industrial systems and control

Industrial Systems and Control Limited

"Control Engineering Services for

the Automotive Industry"

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ISC Background

- Control engineering consultancy
  - ❒ Founded 1987 - as a spin-out from Strathclyde University
- Works across many sectors:
  - ❒ Automotive; Marine; Oil/Gas; Power Generation
  - ❒ Small – 5 full time, 4 part time employees
- However we work with some very large companies:
  - ❒ General Motors; Toyota; Ford; Jaguar; Visteon; BP; Shell; Boeing; BAE Systems; Rolls Royce Marine; SSE; Alstom; EDF

ISC Core Capabilities

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- Dynamic Systems Modelling:
  - ❒ high fidelity first principles models or data-driven identification
- Control Strategy Design – both new and improvements
  - ❒ full software development – NI LabVIEW / CompactRio
- Troubleshooting Control Problems
- Optimisation
- Energy Efficiency Benefits Analysis
- Technology Reviews
- Training – standard and bespoke courses

ISC provides support on novel or challenging control applications.

Close working with clients to get best solution and ensure full transfer.

Dynamic Modelling at the Core

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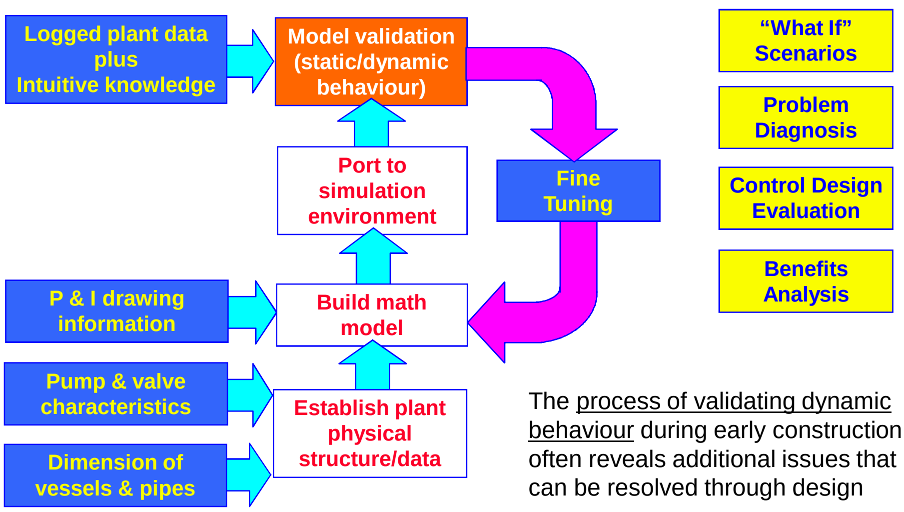

The process of validating dynamic behaviour during early construction often reveals additional issues that can be resolved through design

ISC capabilities in Automotive

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- Projects on Advanced Control:
  - ❒ General Motors, US – Nonlinear Control for Powertrain
  - ❒ GM – Estimation of Aging in Catalyst
  - ❒ GM – New Techniques for Engine Calibration
  - ❒ GM – Advanced Predictive Control for Improved Emissions/Fuel
  - ❒ Toyota, US – New Advanced Control for Automotive Powertrain
  - ❒ Torotrak - Variable transmission system
- Training: Chrysler, Ford, Freescale, GM, Jaguar, Ricardo, Toyota and Visteon.

ISC capabilities in Automotive

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- ISC has National Instruments (NI) Powertrain Control Software and Hardware
  - ❒ complete set of actuator drivers and sensor IO
- Allows rapid control prototyping on test engines
- Customisable software using NI LabVIEW
  - ❒ Fast and flexible implementation
  - ❒ Replication and monitoring of ECU core functions

ISCs Control Engineering Training

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Wide range of highly regarded industrial courses

From basic loop tuning to advanced control

Extensive computer-based hands-on

- When given at company premises can be tailored to exact need
- Bespoke exercises and entire courses can be provided
- Scheduled Training Courses
  - our five most popular and general courses
  - held in central location, scheduled regularly

