The role and impact of open-source models supporting research and development on complex powertrains for sustainable transportation

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Vehicular Systems

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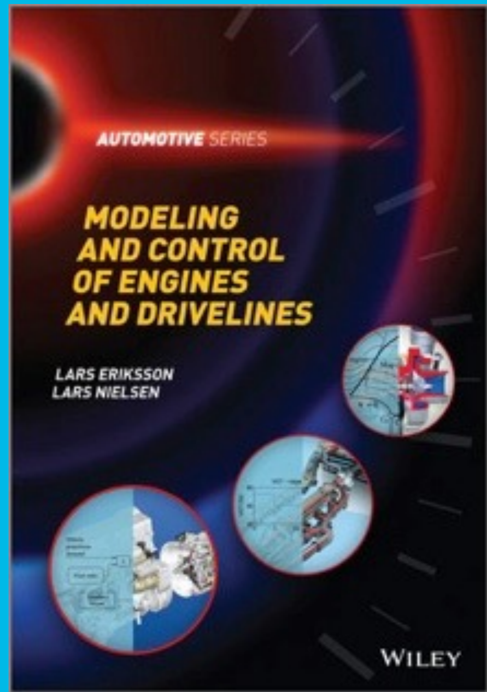

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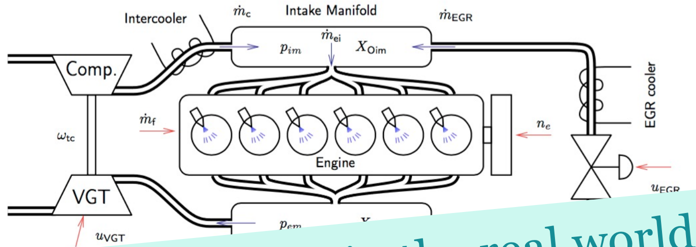
Outline – Open-Source Model and Model-Based Control

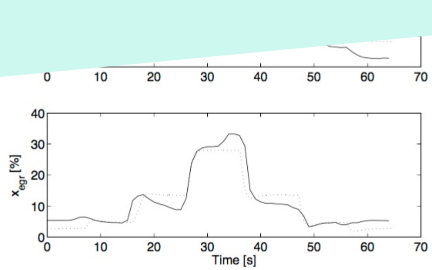
- Consummation and Birth of the Diesel Engine Model
  - Release as open source
- Applications and Evolution of the Model
- Marine Control Case Study
- Widening of the application areas
  - Beyond my imagination
- Lessons Learned

The Diesel Engine Model

- Important and difficult system properties
  - Non-minimum phase
  - Nonlinear behavior, sign reversal.
- Systematic model buil...
- ...
  - Engine Torque, Fuel Economy
  - Exhaust Temperature, Dominating dynamics



A model is a simplified description of a phenomenon or system in the real world!
A model is a predictor for outcomes of future experiments. What happens if …?
-All Models are Wrong!
-But, Some are Useful!
G.P. Box



$$W_f = \frac{10^{-6}}{120} u_\delta n_e n_{cyl}$$
$$\eta_{vol} = c_{vol1}\sqrt{p_{im}} + c_{vol2}\sqrt{n_e} + c_{vol3}$$
$$X_{Oe} = \frac{W_{ei}X_{Oim} - W_f (O/F)_s}{W_{eo}}$$
$$\lambda_O = \frac{W_{ei}X_{Oim}}{W_f (O/F)_s}$$
$$M_e = M_{ig} - M_p - M_{fric}$$
$$M_{ig} = \frac{u_\delta 10^{-6} n_{cyl}\eta_{ig} q_{HV}}{4\pi}$$
$$M_p = \frac{V_d}{4\pi}(p_{em} - p_{im})$$
$$M_{fric} = \frac{V_d 10^5}{4\pi}\left(c_{fric1}\left(\frac{n_e}{1000}\right)^2 + c_{fric2}\left(\frac{n_e}{1000}\right) + c_{fric3}\right)$$
$$\eta_{ig} = \eta_{igch}\left(1 - \frac{1}{r_c^{\gamma_{cyl}-1}}\right)$$

