The CREO Project: Carbon dioxide Reduction through Emissions Optimisation and the Use of MATLAB

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The CREO Project: Overview

1. **What is CREO?**
   - **CO₂ Reduction through Emissions Optimisation**
   - A collaborative R&D project funded by the TSB

2. **Who is involved?**

3. **What is the aim of the project?**
   - A 15% estimated reduction in CO₂ within business and customer constraints.
   - Previous 3 decades has seen engine efficiency deteriorate by an estimated 8% to meet increasingly stringent vehicle emissions legislation.

4. **Impact?**
   - 500K engines per annum within 7 years.
   - 3 million engines per annum globally within 15 years.
5. How will CREO achieve its aim?
   - re-design the engine and exhaust after-treatment as a complete system, meeting all the legislative, customer and business requirements while minimising the CO2 levels.

6. Specific goals?
   i. The use of novel exhaust after-treatment techniques.
   ii. The on-board generation and use of hydrogen.
   iii. The development and application of new emissions optimisation tools.
      - Jaguar Land Rover – led gasoline workstream.
      - Ford – led diesel workstream.

This work is concerned with the Ford path and will describe how MATLAB has been used to help develop an emissions optimisation process.
Emissions Optimisation Process

Define Problem

Data Collection

Transient Engine Model

Aftertreatment Model

sCVSP → Design Space → Collect DoE Data → Global DoE Emission Model → Transient Airpath Model → Calibration → Steady State Deviations → EGR, Boost, SOI → Speed, Torque, EGR, Boost, SOI → Fuel Economy • NOx • Particulates • HC • CO • Noise

FG Emissions Exhaust Flow / Temperature

Global DoE Emission Model

Tailpipe Emission Model

Steady State Deviations

EGR, Boost, SOI

 transient Engine Model

Aftertreatment Model

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Emissions Optimisation Process

Define Problem

Data Collection

Optimise DoE Design

Optimise Objectives

Transient Engine Model

Aftertreatment Model

sCVSP

Design Space

Collect DoE Data

Global DoE Emission Model

Calibration

Transient Airpath Model

FG Emissions Exhaust Flow / Temperature

EGR, Boost, SOI

Steady State Deviations

Optimise DoE Design

Fuel Economy

NOx

Particulates

HC

CO

Noise

Speed, Torque, EGR, Boost, SOI

Speed, Torque

EGR, Boost, SOI

Exhaust Flow / Temperature

EGR

Boost

SOI

FG Emissions

Transients

Speed, Torque

EGR, Boost, SOI

Steady State Deviations

Optimise Objectives

Tailpipe Emission Model

• Fuel Economy
• NOx
• Particulates
• HC
• CO
• Noise

Optimise DoE Design
Emissions Optimisation Process: vehicle simulation

**SCVSP**

- Model-Based-Design is an important tool in efficiently delivering a range of vehicles with an optimised powertrain maintaining minimum complexity.
- Using a physics-based prediction over various legislative and customer driving cycles before a vehicle exists, provides the input data to model-based optimisation of the engine.
Emissions Optimisation Process: DoE

• One factor at a time:
  – Requires expert consultation.
  – One result with narrow boundary constraints & targets.

• DoE process:
  – Minimal testing with maximum information content e.g. 9 factors, 3 levels, quadratic polynomial model:
    • Full factorial: $3^9$ tests – 2 months.
    • D-optimal: 55 tests – 5 hours.
  – Can optimise over a range of boundary constraints and targets
    • Fitting models to data enables optimisations.
    • Optimise for multiple scenarios without additional testing.
    • Optimal trade-off (Pareto front) analysis.
    • Analysis of correlation between inputs & responses.
  – Automated testing
    • Quicker and more repeatable.
    • Requires less interaction – can run overnight.
Emissions Optimisation Process: DoE

