Diesel Locomotive Emissions Upgrade Kit Demonstration Project

Fuel Efficiency, Emissions & Noise Testing

Presentation of Project & Results 10/03/16

Natalie Roberts
Managing Director – ABMARC
0438 352 530 nroberts@abmarc.com.au
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1. About ABMARC
2. Project Overview
3. Testing & Results
NATALIE ROBERTS – Managing Director

Principal of ABMARC, a business Natalie established in 2010, specialising in fuels, environment, automotive, transport, mining and energy business development and strategic marketing.

In 2012, Natalie became an Ian Potter Foundation Fellow, receiving the Fellowship to research Portable Emissions Measurement Systems (PEMS) in Europe and the USA from a regulatory and systems perspective. In 2015, ABMARC brought the first [and only] PEM system into Australia and has been conducting emissions and fuel consumption testing for research and policy development in the locomotive and heavy commercial vehicle sectors.

Holding a Bachelor of Engineering (Aerospace), Natalie first worked for GM (Holden) in powertrain calibration, before accepting a position with Toyota, leading strategic planning and research for the Australian and Middle Eastern vehicle markets. Additionally, Natalie is approved by VicRoads under their Vehicle Assessment Signatory Scheme.

ANDREA WINKELMANN – Engineering Director

Beginning her automotive career in Germany and completing her engineering degree in the UK, Andrea has worked across the heavy and light vehicle sectors for more than 25 years. Andrea immigrated to Australia in 2005, first working at Ford and then GM Holden.

Andrea is Engineering Director at ABMARC, where she is responsible for delivering customer test and engineering projects across all mobility sectors. Specifically focusing on engines, emissions and fuels and testing with a Portable Emissions Measurement System, capable of Euro 6 measurements on customer sites or on mobile applications.

Andrea has been awarded the ISSI – Eddy Dunn Endowment International Fellowship to research the Impact of International Heavy Duty Vehicle OBD Regulation Amendments (2013 onwards) on the Service and Repair Industry in Australia and will be traveling early 2016.
ABOUT ABMARC

ENGINEERING, RESEARCH & CONSULTING

REAL WORLD ECONOMY & EMISSIONS
Australia’s only Portable Emissions Measurement System compliant to EPA 1065 2007 & EC 555 2005
On road or in field emissions & fuel consumption measurement
Development of engines & exhaust after treatment systems
Gaseous & particulate emissions
Laboratory quality emissions data from the real world

RESEARCH, BENCHMARKING & MARKETING
Market insight & product demand studies
Product planning
Policy development for regulation or corporate
Alternative fuels
Vehicle & engine technologies
Benchmarking & competitor analysis

VEHICLE & FLEET ENGINEERING SERVICES
Durability & environmental [hot weather] test programs
Captured fleet programs
Telematics & analytics for validation & certification
Dynamic vehicle testing
Forensic engineering

TECHNICAL WRITING & ILLUSTRATIONS
Sales materials for Automotive suppliers selling to OEMs
Editing & illustration
Maintenance and service manuals
Reports
Job procedures

OUR CUSTOMERS

+ MANY MORE.
Contents

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Test Overview & Locomotives

The objective of the Diesel Locomotive Emission Upgrade Kit Demonstration project was to determine the emissions, fuel efficiency and noise impact of fitting Tier 0+ emission upgrade kits to two EMD locomotives, relative to the same locomotives rebuilt to their original standard.

- Stage 1, Pre Upgrade Test – After standard rebuild
- Stage 2, Post Upgrade [Tier 0+] Test – After Tier 0+ rebuild

EMD16-645 E3B engine ~ 2,460 kW

EMD 16-710 G3A engine ~ 3,030 kW

Two locomotives. Two configurations. Two tests per configuration. Emissions measured with PEMS.
ABMARC engaged AECOM for noise testing and partnered with AVL [emissions equipment manufacturer] for first test. EMD provided Pacific National with emissions kit and supported Downer Edi with the installation.
PROJECT OVERVIEW

Test Location

460 Main Road, Cardiff, NSW

Entrance

Emissions Test Area

Noise Test Area
## Project Timing

### DEC 2014

<table>
<thead>
<tr>
<th>Week</th>
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<th>4</th>
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<td>8113</td>
<td>Standard Rebuild</td>
<td>Run In</td>
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<td>9024</td>
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### JAN 2015

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<tr>
<td>9024</td>
<td>Run In</td>
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### AUG 2015

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<tr>
<td>5</td>
<td>Noise Test</td>
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</tbody>
</table>