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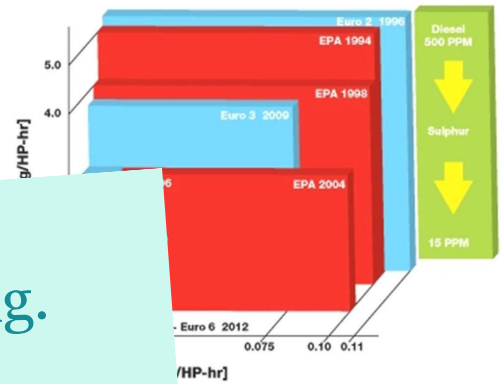
Modelling diesel engines with a variable-geometry turbocharger and exhaust gas recirculation by optimization of model parameters for capturing non-linear system dynamics.
Johan Wahlström, and Lars Eriksson (2011).
In: *Proceedings of the Institution of Mechanical Engineers, Part D, Journal of Automobile Engineering*, 225(7):960--986.

Consummation & Birth of the Model

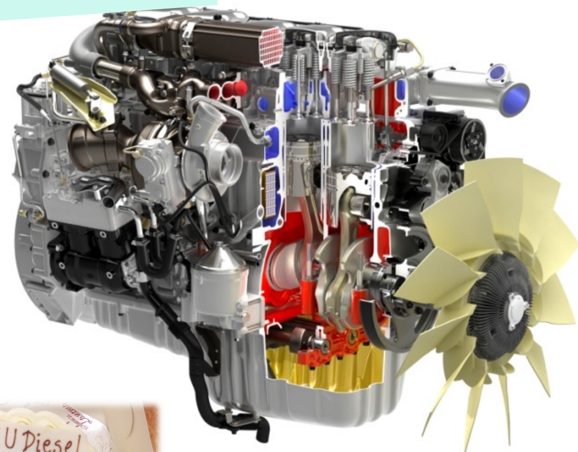
Image by Cummins



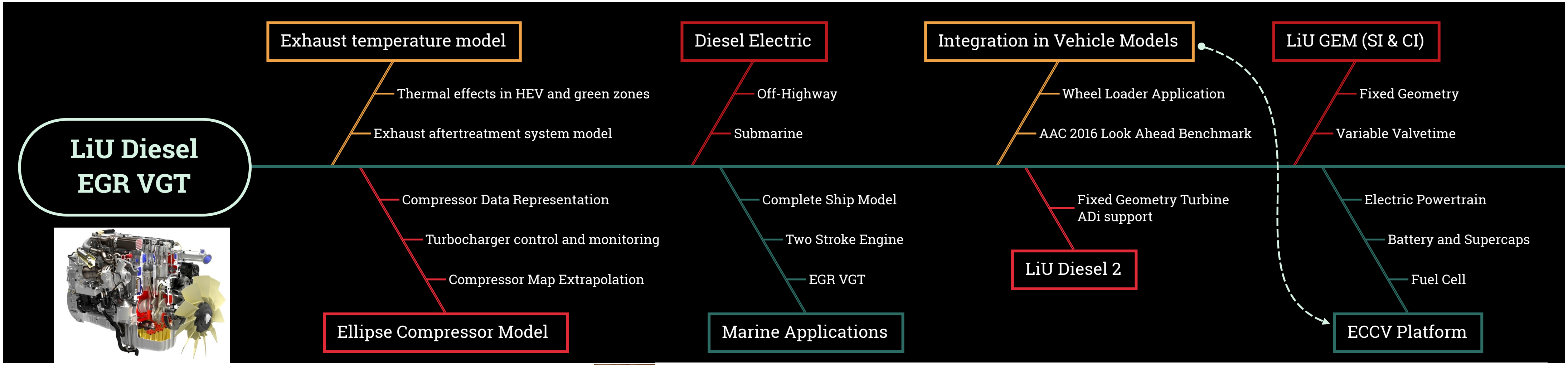
- Swedish Energy Agency Project: 2005-2009
- Control of Coupled Gas Flows in Heavy Diesel Engines
- Collaboration LiU & SCANIA
- How to Rea

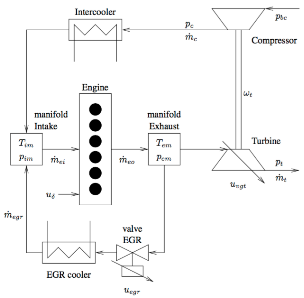
Sharing data – Problem for Industry!
A model is not reality – The savior for sharing.
Our "Control Wizardry" relies on models.

