Developing and deploying optimization strategy for engine calibrations

Akansha Saxena, Cummins
Matt Butts, Cummins

May 02, 2019
B?l?nc? in life is the key to happiness.
Problem statement
• Optimize engine performance calibrations

Approach
• Analytical calibration workflow

Tools used
• MATLAB for almost everything (Data Import, Parallel computing, statistics and Machine Learning, Optimization toolbox, MATLAB compiler)

Results
• Bubble plots representation

Key takeaways
Problem statement

• Due to inherent nature of diesel engine, trying to keep fuel consumption below a certain value yielded increased smoke in some regions of operation that led to EGR fouling.

• Optimize engine performance calibrations. Maintain emissions - NOx and Total Hydro Carbon at or below current levels, while reducing Smoke, and minimizing fuel consumption.

Situation

• A fleet of truck shows engine light on sometimes accompanied by lack of power due to an engine derate.

Investigations

• Existing data showed Exhaust Gas Recirculation (EGR) cooler was fouled due to higher smoke levels in some regions.
• Pursue a smoke reduction effort while maintaining other emissions and fuel economy.

Problem statement

• Optimize engine performance calibrations. Maintain emissions - NOx and Total Hydro Carbon at or below current levels, while reducing Smoke, and minimizing fuel consumption.
Scope / Deliverable:
- Significant smoke reduction
- Maintain acceptable:
  - NOx
  - HC
  - BSFC

Primary levers
- Rail Pressure,
- Main Injection Timing,
- Pilot Injection Quantity and Timing, adding Post Fueling

Levers to balance NOx, THC, and BSFC impact with Smoke reduction.
- EGR Fraction and Charge Flow Optimization
Approach

Analytical calibration workflow

1. Calibration Planning
2. Design of Experiments
3. Conduct experiment and collect Data
4. Data Import
5. Data Analysis
6. Model Development & Model Validation
7. Generate Optimized Tables
Data import

- Data from different loggers, different softwares, different file extensions, formats can be imported, merged, filtered into a fixed format using MATLAB functions.
- It can handle out of memory data.
- Data in this fixed format is used throughout the analytical calibration workflow.
How to analyze data?

Parallel computing allows the desktops to use their multicore processing capability by executing applications on workers that run locally.

The analysis time was drastically reduced. It can be integrated with Cummins internal clusters.
To create analytical model.

MATLAB optimizer implemented in the calibration toolkit gives successful results.

**Tools used**

Statistics and machine learning; Optimization Toolbox

Smoke values getting reduced with the number of optimization iterations.
### Data visualization

- While developing engine performance calibrations, data visualization is done at multiple stages using MATLAB.

<table>
<thead>
<tr>
<th></th>
<th>0.270</th>
<th>0.570</th>
<th>0.730</th>
<th>1.00</th>
<th>1.17</th>
<th>1.30</th>
<th>1.47</th>
<th>1.680</th>
<th>1.860</th>
<th>2.00</th>
<th>2.200</th>
<th>2.400</th>
<th>2.480</th>
<th>2.960</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>1200</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>1600</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>2000</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>2400</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>2800</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>3200</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>3600</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>4000</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>4400</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>4800</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>5200</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>5600</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>6000</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>6400</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>6800</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>7200</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>7600</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>13.9</td>
<td>13.1</td>
<td>12.9</td>
<td>12.8</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
<td>12.6</td>
</tr>
</tbody>
</table>

![Graph showing data visualization]
Tools used Deploying toolkit

- How to deploy toolkit to users who don’t have MATLAB?
- The toolkit is deployed as an standalone executable, that enables users to run compiled MATLAB applications without installing MATLAB.

![Deploying MATLAB toolkit](Image source: Mathworks)
Results achieved

- Engine dyno testing done to verify the results.
- Bubble plots showing
  - Reduction in Smoke
  - Acceptable increase in NOx, HC, PM and fuel consumption.
Smoke was significantly reduced
Results

Acceptable increase in NOx

NOx was on par with the baseline with a slight acceptable increase.
Acceptable increase in Hydrocarbon

HC was on par with the baseline. There was a slight acceptable increase.
Fuel consumption was on par with the baseline.
Proposed Calibration provides significant Smoke Reduction while maintaining other emissions at current levels and having minimal impact on fuel consumption.

Analytical calibration toolkit has been developed using MATLAB, Statistics and Machine Learning toolbox, Optimization Toolbox, Parallel Computing Toolbox.

- MATLAB and its products integrate computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation.

The toolkit is deployed as an executable using MATLAB compiler.

- When deployed as an standalone executable, the toolkit relies on the MATLAB Runtime, which enables users to run compiled MATLAB applications without installing MATLAB.
- MATLAB Compiler enables to run multiple instances of code without acquiring additional licenses.

MATLAB documentation and support from MathWorks engineers is excellent.

This method has been very successful in optimizing engine performance calibrations.
Balance

Isn’t something you find.

It’s something you create!