### Example Schedule For All Tests

<table>
<thead>
<tr>
<th>Day</th>
<th>ITEM</th>
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</thead>
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<tr>
<td>1</td>
<td>Set Up</td>
</tr>
<tr>
<td>2</td>
<td>Emissions and Fuel Consumption Test</td>
</tr>
<tr>
<td>3</td>
<td>Instrumentation Decommission</td>
</tr>
<tr>
<td>4</td>
<td>Noise Test</td>
</tr>
<tr>
<td>5</td>
<td>PM Filters Weighed</td>
</tr>
<tr>
<td>6</td>
<td>Fuel Sample Analysed</td>
</tr>
</tbody>
</table>
Emissions Upgrade Kit Overview

**Ultra Low Lube Oil Power Assembly** - The introduction of a hardened upper bore liner with specially designed bore profile and piston crown with improved piston ring design results in a claimed reduction in oil consumption by 50%.

**Oil Separator** – The Tier 0+ kit includes an improved oil separator to reduce the amount of crankcase oil mist that is carried over to the intake air, leading to further reduction in PM emissions.

**Four Pass Aftercooler** – Improved aftercoolers for more effective cooling of the combustion air from the turbocharger.

**Ecotip Injectors** – The Tier 0+ injectors drip less fuel and have an improved spray pattern to improve combustion efficiency, reduce PM, NO\textsubscript{x} and other emissions along with improving fuel consumption. Additionally the Tier 0+ kit includes an adjustment of the injection timing to aid in reducing NO\textsubscript{x} emissions to below the Tier 0+ limit.

**Key Performance Benefits**

- Fuel consumption reduced by 2% ± 5%
- PM and NO\textsubscript{x} reductions below Tier 0+
- Reduce oil consumption by 50%
**PROJECT OVERVIEW**

### Measurements

**Emissions**

Measured with Portable Emissions Measurement System [PEMS]. Providing repeatability of 1% or better and complying with US EPA and ECE regulations.

- Particulate Matter: Collected on gravimetric filter and weighed
- Soot: Second by second
- Gaseous: THC, CO, CO2, NO, NO2

**Fuel consumption**

Accuracy to 0.2% and repeatability to 0.02%.
Measured from positive displacement [volume] fuel flow meters [incl temp measurement].

**Engine power**

Measured across all motors and calculated instantaneously from the voltage and current outputs. Engine power is calculated from generator efficiencies.

**Noise**

Measured according to AS2377-2002.

### Outputs

- Grams [g] of emissions per unit of work [kW.hr]
- In Litre/hr and Grams [g] of fuel burned per unit of work [kW.hr]
  Also known as Brake Specific Fuel Consumption (BSFC) [g/kW.hr]
- Noise [dB]
Emissions and fuel consumption testing and calculations were conducted according to US EPA CFR Title 40, Volume 33, Part 1065 and 1033.
**Test Standards [Emissions & Fuel Efficiency]**

### Pre-Test
- Filter conditioning and weighing
  - 40 CFR 1065.590
- Temp, humidity, pressure sensors
  - 40 CFR 1065.915

### Calibration
- AVL Gaseous & PM PEMS – All analyser 1% or better repeatability
  - 40 CFR 1065.915
- Span gases
  - 1% accuracy
  - 40 CFR 1065.750

### Testing
- Kral fuel flow meter x 2
  - 0.2% accuracy combined, repeatability to 0.02% combined.
  - Calibration
  - 40 CFR 1065.320
- Yokogawa power analyser – as specified by locomotive manufacturer
- Noise tested to AS2377-2002

### Post-Test
- PEMS Analyser Drift Verification
  - 40 CFR 1065.550
- Fuel samples tested to ASTM D4052 & D240
- Calculations performed to 40 CFR 1065 subpart G
  - With EMD specified BSFC correction factors
  - Density & calorific value used for emissions and fuel consumption calculations.

### Environmental Conditions
- **Temperature**: 5°C to 43°C (emission test)
- **Humidity**: Max 95% at 25°C (emission test)
- **Wind Speed**: ≤10 m/s (noise test)
- **Background Noise Levels**: 10dB below A or C weighted locomotive SPL (noise test)