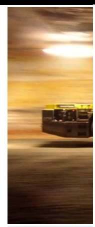
- Modeling w
  can take u
  - Need a lab and experiments consume resources
  - A model is an information collector and carrier
  - Make the model open to increase the pace of innovation
  - Discussion with partner: Release the model and more researchers will work on relevant problems with relevant models.
  - YES
  - Efficient use of Resources

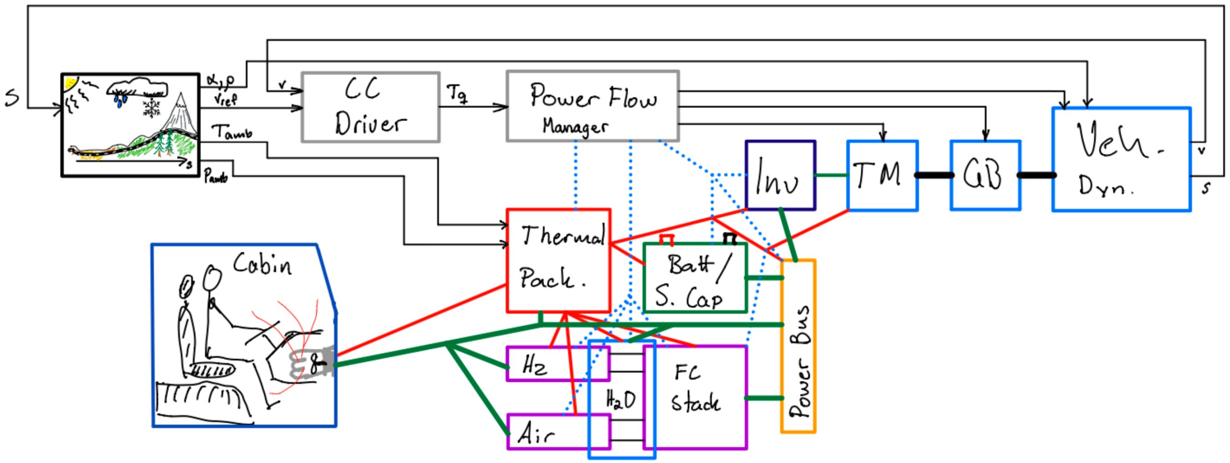


Dynamic & Organic Evolution of the Model

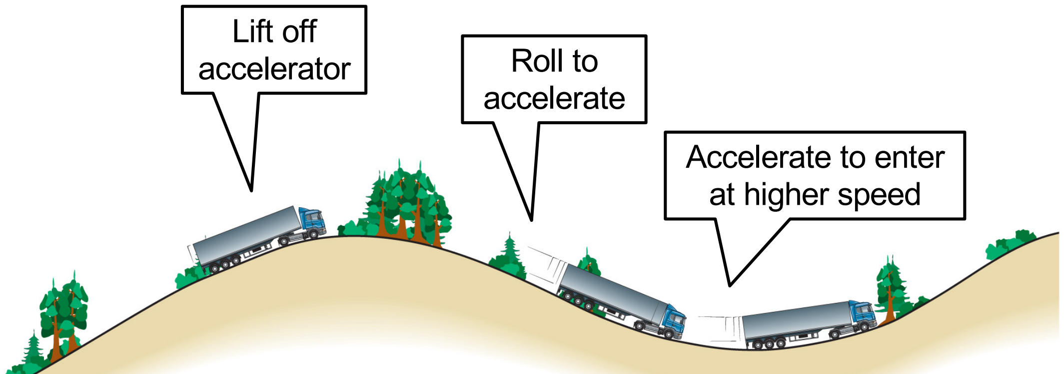




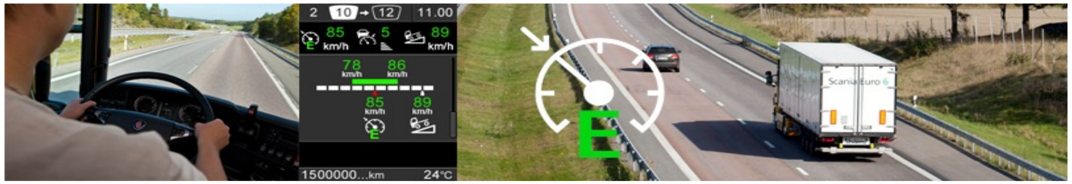


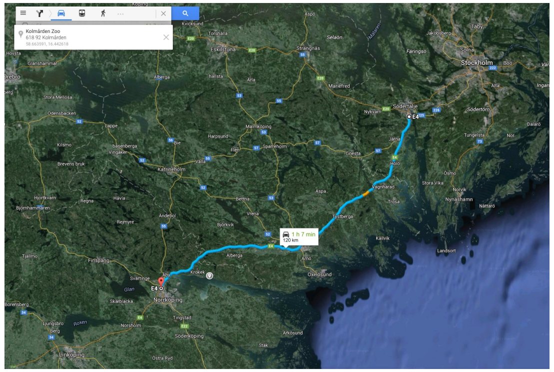


Complete Commercial Vehicle in Driving Mission – AAC 2016 Benchmark Problem (Diesel Engine and Gearbox) – IFAC WC 2023 Benchmark (Fuel Cell, Battery, E.M., and Gearbox)