One factor at a time

Start point

Initial constraint

DoE

Collect DoE Data

Initial constraint
Emissions Optimisation Process: DoE

One factor at a time

DoE

Calculate Pareto front

Constrained optimum

Chosen solution
Emissions Optimisation Process: DoE

One factor at a time

Non-optimal solution

Revised constraint

DoE

Re-optimised to meet constraint without additional testing

Revised constraint
Emissions Optimisation Process: Local vs. Global DoE

- **Local DoEs**
  - Point-by-point (time-weighted) cycle optimisation
    - Can only evaluate model at discrete speed/load points
    - Requires interpolation to get an accurate cycle prediction
  - Requires accurate & repeatable dynamometer control

- **Global DoEs**
  - Requires automated screening
  - More efficient data collection
    - Less points for the same speed/torque area
    - Infinite speed/torque resolution – optimise to calibration breakpoints
  - Enables transient analysis & optimisation
    - Requirement for after-treatment optimisation
  - Enables engine scaling / dimensionless modelling
Emissions Optimisation Process: Airpath DoE

- **Airpath DoE:**
  - Define airpath boundaries without any pre-existing knowledge of engine
  - Run DoE using open loop control
    - More stable EGR rate control
    - Increased repeatability
  - Capture relationship between limits and MAF/Boost/SOI
  - Define “safe” boundary for global DoE
    - Enables use of closed loop control during global DoE with less on-line screening (e.g. “hit” rate increased from 70% to 90% after airpath DoE)
Emissions Optimisation Process: Cycle Optimisation

Engine-out emissions trade-off

- More efficient NOx after-treatment
  - EU 6.1 NOx target
  - Lower CO2

- Lighter C-Class vehicle
- Heavier C-Class vehicle
Emissions Optimisation Process: Cycle Optimisation
(using Model-Based Calibration Toolbox)

Min. weighted sum CO$_2$

Optimisation algorithm info.

Sequence of optimisations with progressively tighter constraints

Constraints

Parameter starting values

Operating points and weights
Emissions Optimisation Process: Cycle Optimisation

(using Model-Based Calibration Toolbox)
Emissions Optimisation Process: Cycle Optimisation

Next Steps:

• Currently experimenting with a multi-objective genetic algorithm to:
  – Generate the Pareto-optimal front in one run.
  – More exhaustively search the decision variable space.
  – Reduced sensitivity (vs. gradient-based optimisers) to start position.
  – Reduced sensitivity to getting stuck in local minima.

• This is a significant computing challenge due to the large number of decision variables and may require:
  – Large populations.
  – Parallel computing.
Emissions Optimisation Process: Transient Emissions

- ECU Calibration
- Empirical DoE-based Model Library
- WAVE-RT Transient Airpath Model
- Inputs
- Outputs
Emissions Optimisation Process: Transient Torque vs. Vehicle

![Graph showing transient torque vs. vehicle time with measured and model data. The graph includes axes for Engine Torque [Nm] and Time [s].]
Emissions Optimisation Process: Aftertreatment Model

Emissions After treatment model

- Chemical Kinetic models execution time is typically too large to be run in the loop with iterative engine optimization
- Empirical “lookup” models are utilized to allow rapid evaluation of engine and after treatment as a “system”.

Process
- Thermal Modelling
- NOx Conversion Modelling

Outputs
- Exhaust Temperature
- Mass Flows
- Gas Composition
- Pressure

Outputs
- Tailpipe
- Emissions
Emissions Optimisation Process: Aftertreatment Model Output

- Vehicle Speed kph
- Pre-LNT Temp
- Post LNT Temp
- NOx Engine Out g
- Post LNT NOx g
- NOx Target

Temperature (°C), NOx Efficiency (%), Vehicle Speed (kph)

0 200 400 600 800 1000 1200

NOx Emission (g), NH3 Emission (g), NOx Stored (g), NOx Capacity (g)
Summary

• A model-based emissions optimisation process has been developed in the MATLAB/Simulink environment.
• This process has yielded fuel economy improvements as well as time/cost efficiencies.
• Furthermore, it enables:
  – Full exploration of the design space for any fuel economy gains.
  – ‘What-If’ studies to explore design and calibration opportunities.
  – Robustness studies using optimisation to explore the impact of real-world noise sources (wear, manufacturing, environment, customer usage).

• Further work to be done includes development of:
  – Better correlation of emissions models.
  – Optimisation capability for high-dimensional problems.
  – Further process automation.
  – User interfaces.