**PEMS emissions and fuel test to 40 CFR 1065.201 - 395**

**Report and data to EPA**
**Accuracy of PEMS**

PEMS provides laboratory accuracy and repeatability on the road and in the field.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>UNEC Reg. 49 Annex 4</th>
<th>AVL PEMS &amp; Fuel Flow Meters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accuracy</td>
<td>Repeatability</td>
</tr>
<tr>
<td>Fuel Flow (Combined)</td>
<td>≤2%</td>
<td>≤1%</td>
</tr>
<tr>
<td>CO/CO₂</td>
<td>≤2%</td>
<td>≤1%</td>
</tr>
<tr>
<td>THC</td>
<td>≤2%</td>
<td>≤1%</td>
</tr>
<tr>
<td>NOx (NO/NO₂)</td>
<td>≤2%</td>
<td>≤1%</td>
</tr>
<tr>
<td>PM (Gravimetric)</td>
<td>≤2%</td>
<td>≤1%</td>
</tr>
</tbody>
</table>
Instrumentation for Emissions and Fuel

VBOX (Data Recorder)

Data Logger

BEM500 (Data Recorder)

Generator

Fuel Flow Sensor

Locomotive Engine

Cylinder Temp

Temperature, Humidity and Barometric Pressure Sensors

Exhaust Temp

Gaseous Emissions Sample Line

Particulate Emissions Sample Line

Data Logger

PEMS (Gaseous & PM)

KEY:
- Emissions Measurement
- Temp & Other Measurement
- Fuel Measurement
- ABMARC Equipment
- Locomotive Components
**PROJECT OVERVIEW**

**Instrumentation for Emissions and Fuel**

- PEM system and emissions sample lines
- Exhaust stack and emissions sample probes on 8113
- PEMS setup on 9024
- High precision fuel flow meter on delivery line
- High precision fuel flow meter on return line
- 9024 In-Cabin data monitoring of all measurement items
Instrumentation for Emissions and Fuel
Emissions Sampling
Emissions Sampling
Power (from Motors)
**PROJECT OVERVIEW**

**Power Measurement**

- Voltage transducer on main DC generator
- Current transducer on main DC generator
- Power measurement device installed in-cabin
- Voltage connections for auxiliary DC generator
- Current clamps on companion AC alternator cables
Acoustic values were recorded in all locomotive operating modes, from idle to notch 8.
Noise Testing
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PEMS Warm Up

Warm up PEMS before calibration and test. Approx 60 minutes. Gaseous sample line to 191°C and PM sample line to 52°C.
PEMS calibration includes a leak check, gaseous calibration with certified gas and data check.
Filters

New filter for each test mode [10 per test]
Emissions and fuel consumption testing and calculations were conducted according to US EPA CFR Title 40, Volume 33, Part 1065 and 1033.
Finish Test

PEMS analyser drift check, leak check and data check.
Send diesel fuel sample and gravimetric filters for analysis.
When compared to the Tier 0+ emissions limits, 8113 achieved reductions of 48.3% and 9.95% for PM and NOx respectively, whilst 9024 achieved reductions of 59.1% for PM and 11.2% for NOx.
8113 – Summary Results
8113 – Ambient Test Conditions

**Emissions Testing**

- PEMS Operation Zone
  - Post Upgrade: Date: 3/07/2015, Temp: 6-14°C, Humidity: 60-90%

- PEMS Operational Limit

Key:
- Emissions Test: Pre Upgrade
- Emissions Test: Post Upgrade
- PEMS operational limit

**Noise Testing**

<table>
<thead>
<tr>
<th>Pre Upgrade</th>
<th>Post Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date: 4/05/2015</td>
<td>Date: 3/07/2015</td>
</tr>
<tr>
<td>Temp: 19°C</td>
<td>Temp: 6-14°C</td>
</tr>
<tr>
<td>Humidity: 82%</td>
<td>Humidity: 60-90%</td>
</tr>
</tbody>
</table>

Weather Condition:
- Pre: Cloudy
- Post: Sunny

Rainfall:
- Pre: 0 mm
- Post: 0 mm

Wind Direction & Speed:
- Pre: SW 5.6 m/s
- Post: SW 6.1 m/s
### 8113 – Cycle Weighted Summary Results

<table>
<thead>
<tr>
<th>BSFC (g/kWhr)</th>
<th>PM (g/kWhr)</th>
<th>NO\textsubscript{x} (g/kWhr)</th>
<th>CO\textsubscript{2} (g/kWhr)</th>
<th>CO (g/kWhr)</th>
<th>THC (g/kWhr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Upgrade</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-Upgrade  [Tier 0+]</td>
<td>5.50%</td>
<td>-66.2%</td>
<td>-44.5%</td>
<td>-26.7%</td>
<td>-30.6%</td>
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</table>