Cruise control system that uses GPS to read the position of the vehicle and predict the topography of the road ahead



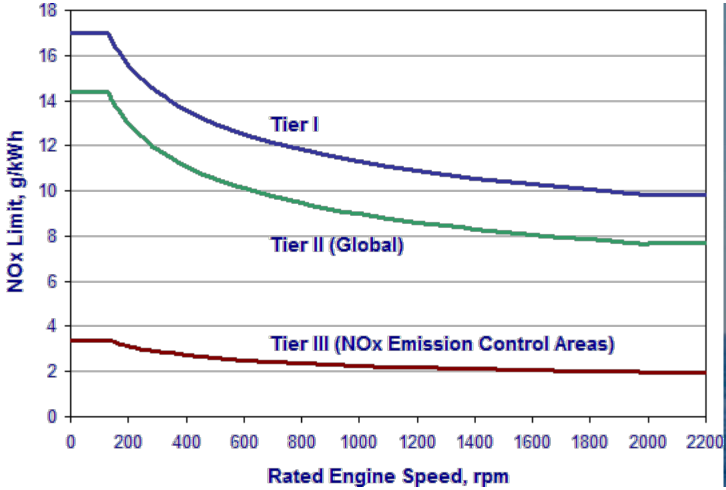


Coupling to Hybrid vehicles
Energy management
Potential & Kinetic

6 different solutions submitted

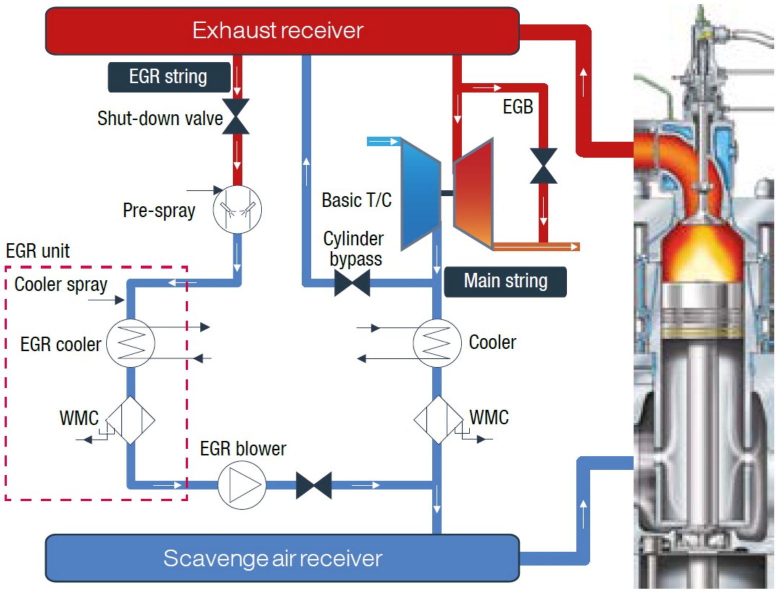
MAN D&T – Clean Marine Vessels

- Combustion engines emit NO_x as part of exhaust.
  - Effects: Smog, acid rain, nutrient enrichment etc.
- Automotive NO_x restrictions. Emission reduction methods are not directly transferable due to differences in 2-stroke vs. 4-stroke engines.
- Marine NO_x restrictions: International Maritime Organization (UN).
  - Tier I, Tier II and Tier III (NECAs).



