The Development of an Advanced Diesel Emission Control System for a Low-Sulfur Diesel-Fueled Heavy-Duty Engine

Prof. Mridul Gautam
Prof. Benjamin Shade

Raffaello Ardanese and Michelangelo Ardanese (PhD Students)

West Virginia University
Department of Mechanical & Aerospace Engineering

Adewale Oshinuga

AQMD Program Manager

Current and 2010 US EPA Heavy-Duty Diesel Engine Emissions Regulation Levels

Emission Constituent	Current Level	2010 Level
NO_X (g/bhp-hr)	2.5*	0.20
NMHC (g/bhp-hr)	0.5	0.14
THC (g/bhp-hr)	1.3	1.3
CO (g/bhp-hr)	15.5	15.5
CO_2 (g/bhp-hr)	(non-regulated)	(non-regulated)
PM (g/bhp-hr)	0.10	0.01

*or 2.4 if NMHC is not reported

Common Diesel Exhaust Gas Aftertreatment Technologies

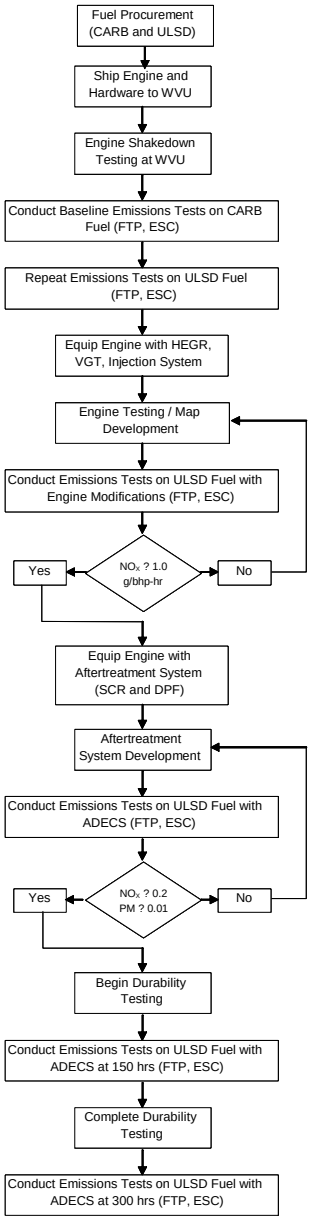
- Oxides of Nitrogen
  - NO_X Adsorber
    - Stores NO_X in catalyst washcoat during lean engine operation and releases it as N_2 during rich engine operation (much like a three-way catalyst)
    - Requires high exhaust gas temperatures (>500 °F) for full regeneration
    - Can operate in excess of 80 – 90 % efficiency
  - Selective Catalytic Reduction (SCR)
    - Able to work with lower exhaust gas temperatures
    - Catalyst often made from precious metals (platinum, vanadium, titanium, or zeolite)
    - Uses nitrogen compounds (ammonia or urea) as a reducing agent to aid in reaction to form N_2 and H_2O
    - Can be used with an oxidation catalyst to control ammonia slip
  - Lean NO_X Catalysts
    - Can be active or passive
    - Requires high exhaust gas temperatures (>700 °F) for reactions to occur
    - Uses hydrocarbons to react with NO_X to form CO_2, N_2, and H_2O
- Particulate Matter
  - Filter / Trap technologies
    - Used to reach US 2010 0.01 g/bhp-hr regulatory level
    - Can be made from ceramic or metallic materials

Objectives

- Overall Objective - To develop an Advanced Diesel Emissions Control System (ADECS)
  - Procure Volvo MD11 (MY2004)
  - Procure Certification diesel fuel and ultra low sulfur diesel fuel suitable for use in the South Coast Air Basin
  - Baseline Volvo MD11 engine over a series of test cycles
    - EPA heavy-duty engine Federal Test Procedure (FTP)
    - Stationary ESC (also known as OICA or SET)
  - Retrofit engine with advanced engine hardware
    - Variable geometry turbocharger
    - High pressure injection system
  - Equip the engine with an exhaust aftertreatment system to reduce engine emissions levels to the 2010 regulatory levels
    - Selective Catalytic Reduction (SCR) system to reduce NO_X
    - Diesel Particulate Filter (DPF) will be added to the engine to reduce PM
  - Conduct a durability study of the ADECS

Overall Work Plan

1. Fuel Procurement
2. Baseline Engine Testing
3. Low-Sulfur Diesel Fuel Engine Testing
4. ADECS Level 1
5. ADECS Level 2
6. ADECS Durability



