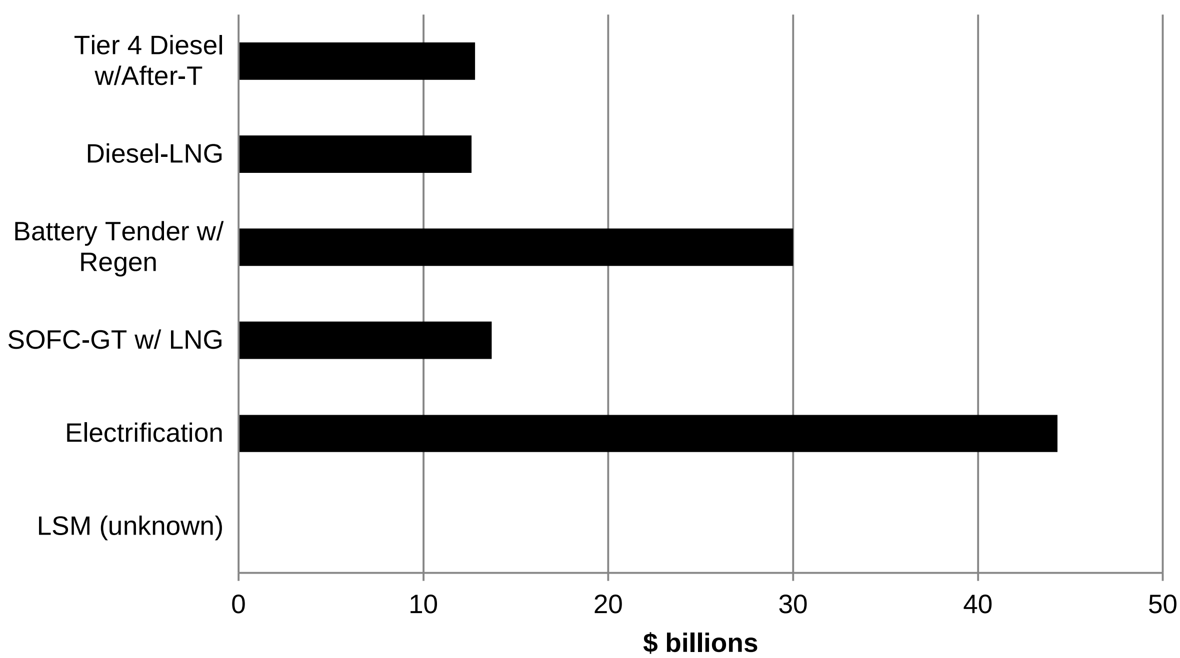


Figure S-6, Total of capital and present value costs for the South Coast scenarios

Interestingly, the three liquid fuel locomotive technologies exhibit a trade-off between total capital and present value of annual non-capital costs. Between the three liquid fuel locomotive technologies, SOFC locomotives have the highest capital cost but lowest annual cost, diesel-LNG has the lowest capital cost but highest annual cost, and Tier 4 with after-treatment falls in the middle for both capital and annual cost. This finding results in the range of total present value cost ($12.6 to $13.7 billion) narrowing compared to the range of capital costs described earlier.

Overall Findings of the Captive Fleet Scenarios

None of the studied locomotive technologies for the South Coast air basin captive fleet scenarios can generate fuel and energy cost reductions large enough to offset increases in annual non-capital costs. This is the case even when mode shift is not considered in the calculation of annual costs. When mode shift is considered, the potential for $1.1 billion in lost revenue each year dominates the annual cost calculation. When combined into a net present value calculation over 15 years, the lost revenue also dominates the economics of the three liquid fueled locomotive technologies even though the locomotive capital costs range from $1.7 to $3.2 billion.

Only for electrification and battery tender locomotives is the revenue loss not the dominant factor in the total net present value calculation. This is due to the high capital cost of both of these technologies at $20.5 billion for battery tenders and $35.5 billion for electrification.

The total present value cost of each technology can be weighed against its relative percent emissions reduction from Tier 2 and Tier 4 levels to assess its performance. Based on the calculated percent reduction in emissions per billion dollars invested, the SOFC-gas turbine locomotive with LNG has the potential to yield the best emissions reduction performance compared to the other locomotive technologies. However, the emissions produced by trucks carrying freight shifted from rail limits the potential benefits of all of the reduced-emission locomotive technologies, even those that are locally “zero emissions”.

North American Deployment Scenarios

To address the primary cost drivers of the captive fleet scenarios, two locomotive technologies were selected for analysis within the context of a North American deployment strategy: Tier 4 diesel-electric with after-treatment and onboard battery storage, and the SOFC-gas turbine locomotive with LNG. North American deployment of either technology appears to offer improved economics relative to operation with exchange points. Although North American deployment requires the purchase of more alternative technology locomotives, they can realize fuel savings over longer train runs and are not burdened by the capital cost, train delay and lost revenue associated with locomotive exchange points. North American deployment of Tier 4 diesel-electric with after-treatment and onboard battery storage technology appears to offer the best economics of any alternative in this study. In the longer-term, the SOFC-gas turbine locomotive with LNG appears to offer potential but requires extensive research and development.

The primary drawback of the North American deployment scenario is the required fleet size of approximately 6,000 units. Due to the capital cost involved and manufacturing constraints, it is likely that the required locomotives would be phased in over time. In this study it is assumed that full emissions benefits are not obtained for 15 years.

In a North American deployment scenario, the line-haul locomotive assignment process must be adjusted to ensure South Coast trains enter the air basin with reduced-emission locomotives. Poor fleet management may result in missed locomotive connections and train delay at terminals, adding cost and potential for shift of freight to other modes.

Conclusions

For the SCAB deployment scenario, with potential train delays and mode shifts, the above findings emphasize the importance of examining operational factors when evaluating new locomotive technology to reduce the emissions of line-haul freight rail in California. For several of the technologies, it is not the equipment capital cost and potential fuel savings that control the economic feasibility of the technology, but instead other factors that arise from the difficulty of integrating new locomotive technology in captive service within a highly interoperable rail network.

The economic feasibility of new locomotive technology is sensitive to the level of service demanded by shippers, the cost of train delay and potential shift of freight to other modes. This finding suggests that to properly evaluate alternatives, improved understanding of these factors is required beyond that found in the literature or developed through this study.

The results of this study are limited in part by the information available on the potential of each technology and its current state of development. To provide a better economic analysis, further research needs to be conducted to determine the exact potential benefits of each locomotive technology:

- For Tier 4 locomotives with after-treatment and diesel-LNG, this means conducting emissions testing of prototype and production units under representative field conditions to determine how much additional reduction beyond Tier 4 levels can be achieved by these technologies. Diesel-LNG tests should also quantify the amount of methane leakage expected during refueling.
- For the SOFC locomotive and LSM, working prototypes need to be developed to demonstrate the feasibility of each technology to provide the power and tractive effort required for line-haul freight operations.
- For the battery tender, working prototypes need to be developed to demonstrate the potential range and service life of the batteries under line-haul freight service conditions.

For the North American deployment scenario, the two locomotive technologies assessed (i.e., Tier 4 with after-treatment and on-board batteries and a Solid Oxide Fuel Cell with Gas Turbine) offer improved economics relative to operation with exchange points in the SCAB deployment scenario. See Conclusions in Chapter 14 for more detailed information.