Final Report

EMD Tier 4 (PM) Aftertreatment Upgrade on a Line Haul Locomotive

FY 2010-2012

Conducted under a grant provided by the California Air Resources Board of the California Environmental Protection Agency.

Grantee: Sacramento Metropolitan Air Quality Management District in partnership with Electro-Motive Diesel Inc. (EMD) and Union Pacific Railroad (UP)
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Prepared by: Sacramento Metropolitan Air Quality Management District, Electro-Motive Diesel Inc. (EMD) and Union Pacific Railroad (UP)

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Acknowledgments – EMD, UP, SMAQMD, CARB

The Advanced Technology Demonstration Project using a Tier 4 Particulate Matter Aftertreatment Upgrade on a Line Haul Locomotive has been funded, administered and made possible by a partnership among:

Electro Motive Diesel Inc., (EMD) EMD designs, manufactures and sells diesel-electric locomotives for all commercial railroad applications and has sold its products in more than 70 countries worldwide. The company is the only diesel-electric locomotive manufacturer to have produced more than 72,500 engines and has the largest installed base in both North America and worldwide. EMD designed and engineered the EMD 710ECO™Tier 2 repower engine as well as the emission upgrade system utilized in the Tier 4 Particulate Matter Aftertreatment Upgrade. EMD is owned by Progress Rail Services, a Caterpillar company.

Union Pacific Railroad (UP) is the largest railroad network in the United States. UP funded the repowering and upgrade of the 1993 vintage 3800 horsepower Tier 0 locomotive to a 3000 horsepower Tier 2 locomotive and also funded the application of Exhaust Gas Recirculation (EGR). UP also made the SD59MX available for the duration of this project, and committed to its operation in northern California for the 2 year project.

Sacramento Metropolitan Air Quality Management District (SMAQMD) aims to achieve clean air and protect public health and the environment. This intent is attained in part through the administration of grants to fund emission reductions throughout its air basin. SMAQMD has previously partnered with EMD to upgrade a Tier 0 EMD 710 engine to Tier 2 emission standards on an F59PH passenger locomotive for the California Capitol Corridor line.

California Air Resources Board (CARB) promotes the health and welfare of California residents by establishing and implementing air quality standards to reduce greenhouse gas emissions and air pollutants through the promulgation of air quality standards and grant administration to promote the adoption of clean technologies. In June 2010, CARB awarded a $502,865 Grant Award to SMAQMD to fund a project that would demonstrate the feasibility of EMD Tier 4 Particulate Matter (PM) and Diesel Oxidation Catalyst Aftertreatment Technology on a Tier 2 Experimental Line Haul Locomotive.

Abstract

The intent of the **California Air Resources Board** (CARB) is to promote and protect the health and welfare of California residents. The Advanced Technology Demonstration Project is part of California Air Resources Board's **AB 118** Program. The AQIP was created and funded under Assembly Bill 118, which uses vehicle and vessel registration fee increases to generate approximately $130 million in funds. The AQIP program is funded at $30 million per year. The purpose of these programs is to advance the development, implementation, and adoption of alternative and renewable fuel and vehicle technology.

Advanced Technology Demonstration Projects accelerate the next generation of advanced technology vehicles, equipment, or emission controls which are not yet commercialized. Sacramento Metropolitan Air Quality Management District in partnership with Electro Motive Diesel (EMD) and Union Pacific (UP) Railroad applied to administer the demonstration of promising advanced locomotive aftertreatment technologies to reduce emissions in Sacramento and San Joaquin trade corridor regions, and northern California.

In June 2010, CARB awarded a $502,865 Grant Award to SMAQMD to fund the demonstration of the feasibility of using an EMD Tier 4 particulate matter (PM) and diesel oxidation catalyst aftertreatment technology on a Tier 2 experimental line haul locomotive. In the preliminary phase of the experimental line haul locomotive project, stationary testing of the aftertreatment technology in the laboratory has provided emissions reductions which exceeded expectations.

Actual operation in revenue freight train service in northern California (and maintenance by regular railroad maintenance personnel) is a critical step to validate in-service performance, durability and maintainability of the aftertreatment system. Unit 9900 is to be FTP tested at least once in LaGrange, Illinois during the 2 year test.