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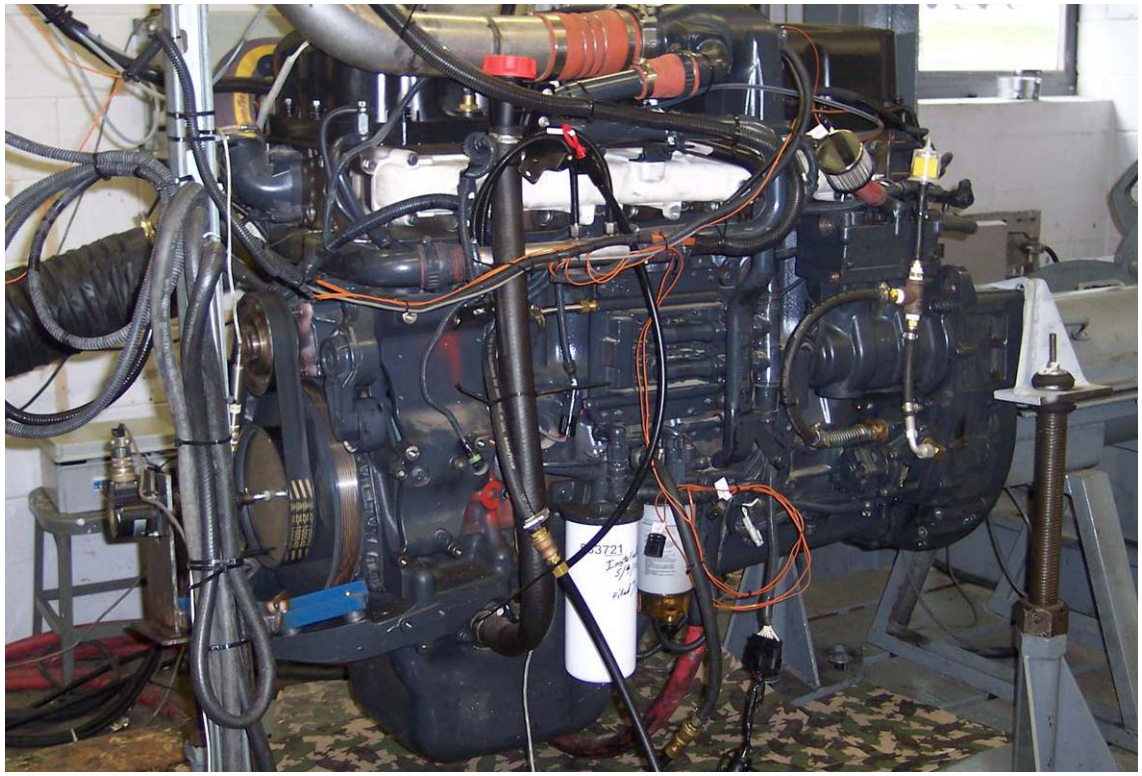
Engine Test Sequence

Engine Configuration	Test	Fuel	Emissions Measurements
Baseline 1	FTP01	Certification Fuel	NOx, NO, NO_2, TPM, THC, CO, CO_2
	FTP02		
	FTP03		
	ESC01		
	ESC02		
	ESC03		
Baseline 2	FTP01	Ultra-Low Sulfur Diesel Fuel	NOx, NO, NO_2, TPM, THC, CO, CO_2
	FTP02		
	FTP03		
	ESC01		
	ESC02		
	ESC03		
Development Testing		Ultra-Low Sulfur Diesel Fuel	
ADECS Level 1	FTP01	Ultra-Low Sulfur Diesel Fuel	NOx, NO, NO_2, TPM, THC, CO, CO_2
	FTP02		
	FTP03		
	ESC01		
	ESC02		
	ESC03		
Development Testing		Ultra-Low Sulfur Diesel Fuel	
ADECS Level 2	FTP01	Ultra-Low Sulfur Diesel Fuel	NOx, NO, NO_2, TPM, THC, CO, CO_2, NH_3
	FTP02		
	FTP03		
	ESC01		
	ESC02		
	ESC03		
ADECS Durability		Ultra-Low Sulfur Diesel Fuel	
ADECS - 150 hr Durability	FTP01	Ultra-Low Sulfur Diesel Fuel	NOx, NO, NO_2, TPM, THC, CO, CO_2, NH_3
	FTP02		
	FTP03		
	ESC01		
	ESC02		
	ESC03		
ADECS Durability		Ultra-Low Sulfur Diesel Fuel	
ADECS - 300 hr Durability	FTP01	Ultra-Low Sulfur Diesel Fuel	NOx, NO, NO_2, TPM, THC, CO, CO_2, NH_3
	FTP02		
	FTP03		
	ESC01		
	ESC02		
	ESC03		