ISC courses for Automotive Control

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- Control Engineering Practice
- Control Fundamentals – System Identification
- Model Based Control for Automotive Applications
- Nonlinear Control for Automotive Applications
- Kalman Filtering
- Optimization and System Identification
- Introduction to Modelling, Simulation & Control for Automotive Applications

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Automotive Control Projects

#1 Diesel Engine Control

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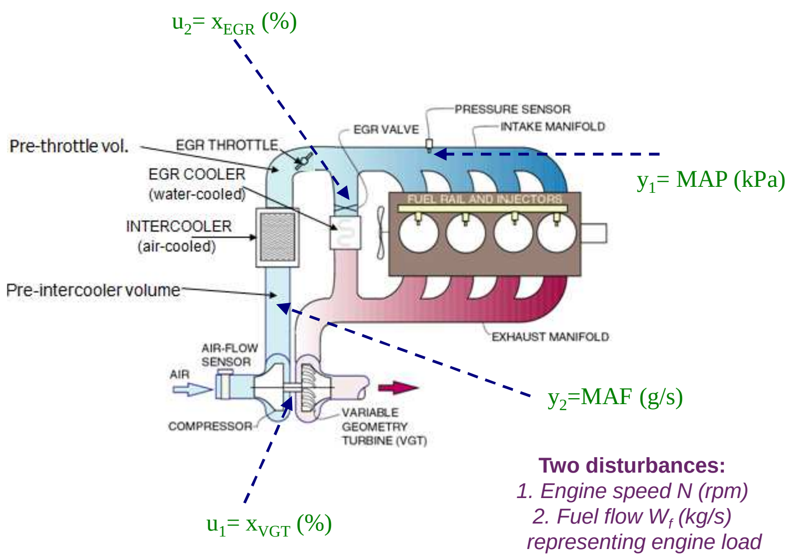
Diesel Engine 2x2 System



Two disturbances:

1. Engine speed N (rpm)

2. Fuel flow W_f (kg/s)

representing engine load

Diesel Engine Model Example

- To control:
  - Intake manifold pressure or Manifold Absolute Pressure (MAP)
  - Exhaust gas recirculation (EGR) rate (or fraction)
- Two control signals:
  - Variable Geometry Turbine (VGT) vane lift u_{vgt} [% closed]
  - EGR valve stem position u_{egr} [% open]
- Includes additional actuator:
  - EGR throttle u_{thr} [% closed]
  - Normally kept fully open - can be used to extend authority of EGR valve

Diesel Engine Model Example

- Both VGT and EGR introduce internal feedback paths in engine
  - Potentially, depending on engine operating conditions, cause:
    - Response overshoots
    - Non-minimum phase behavior
    - DC sign reversal

Simulation Test Bed

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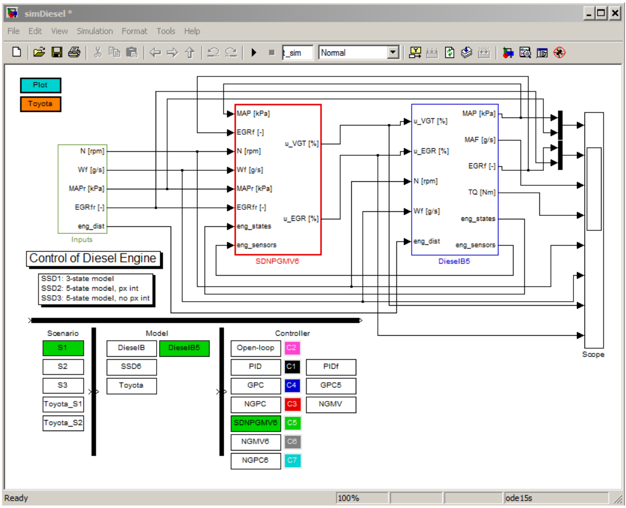
- Allows selection of desired:
  - Engine model
  - Controller
  - Simulation scenario
- Used in conjunction with MATLAB design script