Executive Summary

Background

The Sacramento Federal Nonattainment Area, including the SMAQMD, Placer and El Dorado County APCD (excluding the Lake Tahoe Air Basin), Yolo-Solano AQMD, a portion of the Feather AQMD (southern Sutter County), is currently classified as "Serious" Nonattainment area for the Federal 8-hour ozone air quality standard and will likely be reclassified as "Severe". It is also likely that the SMAQMD will be classified as "Nonattainment" under the federal $PM_{2.5}$ 24-hour standard.

The intent of the **California Air Resources Board** (CARB) is to promote and protect the health and welfare of California residents. The Advanced Technology Demonstration Project is part of California Air Resources Board's **Air Quality Improvement Program** (AQIP). The AQIP was created and funded under Assembly Bill 118, which uses vehicle and vessel registration fee increases to generate approximately $130 million in funds. The AQIP program is funded at $30 million per year. The purpose of these programs is to advance the development, implementation, and adoption of alternative and renewable fuel and vehicle technology.

Advanced Technology Demonstration Projects accelerate the next generation of advanced technology vehicles, equipment, or emission controls which are not yet commercialized. Sacramento Metropolitan Air Quality Management District in partnership with Electro Motive Diesel (EMD) and Union Pacific (UP) Railroad applied to administer the demonstration of promising advanced locomotive aftertreatment technologies to reduce particulate matter (PM) emissions on a line haul locomotive.

The parties to this project are committed to rail continuing as one of the most environmentally friendly forms of transportation and have made ongoing efforts to evaluate new, cleaner, advanced technologies that will support the development of future Tier 4 compliant locomotives.

Project Purpose

This project proposed to upgrade an experimental* Tier 2, 3200 bhp, 12-710, 2-cycle, line haul locomotive with exhaust gas recirculation (EGR) using an aftertreatment device consisting of multiple diesel oxidation catalysts (DOC) and diesel particulate filters (DPF). This aftertreatment upgrade is possible because of the internal carbody modifications to allow space to apply the large aftertreatment system (ATS) to the top of the engine.

Numerous laboratory testing efforts indicate that the design is ready for field test to verify emissions output and system durability. The goal of this project was to provide an experimental* locomotive that achieved an 80 percent PM reduction from Tier 2 levels.

* Experimental means not ready for commercial production

Overview of Project Goals and Objectives

This **Advanced Technology Demonstration Project** had the following **goals**:

- Demonstrate the durability of aftertreatment engine retrofit devices providing significant emission reduction benefits for PM
- Evaluate the performance of aftertreatment technologies installed on a medium horsepower Tier 2 locomotive
- Achieve EPA Tier 4 PM levels

The goal of this project was to provide an experimental locomotive that achieved greater than an 80 percent PM reduction from Tier 2 levels. The following tasks were scheduled:

- Activities to upgrade and test the experimental locomotive with partners and vendors:
    - Pre-inspection of Tier 2 EMD SD59MX experimental line haul (UP 2489) locomotive in La Grange, IL accomplished by EMD consistent with SMAQMD requirements (Exhibit 1).
    - Application of Exhaust Gas Recirculation (EGR), funded by UP in LaGrange, IL.
    - Ship experimental line haul locomotive to EMD facility in Patterson, GA for installation of a new carbody structure, modifications to the access bubble, cooling system modifications and locomotive overhaul.
    - Modify carbody to accommodate the aftertreatment upgrade, incorporating new cooling hood, engine hood and modifications to Clean Air Room.
    - Simultaneously procure upgrade devices: carbody, Exhaust Manifold adapter, Turbo Exhaust Manifold in La Grange, IL
    - Rename locomotive to UP 9900 (Exhibit 2.2)
    - Ship experimental line haul locomotive to EMD facility in La Grange, IL for installation of upgrade, which included application of aftertreatment system (ATS), controllers and cooling system.
    - Testing and shakedown of experimental line haul locomotive, including engine performance and emissions, cooling system tests, vibration and sound testing. Unit complies with FRA Way Side and Horn sound levels.
    - Ship experimental line haul locomotive to J.R. Davis Rail Yard in Roseville, CA. Unit arrived Roseville July 20, 2012.
    - SMAQMD conducts post-inspection. Inspection completed at Roseville with EMD/UP on July 24, 2012.
    - Hold a training workshop for UP employees to exhibit the aftertreatment technology – training included service and maintenance of EGR and ATS systems and was conducted July 25, 2012 (Exhibit 7).
    - Sacramento testing phase of durability/reliability. When completed, UP 9900 will operate throughout Northern California
    - Annual reports on UP 9900 operations will be submitted and monitored by EMD until 30 June 2015
- Regular meetings between EMD and agencies in partnership on project (Exhibit 3) to address:
    - Progress reporting
    - Anticipated progress for next meeting
    - Project milestone completions
    - Challenges to program implementation
    - Budget expenditures