Significant reductions in particulate and regulated gaseous emissions were achieved in the cycle weighted emissions results after the installation of the Tier 0+ engine emissions kit. BSFC results have been corrected for temperature and humidity as per the Association of American Railroads (AAR) practice, whereas emissions results are uncorrected. For this reason, there is a difference between the percentage change in BSFC and CO\textsubscript{2} presented within the report.
The change in BSFC between test configurations was lowest in the higher notches. Percentage change in BSFC ranged between 1.42% in notch 7 to 115% in idle. The test to test repeatability in both pre and post emissions upgrade configurations was excellent, and within 1%, with the exception of modes 1 and 2 which varied between 1.78% and 10.4%.
PM emissions increased after installation of the emissions upgrade kit in modes 1, 3 and 4, by 23.7% to 202%. In all other modes, PM was significantly reduced by between 33.6%, in dynamic brake and 78.9%, in notch 8 when compared to the standard engine rebuild results.
NOx emissions increased after installation of the emissions upgrade kit only in mode 1 (idle), by 72.1%. In all other modes, NOx was significantly reduced by between 24.9%, in dynamic brake and 47.7%, in notch 8 when compared to the standard engine rebuild results. Test to test repeatability was excellent, typically within 1%, with the exception of testing in mode 1.
The A weighted measurements filter the noise by frequencies to which the human ear is most sensitive, representing how a person will likely hear sounds. The maximum measured A weighted noise level change was 7.20 dB(A) lower. A change of this magnitude provides a noticeable noise reduction.
9024 – Summary Results
9024 – Ambient Test Conditions

**Emissions Testing**

- **PEMS Operation Zone**
  - Post Upgrade 1
    - Date: 20/05/2015
    - Temp: 15-16°C
    - Humidity: 73-77%
  - Post Upgrade 2
    - Date: 21/05/2015
    - Temp: 18°C
    - Humidity: 70-75%

- **PEMS Operational Limit**

**Noise Testing**

- **Pre Upgrade**
  - Date: 21/05/2015
  - Temp: 18°C
  - Humidity: 77%
  - Weather Condition:
    - Rainfall: 2.2 mm
    - Wind Direction & Speed: NW 3.6 m/s

- **Post Upgrade**
  - Date: 03/07/2015
  - Temp: 6-14°C
  - Humidity: 60-90%
  - Weather Condition:
    - Rainfall: 0 mm
    - Wind Direction & Speed: SW 6.1 m/s

**Key:**
- Emissions Test: Pre Upgrade
- Emissions Test: Post Upgrade
- PEMS operational limit
### 9024 – Cycle Weighted Summary Results

<table>
<thead>
<tr>
<th></th>
<th>BSFC (g/kWhr)</th>
<th>PM (g/kWhr)</th>
<th>NOₓ (g/kWhr)</th>
<th>CO₂ (g/kWhr)</th>
<th>CO (g/kWhr)</th>
<th>THC (g/kWhr)</th>
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<tbody>
<tr>
<td>Pre-Upgrade</td>
<td>212</td>
<td>0.296</td>
<td>13.7</td>
<td>661</td>
<td>2.01</td>
<td>0.343</td>
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<tr>
<td>Post-Upgrade [Tier 0+]</td>
<td>217</td>
<td>0.121</td>
<td>9.52</td>
<td>674</td>
<td>0.592</td>
<td>0.176</td>
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<td><strong>% Change</strong></td>
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<tr>
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<td>2.57%</td>
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<tr>
<td>PM</td>
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<td>-48.7%</td>
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</table>

Significant reductions in particulate and regulated gaseous emissions were achieved in the cycle weighted emissions results after the installation of the Tier 0+ engine emissions kit. An increase in the BSFC with the upgrade kit installed, indicates lower engine efficiency.
The change in BSFC was lowest in the higher notches. Percentage change in BSFC ranged between 1.09% in notch 5 to 61.2% in idle. Overall, the test to test repeatability in both pre and post emissions upgrade configurations was very good.
In all modes, PM was significantly reduced by between 10.4%, in idle and 75.6%, in notch 4 when compared to the standard engine rebuild results. The greatest improvements in PM emissions were measured in notch 3 to 5.
NOx emissions improved significantly after the installation of the upgrade kit with cycle weighted NOx emissions reducing by 30.4%. NOx was significantly reduced by between 10.0% in dynamic brake and 32.8% in notch 6 when compared to the standard engine rebuild results.
The A weighted measurements filter the noise by frequencies to which the human ear is most sensitive, representing how a person will likely hear sounds. The maximum A weighted noise level increase at idle was 2.32 dB(A). At this level, it would be difficult for the human ear to distinguish.
Thank-you!

Natalie Roberts
Managing Director – ABMARC
0438 352 530 nroberts@abmarc.com.au