MAN D&T – The Engines

- Used as Vessel Prime Movers or Stationary Power Plants
- Come in sizes up to
  - 14 m high and 30 m long.
  - 2300 tons.
  - 14 cylinders.
  - 100.000+ hp
- EGR System
  - Valve, cooler
  - Scrubber
  - Blowers

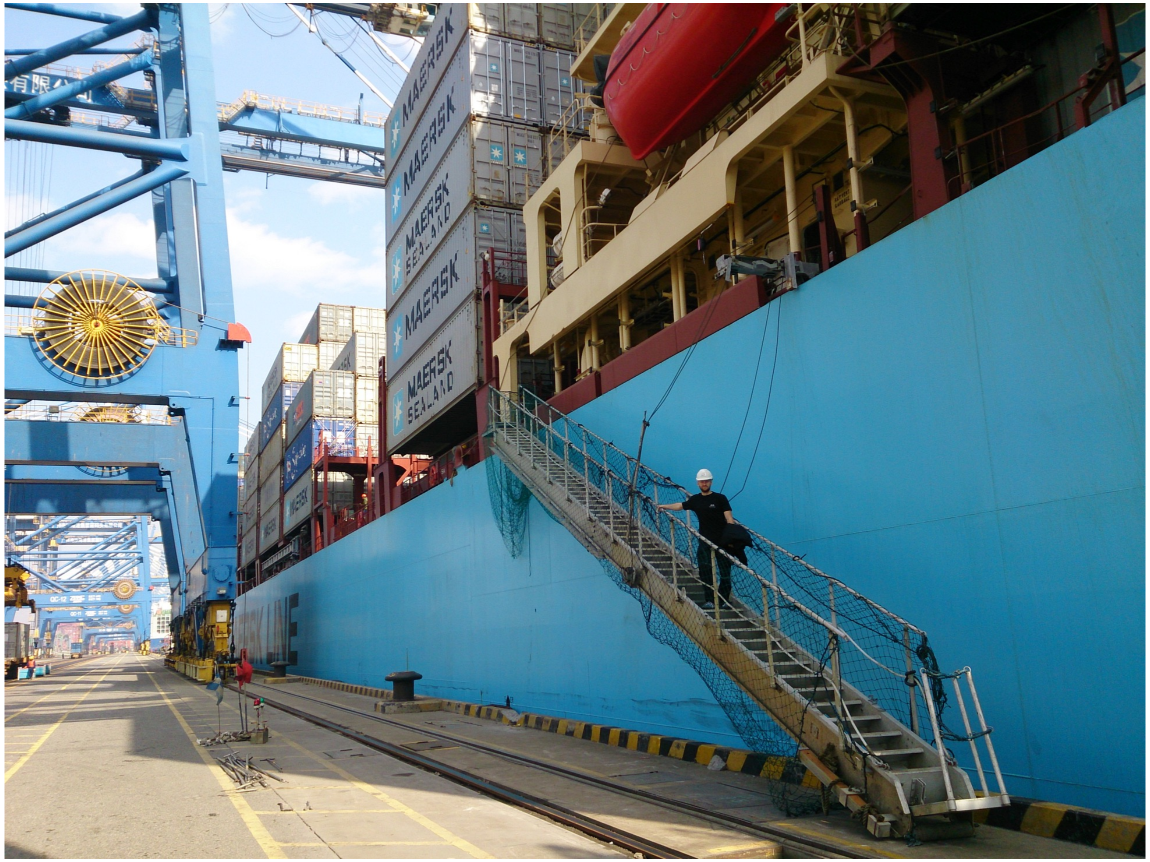


MAN D&T – EGR Systems

- Real World Experiments
  - Modeling, parametrization, validation
  - Controller testing and validation

- MAN Diesel & Turbo engines with EGR in 2014
  - Diesel Research Center, Copenhagen.
  - Alexander Maersk.
  - Maersk Cardiff.
  - Polaris and Pegasus Voyagers.
  - Key Pacifico.