Volvo MD11 Engine



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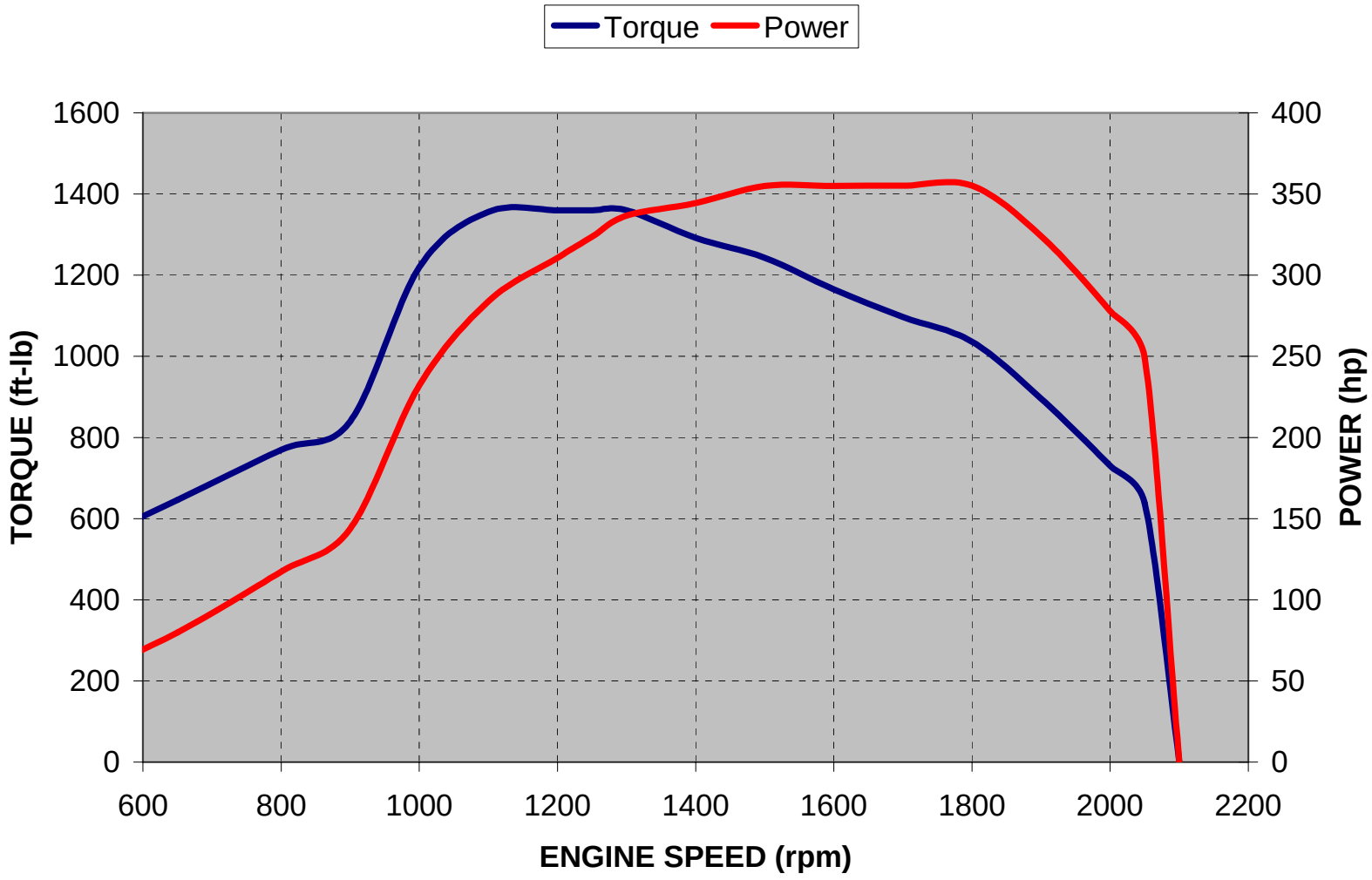
Engine Specifications

Engine Manufacturer	Volvo
Engine Model	MD11
Engine Type	Direct-Injection Diesel
Configuration	In-Line 6 Cylinder
Engine Output	355 hp @ 1800 rpm / 1360 lb-ft @ 1200 rpm
Displacement	10.8 L
Bore x Stroke	123 mm x 152 mm

