Analytical and Experimental Evaluation of Cylinder Deactivation on a Diesel Engine

S. Pillai, J. LoRusso, M. Van Benschoten, Roush Industries

GT Users Conference
November 9, 2015
Contents

- Introduction
- Cylinder Deactivation – Analytical Evaluation
  - Modeling Approach
  - Calibration Approach
  - Results
  - Energy Analysis
- Cylinder Deactivation – Experimental Evaluation
  - Experimental setup
  - Results
  - Energy Analysis
- Conclusions
Introduction

Objective
• Identify cylinder deactivation as a technology enabler for fuel economy and emission improvements in diesel engines

Background
• Six cylinder, series turbo layout for Tier 4 emissions
• Cylinder deactivation for diesel engines
  • Analytical evaluation using 1D simulation tools
  • Experimental evaluation – Engine dynamometer
• Identify potential benefits and trade-offs
• Limited published information available
  • Compression Ignition (CI) deactivation

Observations
• Potential benefits in fuel consumption
  • Low load/Part load operating conditions
• Increased exhaust temperatures
  • After-treatment efficiency and catalyst light off temperature
Analytical Evaluation: Modeling Approach

- I6 mode – Baseline
- I3 mode – Deactivated mode
- Indicated torque and Friction torque
  - Recomputed based on firing cylinders
- Corrected Brake torque and power
- Corrected Emissions and BSFC
Analytical Evaluation: Modeling Loop

1. **Logic flow - Baseline 13**
   - **Run Base 13 Model**
     - **Optimize**
       - Re-parameterize case setup to vary fuel injection
     - **Optimizer**
       - Not an achievable target in 13 mode
     - **Compare Torque**
       - **Yes**
         - **EGR DOE Setup - EGR_VGT_PID Controller**
           - **DOE Sweep**
             - **EGR - DOE loop**
               - **Emission Levels not acceptable**
               - **No**
                 - **Yes**
                   - **Check Emission Limits**
                     - **Yes**
                       - **Verify Indicated parameters**
                         - **Yes**
                           - **Physical limit violation**
                             - **13_EGR_opt**
                           - **No**
                             - **Net decrease in BSFC**
                   - **No**
                     - **Yes**
                       - **Comparative Analytical evaluation**
                         - **Net decrease in BSFC**
               - **No**
                 - **Yes**
                   - **Optimizer loop**
                     - **Yes**
                       - **Verify Indicated parameters**
                         - **Yes**
                           - **Physical limit violation**
                             - **13_EGR_opt**
                         - **No**
                           - **Net decrease in BSFC**
                   - **No**
                 - **No**
                   - **Model not validated**
                 - **No**
               - **No**
             - **Yes**
               - **Check Emission Limits**
                 - **Yes**
                   - **Verify Indicated parameters**
                     - **Yes**
                       - **Physical limit violation**
                         - **13_EGR_opt**
                     - **No**
                       - **Net decrease in BSFC**
                   - **No**
                 - **Yes**
                   - **Comparative Analytical evaluation**
                     - **Net decrease in BSFC**
             - **No**
               - **Yes**
                 - **Verify Indicated parameters**
                   - **Yes**
                       - **Physical limit violation**
                         - **13_EGR_opt**
                       - **No**
                         - **Net decrease in BSFC**
                 - **No**
                   - **Comparative Analytical evaluation**
                     - **Net decrease in BSFC**
                 - **No**
               - **No**
             - **Yes**
               - **Check Emission Limits**
                 - **Yes**
                   - **Verify Indicated parameters**
                     - **Yes**
                       - **Physical limit violation**
                         - **13_EGR_opt**
                       - **No**
                         - **Net decrease in BSFC**
                   - **No**
                 - **Yes**
                   - **Comparative Analytical evaluation**
                     - **Net decrease in BSFC**
                 - **No**
               - **No**
             - **Yes**
               - **Check Emission Limits**
                 - **Yes**
                   - **Verify Indicated parameters**
                     - **Yes**
                       - **Physical limit violation**
                         - **13_EGR_opt**
                       - **No**
                         - **Net decrease in BSFC**
                   - **No**
                 - **Yes**
                   - **Comparative Analytical evaluation**
                     - **Net decrease in BSFC**
                 - **No**
               - **No**
             - **Yes**
               - **Verify Indicated parameters**
                 - **Yes**
                 - **No**
               - **Net decrease in BSFC**
             - **No**
           - **Yes**
             - **Comparator Analytical evaluation**
               - **Net decrease in BSFC**
         - **No**
   - **Validate Results**
     - **Yes**
       - **16_base**
     - **No**
       - **Model not validated**
   - **No**