Control Objectives

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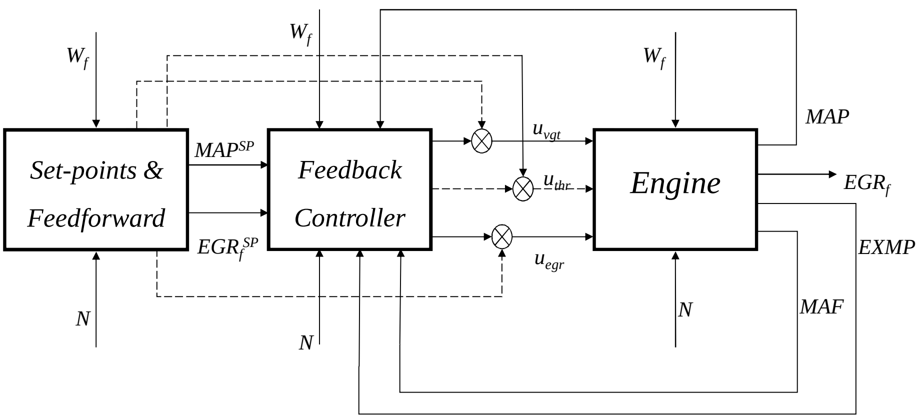
- Diesel engine control objectives
  - Supply driver's requested engine torque
  - Minimize fuel consumption
  - Keep NO_x conc. in exhaust and smoke as low as possible
- In this study, torque control not considered
  - Fuel flow W_f is given - represents engine load.
- EGR is ratio of exhaust gas flow recirculated into intake manifold to total gas flow into cylinders
  - Defined as: $$EGR_f = \frac{W_{egr}}{MAF + W_{egr}}$$

Control Objectives

- Set-points for EGR_f and MAP are computed on-line from static maps (given as look-up tables)
  - ❒ Maps are functions of engine conditions - i.e. engine speed and fuel flow rate
- General block diagram of Diesel Engine control system may be constructed as in following Figure

Diesel Engine Control System Schematic Diagram

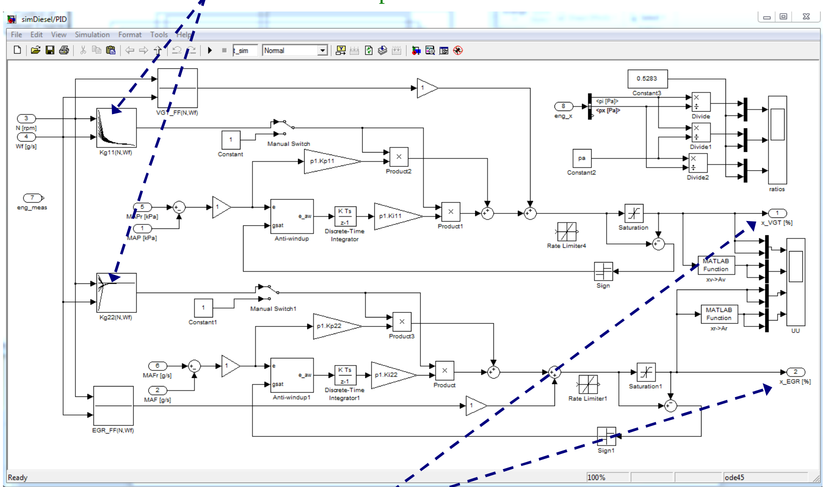


Control Structure

- EGR throttle assumed to remain fully open
  - ❒ To simplify control problem
  - ❒ Results in square 2×2 system
  - ❒ Feedforward signals not included explicitly in solution
    - ➢ Denoted by dashed lines in figure
- Feedback Controller block includes Kalman Filter
  - ❒ Estimates engine states based on:
    - ➢ Model
    - ➢ Measurements of MAP, MAF and exhaust manifold pressure EXMP

Gain-Scheduled PID Control

Gain-scheduled parameters



(x_v, x_r) used as controller outputs

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#2 Predictive Control for SI and Diesel Engines

MPC Performance Index and Design

- Control vector D***U***(t) is often costed and calculated to minimize:
  - Predicted errors over prediction horizon N
  - Size of control move over control horizon N_u
- Consider the quadratic performance index:

$$\min_{\Delta \boldsymbol{U}(t)} \boldsymbol{J} = \hat{\boldsymbol{E}}(t+1)^T \boldsymbol{Q} \hat{\boldsymbol{E}}(t+1) + \Delta \boldsymbol{U}(t)^T \boldsymbol{R} \Delta \boldsymbol{U}(t)$$