- Engine is typical of those found in refuse collection and refuse hauling vehicles
- Scheduled to be in production late 2005 for use in Mack, Volvo, and Renault heavy-duty vehicles

Volvo MD11 Engine Torque Curve



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Volvo MD11 US04

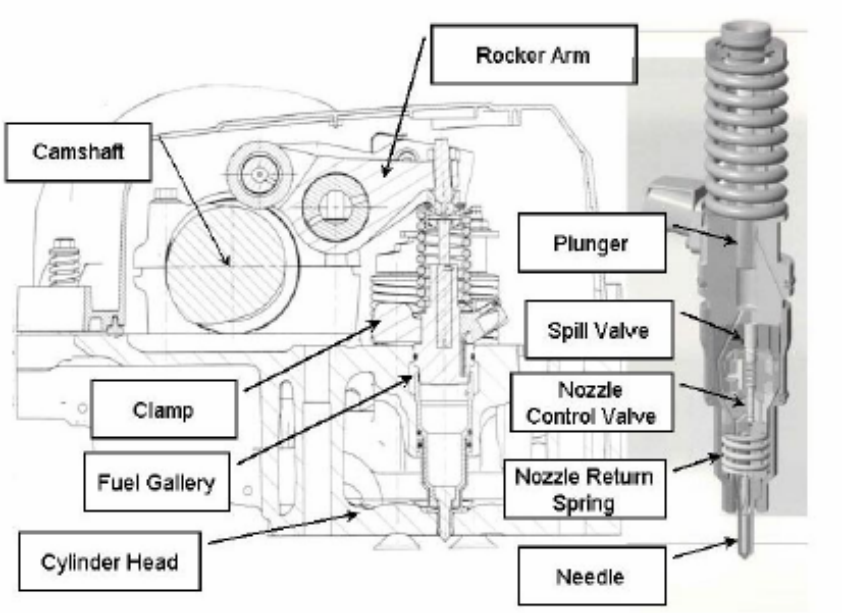
- Electronic actuated VGT for precise position control.
- Cooled EGR to reduce NOx to 2.5 g/bhp-hr.
- Overhead cam with unit mechanically actuated injectors. 4 valves per cylinder.
- PM reduction to 0.1 g/bhp-hr.
- Direct EGR mass flow measurement.
- Advanced Electronic controls for engine management.

Delphi E3 Unit Injection System

- Compact design works well with overhead camshaft engines
- Electronic Control can allow for multiple injection events, flexibility in fuel metering, and timing
- Injection event controlled by two valves
  - Spill control valve (SCV)
  - Needle control valve (NCV)

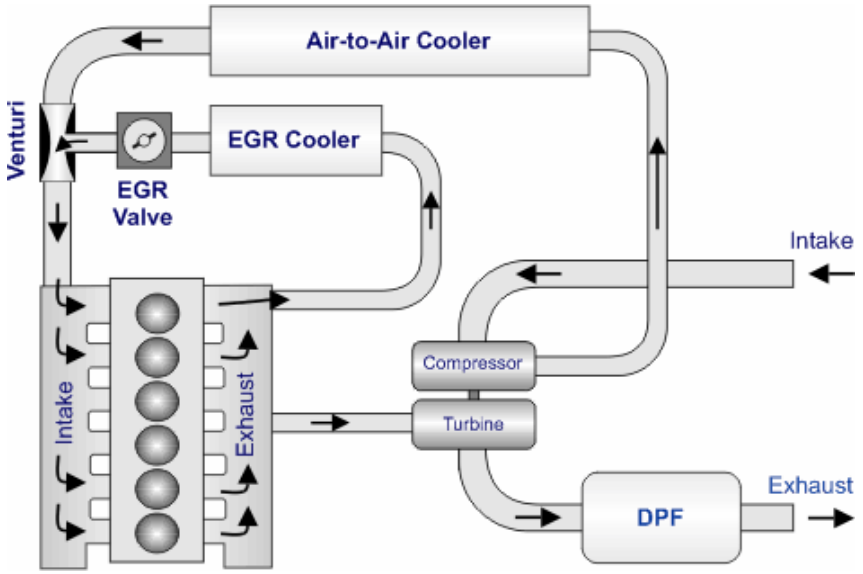
Delphi E3 Unit Injection System

- SCV is energized until its closure, resulting in fuel pressure building up in the system
- SCV is opened allowing fuel to spill into the fuel gallery so pressure collapses in the system
- NCV controls the timing of the opening and closing of the nozzle needle by determining whether or not the pumped fuel pressure is applied to the back of the nozzle needle (return spring ensures closure)
- Injection system allows changing of timing of the injection event by delaying the opening of the NCV after SCV is closed resulting in the flexibility to adjust the nozzle opening pressure (NOP)