Program Results:

Emissions data for the SD59MX with the EMD 710ECO™Tier 2 repower engine alone are consistent with U.S. EPA Tier 2 requirements, per the results in Table 1:

Table 1. Baseline Tier 2 Engine Emissions Performance Data.

Line Haul Duty Cycle

	BSCO	BSCO2	BSNOX	BSHC	BSPM
	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
Test Data	0.210	525.1	5.285	0.149	0.122
Tier 2 Standard	1.5	NA	5.5	0.30	0.20

After application of EMD experimental EGR technologies for NOx reduction, prototype turbocharger and aftertreatment device consisting of DOC/DPF, the results in Table 2 were obtained:

Table 2. Final Engine Emissions Performance Data.

Line Haul Duty Cycle

	BSCO	BSCO2	BSNOX	BSHC	BSCH4	BSPM
	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
Test Data	0.052	538.4	3.387	0.015	0.003	0.011
Tier 4 Standard	1.5	NA	1.3	0.14	NA	0.03

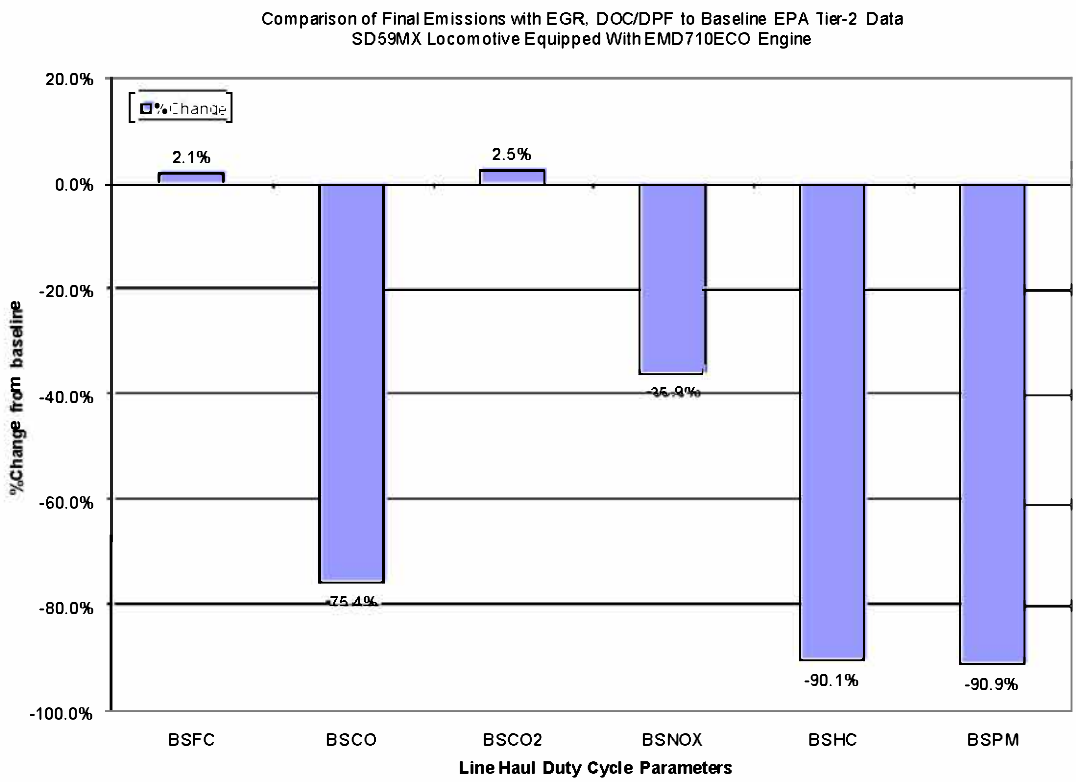
Reference:

BSxx	Brake Specific measurement
CO	Carbon Monoxide
CO2	Carbon Dioxide
NOx	Oxides of Nitrogen
PM	Particulate Matter
HC	Hydro-carbons

Summary of U.S. EPA FTP Emission Results

Figure 1 shows a comparison of the baseline Tier 2 data to the final performance with EGR and DOC/DPF:

Figure 1. Comparison of emissions results.