  - where **Q** is positive-definite weighting matrix and R is positive semi-definite matrix
  - Both **Q** and **R** are usually diagonal matrices with positive diagonal elements
  - Weighting matrices are used to weight most important outputs and inputs

Design Guidance in using Predictive Control for Engines

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- Methods to deal with uncertainties, disturbances and robustness
  - ❒ Cost weightings and additional sensitivity cost terms
  - ❒ Disturbance models
  - ❒ System descriptions
- Tuning Procedures for Robustness:
  - ❒ PID inspired / Free cost weighting choice
- Modifications to the Estimator:
  - ❒ Modelling error compensation
- Application of constraints:
  - ❒ Hard constraints / Soft constraints
- Delay compensation - similar ideal response as Smith Predictor

Integral Action

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- Note steady state error
  - ❒ MPC (in basic form) has no integral action
  - ❒ Needs to be introduced artificially
- Recommended:
  - ❒ Introduce integrator on dynamic control error weighting
  - ❒ Weight incremental control action and modify plant by augmenting an integrator

State Dependent LPV Systems

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- System with state equation matrices that depend upon:
  - ❒ States
  - ❒ Control inputs
  - ❒ Parameters

$$x(t+1) = \mathcal{A}(x,u,p)x(t) + \mathcal{B}(x,u,p)u(t) + \mathcal{D}(x,u,p)d(t)$$
$$y(t) = \mathcal{C}(x,u,p)x(t) + \mathcal{E}(x,u,p)u(t)$$

State Dependent LPV Systems

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- State-dependent LPV systems include:
  - ❒ Pseudo-LPV systems
  - ❒ PWA systems
  - ❒ Some Hybrid systems
- Choice of model is a problem:
  - ❒ Uniqueness
  - ❒ Type of model due to origin (physical equations, Jacobian, ...)
  - ❒ Uncertainty representation (unstructured, parametric, ...)
  - ❒ Numerical computations and sensitivity
  - ❒ Implications for Control law solution (bias terms, scaling, ...)

Cost-Function Definition: Engines

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- Optimal control problem and cost-function must have simple base level
  - ❒ Which is well understood
  - ❒ But must also be able to cope with:
    - ➢ Future enhancements
    - ➢ Changes to performance, drivability & fatigue knowledge
- Generalized Predictive Control (GPC) related cost-function and solution approach was first proposed
  - ❒ Reason: very successful in process industries