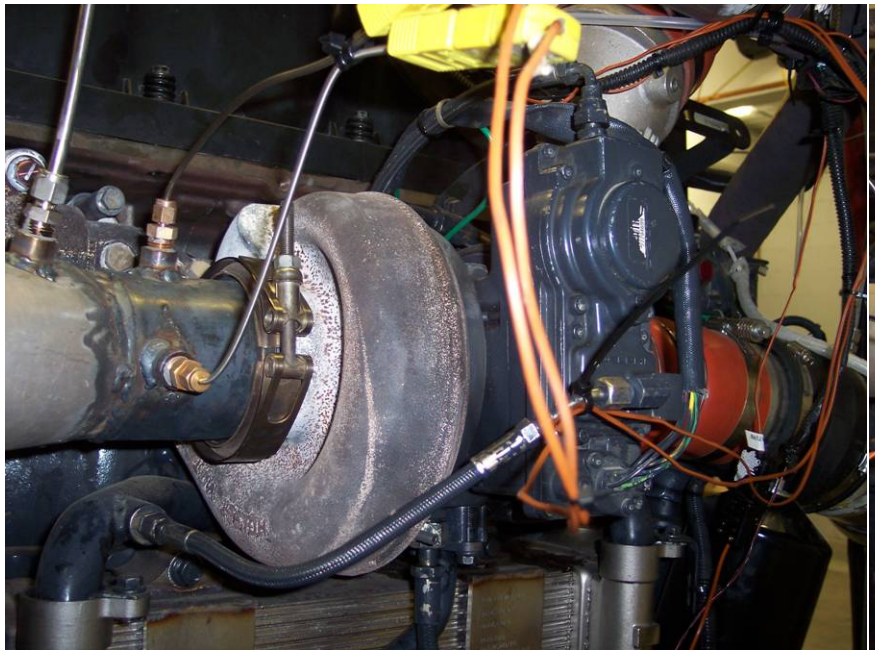
Exhaust Gas Recirculation – High Pressure Loop System

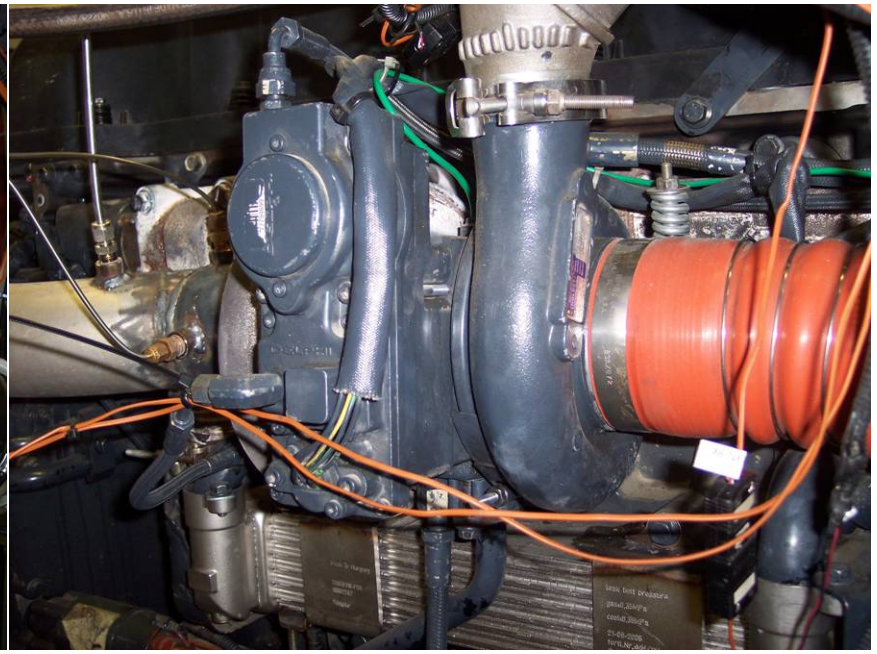
- Advantages
  - Quick response to demand of EGR
- Disadvantages
  - EGR cooler exposed to extremely high exhaust gas temperatures
  - Large ΔP