Introduction: Tier 4 (PM) Aftertreatment Upgrade

Test locomotive discussion

The base platform for this project was an EMD SD60M locomotive that was repowered with an EMD 710ECO™ engine, which is U.S. EPA-Certified and manufactured by Electro Motive Diesel (EMD). This project utilizes a prototype Tier 2 12-710 engine to provide 25 percent increase in carbody space for application of the EGR system along with a larger cooling system. Diesel particulate emissions were to be reduced by installing aftertreatment equipment. The aftertreatment device consists of diesel oxidation catalysts (DOC) and diesel particulate filters (DPF) in series, integrated with the experimental EMD 710ECO™, twelve-cylinder, 3200 bhp, two-cycle engine. The experimental engine had been designed for the EGR system and included a new turbocharger with sufficient boost to accommodate the DOC/DPF. EMD is committed to commercialize this advanced aftertreatment technology after the demonstration phase proves the aftertreatment to deliver acceptable performance, durability, serviceability and reliability.

Table 3 provides a comparison of the final locomotive configuration to the original SD60M locomotive.

Table 3. Comparison of Locomotive Configuration before and After.

	Original SD60M Locomotive	**Experimental SD59MX Locomotive**
Engine	16-710G3B	Experimental EMD 12-710ECO™
Brake Horsepower	3800	3200
Emissions Level	Tier 0	Tier 2 plus Tier 4 PM
Control System	EMD "Mod 3"	EMD "EM2000"
Cooling System	Traditional	Split Cooling with Larger Radiators
Emissions Equipment	In-engine	EGR + DOC/DPF

Locomotive Program Results

Aftertreatment technology approach and hardware / device retrofitted.

Repowering the SD60M locomotive started with the removal of the existing 16-cylinder EPA Tier 0 diesel engine and replacing it with the smaller 12-cylinder EMD 710ECO™ Tier 2 engine. By reducing the size of the engine by 25 percent, space was created for the installation of an experimental EGR system. A new carbody provided additional space above the engine for application of the aftertreatment package.

The photographs in Figures 2 and 3 show an SD60M locomotive before re-powering and rebuilding, and an SD59MX locomotive as equipped with the smaller engine, split cooling system and EGR. Externally, there are only two changes. The SD59MX split cooling system involves larger radiator cores necessitating "flared" radiator side inlets, and UP opted for a new AAR S-5506 high-impact crashworthy fuel tank holding 18,927 liters (5,000 US gallon) of fuel.

Figure 2. SD60M locomotives pre-re-power and EGR in 2009.

Figure 3. Re-powered SD59MX locomotive with EGR in 2011.

Unit 9900 SD59MX locomotive was equipped with an experimental whole-engine DOC/DPF package for PM reduction. The first step was to remove the engine carbody (Figure 4).

Figure 4. EMD 9900 with engine hood removed.

The whole-engine DOC/DPF is assembled into a rooftop "tray" which sits above the diesel engine. There are a total of nine DOC/DPF sets, arranged in three "legs" each containing three groups of DOC/DPF elements. This array treats 100 percent of the engine exhaust gases and is shown in the photos in Figures 5 and 6.

Figure 5. EMD Aftertreatment Exhaust Adapter.