Cost-Functions: GPC Augmentation

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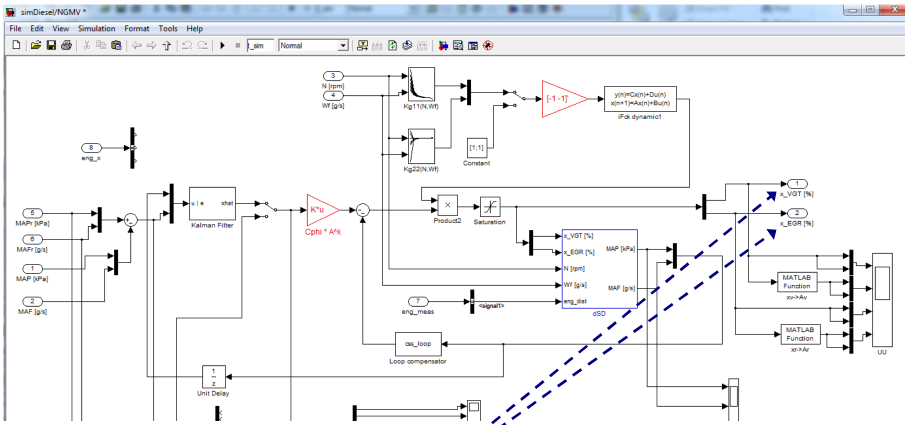
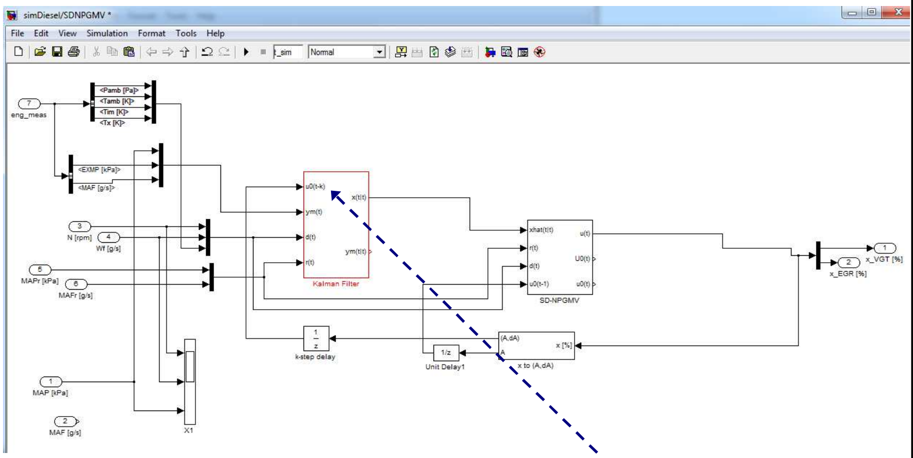
- Cost-function can however include dynamic weightings
  - ❒ To enable frequency response shaping of designs
- Weightings may approximate nonlinearities if made state-dependent
  - ❒ Possibly needed in drivability/fatigue minimization problem
  - ❒ Involves little additional complexity
- Cost-function will also include:
  - ❒ Traditional tracking error term; control action costing term
- Cn also include nonlinear control weighting term to introduce:
  - ❒ Wind-up protection; Hard constraint limits

NGMV Control



(x_v, x_r) used as controller outputs

SD-NPGMV Controller Structure



u(t) refers to (x_v, x_r) controls

u_0(t) refers to (A_v, A_r) controls

SD model used in Kalman Filter so u0(t-k) fed back

SD-NPGMV block

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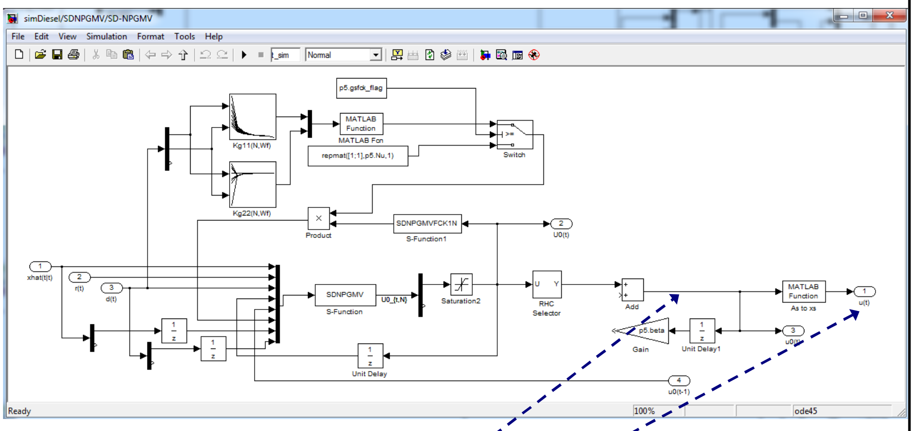

Controller computes optimal (A_v, A_r)

Transformed to (x_v, x_r)