**Logic flow - Baseline 16**

**Run Base 16 Model**
Analytical Evaluation : GT Key Elements/Features

• Deactivation
  • Zero fuel injection quantity
  • Zero lift profile for deactivated cylinders – Both intake and exhaust valves

• Emission Optimization
  • EGR – VGT optimization

• Predictive Combustion
  • Calibrated Direction Injection Diesel Jet Combustion model
  • Calibrated NOx model
  • Calibrated modified Hiroyasu soot model

• Friction
  • Calibrated Chen-Flynn Engine Friction Model
Analytical Evaluation : Calibration approach

• I3_base
  • Similar injection timing, boost pressure, rail pressure and EGR% to I6 mode at equivalent injection quantities

• I3_EGR_opt
  • Turbo optimization through Design of Experiments (DOE) for optimized EGR%
  • Demonstrated greater overall improvements in Brake Specific Fuel Consumption (BSFC), increased exhaust temperature and reduced NOx
Analytical Evaluation : Results

BSFC

- BSFC improvements at lower loads to diminishing returns as I3 mode reaches torque limit
Analytical Evaluation: Results

BSFC (cont.)

• Most influencing factors: Pumping work, heat transfer, and friction

• Pumping work
  • Reduced pumping loop area in I3
  • Overall pumping torque reduction at light loads
  • Higher boost and exhaust back pressure required in I3 mode
  • Higher exhaust pressures due to turbo restrictions for higher EGR rates
  • I3 requires more air and fuel, delivering similar work
Analytical Evaluation : Results

BSFC (cont.)

- **Heat Transfer**
  - Reduced surface area for combustion in I3 mode
  - Lower heat transfer loss

- **Friction**
  - Chenn-Flynn model
  - Based on peak cylinder pressure and mean piston speed
  - Increase in firing cylinder pressure is less than the pressure drop in the deactivated cylinders at equivalent brake torque
  - Overall friction reduction in I3 mode
Analytical Evaluation: Results

Exhaust Energy and Emissions

- Brake specific, emission parameters evaluated:
  - Lower NOx: higher fraction of combustion during diffusion phase resulting in lower rate of formation
  - CO: optimized EGR to lower CO emissions
  - Hydrocarbons (HC): optimized EGR to lower HC emissions, increase load limit
  - Soot: similar trends to HC and CO
Analytical Evaluation: Results

Exhaust Temperature

- Low air fuel ratio lead to high exhaust temperatures compared to I6 mode
- Lower exhaust energy at low loads
- Higher enthalpy at higher loads due to increased exhaust mass flow
- Higher exhaust temperatures – improve catalyst light-off efficiency
Analytical Evaluation: Results

Energy Analysis

• I3 and I6 operation at same brake power for three cases
• I3 improves brake and indicated thermal efficiency in nearly every area including lower pumping, friction and heat loss
Analytical Evaluation : Challenges

- Direct optimization was not possible in the I3 mode
- Post correction of brake torque and brake specific emissions makes optimization targets harder to define.
- Optimization involve bin/range approach to narrow optimization target range
- Increased post processing associated with different target combinations. – e.g. Min BSFC + Min Emissions
Experimental Evaluation: Setup