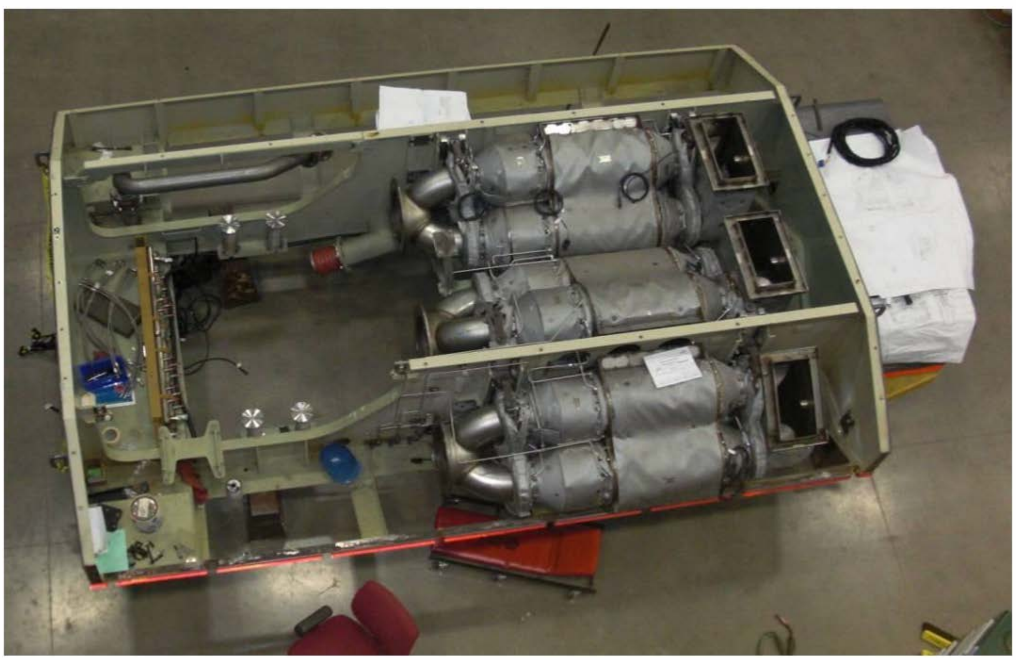


Figure 6. EMD Aftertreatment Tray build up prior to application on locomotive

The UP 9900 SD59MX EGR-equipped locomotive with the experimental whole-engine DOC/DPF aftertreatment "tray" installed above the diesel engine in mid-carbody (Figures 7, 8)

Figure 7. SD59MX UP 9900 with EGR and DOC/DPF "tray" (Electro-Motive Diesel, Inc., Copyright ©, March 01, 2012).

Figure 8. Overhang of DOC/DPF "tray" on engine compartment at mid-locomotive (Electro-Motive Diesel, Inc., Copyright ©, March 01, 2012).

Figure 8 in particular shows the large size of the experimental whole-engine DOC/DPF "tray". In fact, the "tray" extends outward from the engine compartment and is above the access walkway on both sides of the locomotive. The tray is 219" X 125" x 42" and weighs 9000 pounds.

The diesel oxidation catalysts (DOC) are constructed of ceramic or metal substrates coated with a catalyst (platinum or palladium). Under desired operating conditions, the DOC breaks down or oxidizes CO, HC and NO emissions into more benign components. The diesel particulate filters (DPF) are ceramic catalyzed filters which trap particulate matter. These catalyzed filters also accelerate the regeneration process, where the trapped soot is converted to CO_2. Regeneration is done passively with further chemical reactions that convert deposited soot to CO_2. Passive regeneration operates under higher load conditions where the temperature is high enough to oxidize the soot to CO_2 without the injection of hydrocarbons.

EMD refined and optimized the DPF regeneration process on the SD59MX locomotive, limiting ash buildup and extending the de-ashing or cleaning interval to a projected 184 days. Other key challenges in implementing this aftertreatment technology include:

- Meeting size, weight, and vehicle temperature restrictions within the locomotive carbody
- Accessibility for service by maintenance personnel (not achieved)
- Minimizing negative impacts on operational engine performance, such as horsepower, fuel economy, vibration, and maximum allowable backpressure.

There is one major maintenance issue with the whole-engine PM aftertreatment system installed on SD59MX UP 9900 which could not be avoided without an extensive and impractical reconfiguration of the entire existing locomotive, especially the locomotive underframe. The DOC/DPF "tray" sitting above the diesel engine does not leave sufficient space above the diesel engine in which to remove or replace power assemblies. If one of the twelve power assemblies should fail or otherwise require replacement, the entire DOC/DPF "tray" on the roof of the SD59MX UP 9900 will have to be removed and placed on the locomotive shop floor before any power assembly work can be done on the diesel engine. Removal of the "tray" requires availability of an overhead crane, and space to store the equipment for the duration of the engine repair, neither of which is available at many of the service locations. In addition to the extra time (possibly days depending upon logistics) to transport the UP 9900 to a shop capable of removing the "tray," its removal and re-application would add 16-32 hours to each power assembly maintenance event.