NGPC with PID Inspired Weightings and Dynamic Control Costing

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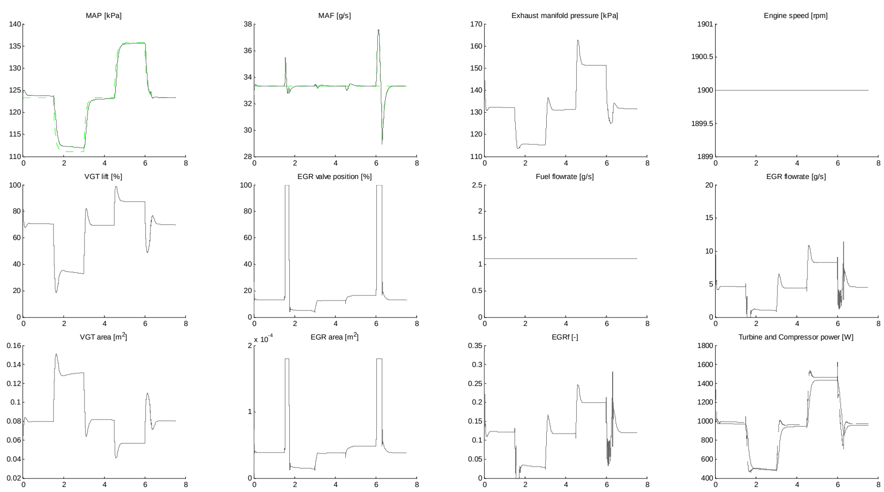
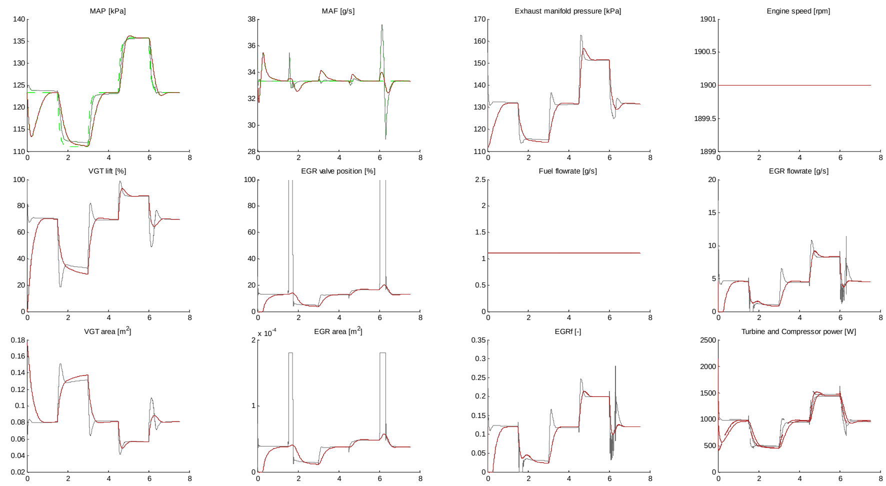
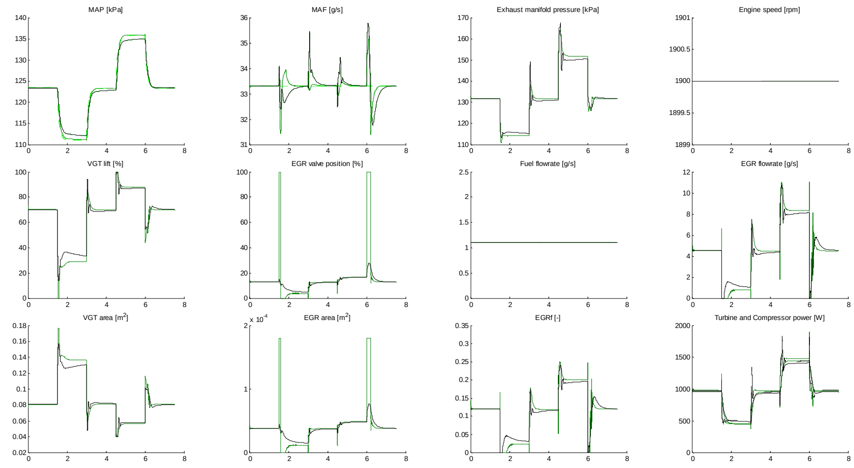


Comparison of NGPC with Dynamic Control Costing and NGMV (red) both with PID Inspired Weightings



Comparison of NPGMV with PID Inspired Weightings and F_{ck} Costing and PID Controller (black)



Thank you. Any questions ?

Dr Andy Clegg, Managing Director, ISC Ltd

Tel: (+44) 0141 847 0515

Direct: (+44) 0141 225 0127

Fax: (+44) 0141 221 1706

Web: www.isc-ltd.com

36 Renfield Street, Glasgow, G2 1LU, Scotland, UK