• Simple mechanism to deactivate intake and exhaust valves
  • Deactivating pushrods and securing lifters from engaging
  • Fuel injection – physically disconnecting the injectors

• Production turbo hardware retained
  • Limited I3 operation – lower engine speeds

• Charge Air Cooling (CAC) matched to expected vehicle effectiveness

• No aftertreatment devices
  • Simulated backpressure via orifice plate
Experimental Evaluation: Optimization

• Parameterization
  • Controls factors and response variables

<table>
<thead>
<tr>
<th>Control Factors</th>
<th>Output Variables of Interest Include:</th>
</tr>
</thead>
<tbody>
<tr>
<td>VGT Vane Position</td>
<td>BSFC</td>
</tr>
<tr>
<td>EGR Valve Area</td>
<td>LP Turbine-Out Temperature</td>
</tr>
<tr>
<td>Main Timing</td>
<td>Brake Specific Emissions</td>
</tr>
<tr>
<td>Pilot Quantity – On/Off</td>
<td>- NO_x</td>
</tr>
<tr>
<td>Rail Pressure</td>
<td>- HC</td>
</tr>
<tr>
<td></td>
<td>- FSN</td>
</tr>
</tbody>
</table>

• Survey DOE
  • To determine suitable range of control factors to help design DOE with maximum fidelity and minimum test runs to provide accurate optimization results

• Variation
  • D-optimal DOE design matrix was generated which provided the most efficient distribution of test points over design space with minimum test runs
Experimental Evaluation : Optimization

• Dynamometer test run
  • Dynamometer, ECU, combustion and emission data recorded for each DOE test point

• Regression Model Development and Validation
  • Multi-variable polynomial regression models were generated for BSFC, emissions and turbine out exhaust temperatures
  • Model factor, residual analysis, normal probability and coefficient of determination were regression statistics used to validate integrity of the model

• Target functions
  • Target functions defined to achieve objective – emissions, BSFC and exhaust temperature

• Experimental Validation
  • Optimal calibration settings were experimentally validated
Experimental Evaluation: Results

- BSFC reductions ranged from 5% to 30%
  - Diminishing benefits with increasing load
- Turbine out temperatures increased by 45-170°C
  - Higher temperatures were accompanied by lower enthalpy

![BSFC Reduction Chart]

- Enthalpy energy reduction

- Turbine-out temperature delta
Experimental Evaluation : Results

- Emissions were lower for most of test data points collected
  - Any increase within reasonable limits were deemed acceptable
- Higher load ranges limited in I3 mode due to carry over air handling system
- Vibrations encountered at low idle engine speed
Experimental Evaluation: Results

Energy Balance

- I3 mode exhibited lower pumping work and reduced heat transfer to the cylinder walls resulting in reduced fuel consumption.
Experimental Evaluation: Correlation & Validation

- Baseline 16 mode was correlated to experimental results prior to evaluating cylinder deactivation.
  - Performance characteristics
  - Emissions (where available)
  - Thermal characteristics

- All test points modelled were not experimentally evaluated

- Slightly different calibration levels were applied from some of the test points during the experimental evaluation
  - Hardware operational limits / Boundary conditions
  - Air handling system limitations
  - Emission measurements

- In general, 1D simulation helped establish directional trends
Cylinder Deactivation: Conclusions

- Steady state BSFC improvements at low load with uncompromised engine emissions when compared to I6 mode
- Fuel consumption reductions
  - Lower pumping work
  - Reduced heat transfer
- Experimental results validated analytical evaluation with directional trends established.
  - Friction was one exception that needs more evaluation
- Increase in turbine out temperatures in the range 40-160°C
  - Higher exhaust temperature could yield improvements in catalyst light off
- Carry-over air handling system limited operation at lower engine speeds
  - Operating range could be expanded by appropriate hardware selection
Thank You

• Publications
  – SAE Paper #:2015-01-2809

Sajit Pillai
sajit.pillai@roush.com
734-779-7521