Project Milestones

This demonstration project had milestones as shown in Table 3:

Table 3: Project Milestones

Date	Milestone/Event
June 30, 2010	Project Award Notice Received
August 26, 2010	SMAQMD Board Resolution Action
November 2010	Project Kick-Off Meeting
December 2010	Contract Agreement Executed
December 2010	Disbursement Request
December 2010	Locomotive Pre-Inspection
Dec 2010-March 2011	Design Aftertreatment Exhaust System and Structure
October 2010	Progress Report
Dec 2010-June 2011	Procure Long Lead Exhaust System Components
January 2011	Progress Report
March 2011-June 2011	Procure New Engine Hood, Exhaust Components, Support Structure, Related Hardware, and Engine Modification Components
April 2011	Progress Report
June 2011	Ship Locomotive to LaGrange , IL

June 2011-Sept. 2011	Modify SD59MX Experimental Locomot8ve to Accept New Hood and Exhaust System
July 2011	Progress Report
Sept. 2011-Oct. 2011	Test Exhaust Flow, Control Systems, Sensors, and Engine Performance
Oct. -Nov 2011	Optimization of Aftertreatment Regeneration
October 2011	Progress Report
Nov 2011-June 2012	Conduct Emission and Fuel Economy Testing
June 9, 2012	Ship Locomotive to Sacramento, CA for Operational Testing
August 7, 2012	Locomotive Post-Inspection
August 15, 2012	Final Report Deadline
August 31, 2012	Final Disbursement Request Deadline
2013	Annual Usage Reporting to SMAQMD
2014	Annual Usage Reporting to SMAQMD
2015	Annual Usage Reporting to SMAQMD and Closing Summary Usage Report
June 30, 2015	SMAQMD Contract Complete
June 30, 2015-June 30, 2018	SMAQMD and Contractor maintain project records

Emissions Testing Results

The goal of this project was to provide an experimental locomotive that achieved greater than an 80 percent PM reduction from Tier 2 levels. Actual PM emissions were 95 percent lower than Tier 2 levels and well below the Tier 4 line haul standard of 0.03 g/hp-hr. Also of note, hydrocarbon (HC) emissions were reduced by 90 percent.

Discussion of U.S. EPA Test Procedure Utilized

Tier 2 baseline locomotive testing followed the federal test procedure (FTP) protocols in 40 CFR Part 92 for test configuration and fuel requirements. NOx emissions were corrected for temperature and humidity using EPA approved EMD developed correction factors for Tier 2.

Final locomotive testing with EGR and DOC/DPF followed the FTP protocols in 40 CFR Part 92 for test configuration and fuel requirements. However, NOx emissions were corrected for humidity using correction factor provided in 40 CFR 1065.

Gaseous Emission Analysis System

The EMD emissions testing system consists of a heavy duty diesel analytical bench that meets EPA Federal Regulation 40 CFR part 92 and part 94 requirements for locomotive engine and marine emissions testing. The bench incorporates the following:

- Total Hydrocarbons Analyzer - heated flame ionization detector type, with various analyzer ranges from 0 to 100 ppm C_1 up to 0 to 1000 ppm C_1
- Oxides of Nitrogen Analyzer - chemiluminescent type utilizing a heated NOx to NO converter, with various analyzer ranges from 0 to 300 ppm up to 0 to 5000 ppm

- Carbon Monoxide/Carbon Dioxide analyzer - non-dispersive infra-red type, with various analyzer ranges from 0 to 200 ppm CO up to 0 to 1000 ppm CO and 0 to 5 percent CO_2 up to 0 to 25 percent CO_2
- Oxygen analyzer - magneto-pneumatic oxygen type, with analyzer range from 0 to 21percent
- NOx Efficiency Test Equipment including NOx generator
- Gas Divider for calibration curve generation and analyzer linearity checks
- Heated sample system to maintain exhaust sample temperature of 375°F into the heated hydrocarbon analyzer and 140°F minimum sample temperature into the heated NOx/NO converter

Particulate Measurement System

This system consists of an EPA approved Micro-Dilution Test Stand manufactured by Sierra Instruments, Inc. of Monterey California. The system is a Sierra BG-2 particulate measurement test stand. This system incorporates the following:

- Digital mass flow controllers (Sierra model 860) used for variable control of sample dilution and total sampling
- The BG-2 is a partial-flow dilution, total sampler. In this system, a portion of the exhaust is extracted from the locomotive exhaust stack, diluted with dry, clean air and then the entire diluted sample is passed through the particulate sample filter. In our Sierra BG-2 system, the exhaust sample dilution and the particulate filter sample collection occurs within a couple feet of the sampling probe connection into the locomotive exhaust stack.