Source: http://www.dieselnet.com/tech/engine_egr.html

Variable Geometry Turbocharging Technology – Sliding Nozzle Assembly





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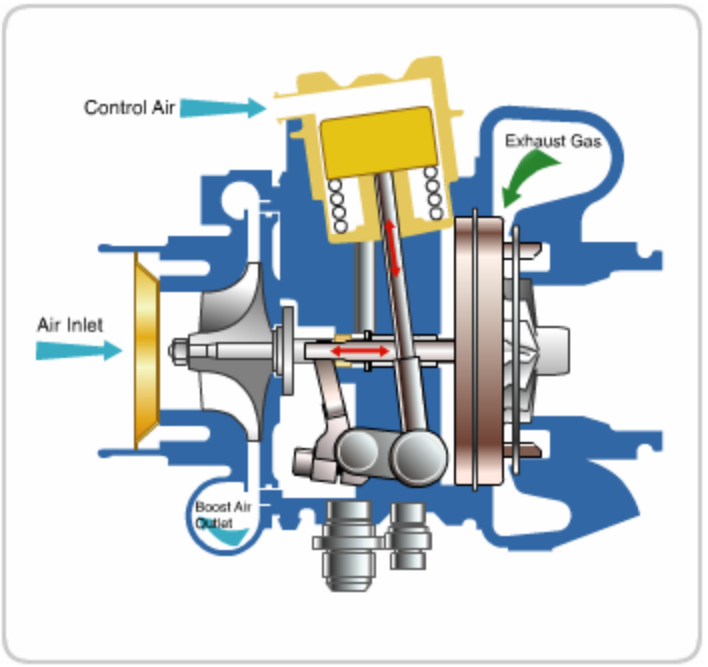
Variable Geometry Turbocharging Technology – Sliding Nozzle Assembly

- Advantages
  - Smaller size than variable vane VGT
  - Greater boost control
- Disadvantages
  - Moving parts
  - Cost



Source: http://www.holset.co.uk/files/2_5_1_5-variable%20geometry.php

Baseline Test Results

- Engine tested over FTP and ESC test cycles using certification fuel
- Data averaged over three repeat test cycles

Cycle	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	NOx (g/bhp-hr)	NOx+NMHC (g/bhp-hr)	PM (g/bhp-hr)
FTP	0.11	1.5	551.1	2.2	2.3	0.11
ESC	0.062	1.1	509.7	2.1	2.2	0.037

Volvo MD11 US07

- Electronic actuated VGT for precise position control carried over for US07.
- Enhanced cooled EGR to reduce NOx to 1.2 g/bhp-hr, and DPF to reduce PM to 0.01 g/bhp-hr.
  - –Larger EGC.
  - –Increased piping diameter to handle increased EGR flow rates.
  - –Venturi and delta P sensor to measure EGR flow.
- New EGR mixer for 2007

Volvo MD11 US07

- New injectors capable of 2400 bar injection pressure
  - Increased injection pressure for better PM control.
- New overhead camshaft with modified injector lobe with unit mechanically actuated injectors.
- Shorter injector rocker arms to maintain the proper stroke
- Strengthened gear train to accommodate the 2400 bar injection pressure
- “Seventh Injector” for active DPF regeneration.