Test Fuel Properties

Both baseline and final emissions tests used Ultra-Low Sulfur Diesel (ULSD) fuel meeting EPA's specification with no correction for the sulfur content being made to the final data. Fuel properties for these tests are provided in Table 4.

Table 4. Properties of fuel used in Baseline and Final Emissions Test.

Description	EPA Baseline Tier-2	Final w/ EGR, DOC/DPF
Cetane No (ASTM D976)	42.5	44.4
Cetane Index (ASTM D976)	45.6	43.0
Flash Point, PMCC (ASTM D93)	46°C	68.3°C
API Gravity, @ 60°F	34.8	32.4
Sulfur (ASTM D5453), ppm	8.2	5.7
Carbon, %	86.84	86.98
Hydrogen, %	12.87	12.58
Gross Heat of Combustion, btu/lb	19618	19454
Net Heat of Combustion, btu/lb	18444	18307
Viscosity @ 100°F, cSt	2.70	2.93
Hydrocarbon Types by FIA		
Saturates	72.2	57.1
Aromatics	26.3	41.1*
Olefins	1.5	1.8
Distillation °F (ASTM D86)		
Initial Boil. Pt.	354	346
5%	387	386
20%	431	443
50%	493	506

70%	540	554
95%	626	640
End Pt.	650	669
Recovery	98.0	98.0
Residue	1.9	1.9
Loss	0.1	0.1

*Higher aromatics test level was produced with a larger cetane level

Typical data that may be collected during the testing phase include notch profile data as shown in Table 7:

Table 7. Typical Notch Profile

Notch Profile						
Mode	Total Time	Percentage of engine hours (%)	Assumed Fuel Rate (Gal)	Estimated Fuel Burn (Gal)	Traction HP (KW)	Totals (MWHRS)
Idle						
Dynamic Brake						
Notch 1						
Notch 2						
Notch 3						
Notch 4						
Notch 5						
Notch 6						
Notch 7						
Notch 8						

Commercialization Prospects

The base platform for the proposed project is an EMD SD60M locomotive. That SD60M was recently upgraded with a 710ECO™ Repower solution from EMD, which included the engine and the cooling system. The 710ECO™ engine in this experimental locomotive is a derivative of a 3200 bhp, 12-710, 2-cycle, line haul locomotive engine that is certified to EPA Tier 2 locomotive limits and performs to superior levels above and beyond the standard. EMD has invested significant R&D effort in developing this engine which contains technology beyond that required for Tier2. The project proposed to upgrade this experimental locomotive using a fully integrated system that achieves the necessary Tier 4 PM emissions reductions while providing a reliable and cost effective product.

The above mentioned 710ECO™ Repower of the SD60M locomotive is the backbone of this project, specifically providing the following enablers: The prototype turbocharger provides the additional boost that is critical to drive aftertreatment devices, and the internal carbody space freed up due to the switch in prime mover (from the original 16-cylinder 710 turbocharged engine to the 25 percent smaller 12-710ECO™ Repower engine). Without these two features the proposed project goals would be unattainable.

EMD notes that this DOC/DPF prototype will be one step in developing an emissions reduction technology with high potential for future commercialization. This project will assist EMD with the development of the 710 engine family for Tier 4 PM emissions and will allow the necessary reliability data to be gathered supporting new 4,000+bhp line haul locomotives.

There are nearly 21,000 active EMD locomotives currently operating in North America. Approximately 4,000 of these engines move through California. This PM reduction technology is intended to help attain the US EPA Tier 4 standards for line haul locomotives. It is most likely to be too expensive, too big or too heavy for practical implementation as retrofit technology to reduce PM on existing line haul locomotives. Also, the current configuration is marginally maintainable. It remains to be seen if this technology can be commercialized beyond application to new locomotives.