DPF and SCR

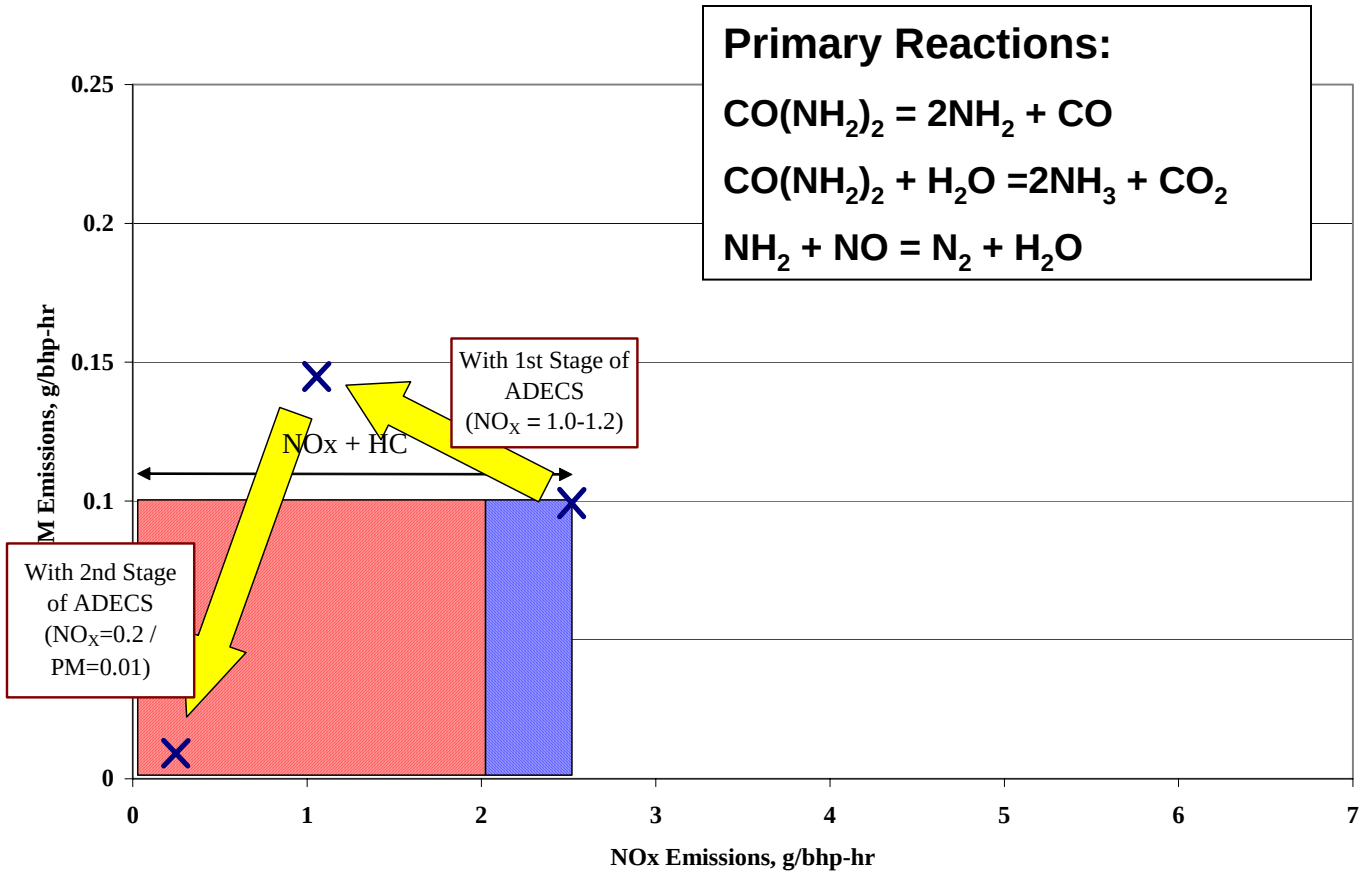
- Active DPF system for particulate reduction to meet 2007 and 2010 standards (0.01 g/bhp-hr).

- A Urea SCR system designed to meet Euro IV emissions will be used to reduce NOx to 0.2 g/bhp-hr over the ESC and FTP cycles. The dosing system and SCR catalyst will be the same as that used in Europe, and are considered production units. NOx conversion rates of 80-90% are possible with the proposed urea SCR system.

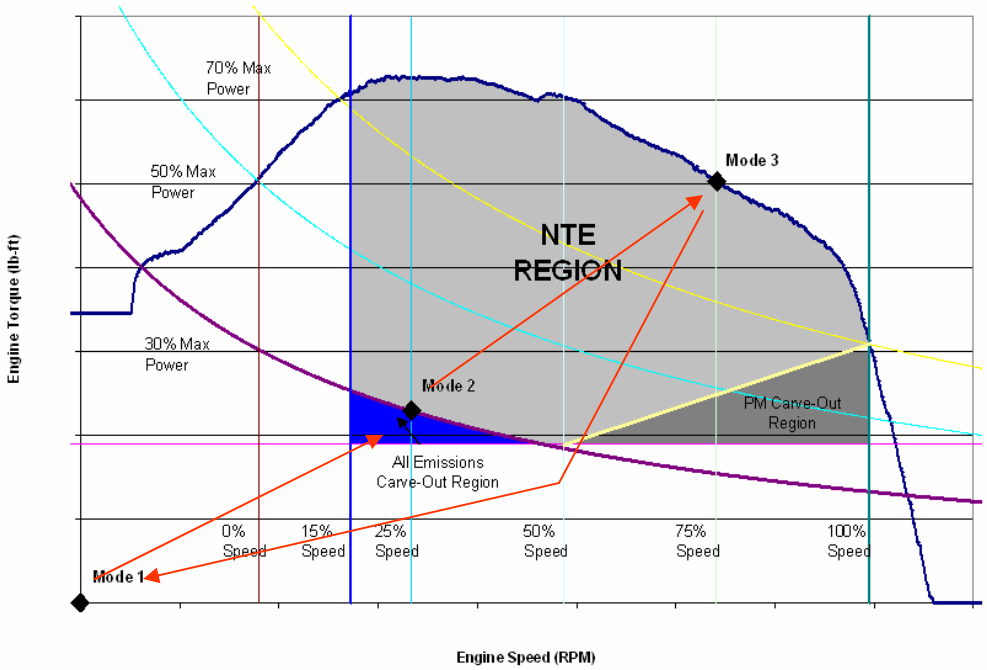
DPF and SCR

- SCR manufacturer is Johnson Matthey. There will also be a control module, urea pump, and urea injector to control the amount of urea supplied for NOx reduction. Two NOx sensors will be used before and after the catalyst to monitor how well system is reducing NOx. The aftertreatment control module (ACM) is a dumb controller and receives commands over the CAN bus from the engine ECU.

Effect of SCR on NO_X / PM Tradeoff



ADECS Durability Study



- Consists of 3 modes cycling for a total of 300 hours
- Cycle in and out of Not-To-Exceed region to stress components of ADECS

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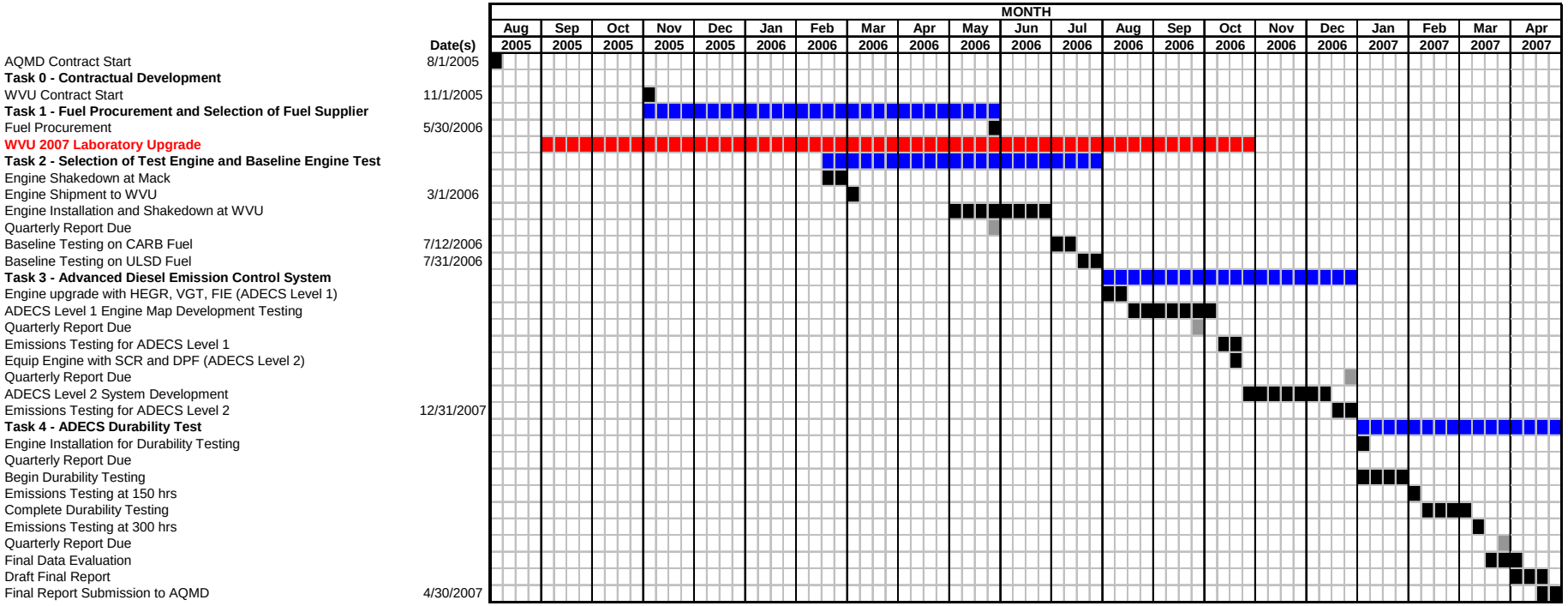
Project Schedule



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Conclusions and Goals

- Develop the Volvo MD11 engine equipped with ADECS to meet US 2010 emissions regulations
  - Advanced engine technologies (FIE, VGT, HEGR)
  - Exhaust gas aftertreatment (SCR, DPF)
- Maintain schedule to meet deliverables for South Coast Air Quality Management Division
- Produce results that can be used in real-world applications in a practical manner

Thank you for your attention.

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