  - many more were & are being built and ordered.



MAN D&T – EGR Engine Model

- Existing model: Mean-Value Engine Model – Extended
  - Molar Flows

    $$\dot{n}_i = f(p_{in}, p_{out}, T_{in}, \varepsilon)$$

  - Pressures

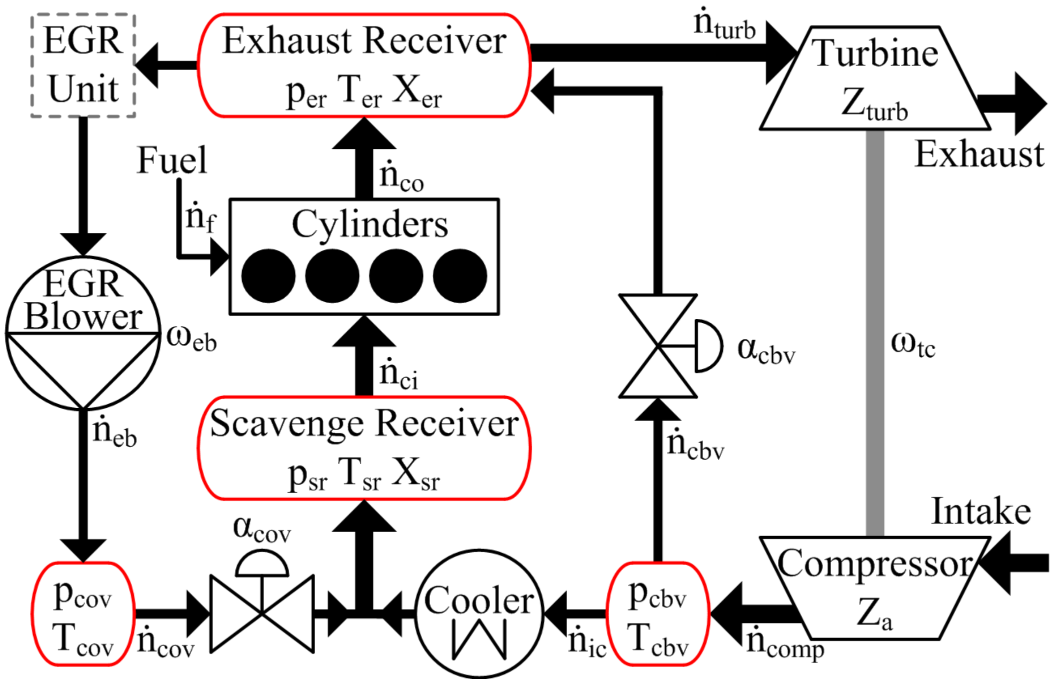
    $$\dot{p}_i = \frac{RT_i}{V_i}(\dot{n}_{in} - \dot{n}_{out})$$

  - Gas composition

    $$\dot{X}_i = \frac{RT_i}{p_i V_i} \sum_{input=j} \dot{n}_j (X_j - X_i)$$

  - Turbocharger speed

    $$\dot{\omega}_{tc} = \frac{P_{turb} - P_{comp}}{J_{tc}\omega_{tc}}$$



Modeling of a Large Marine Two-Stroke Diesel Engine with Cylinder Bypass Valve and EGR System.
Guillem Alegret, Xavier Llamas, Morten Vejlgaard-Laursen, and Lars Eriksson (2015).
In: *10th IFAC Conference on Manoeuvring and Control of Marine Craft*. Copenhagen, Denmark.

MAN D&T – The Extended Model

Scavenge receiver

$$\frac{d}{dt}p_{scav} = \frac{R_a}{V_{scav}}(T_{comp}\dot{m}_{comp} + T_{egr}\dot{m}_{egr} - T_{scav}\dot{m}_{engIn})$$

$$\frac{d}{dt}O_{scav} = \frac{R_a}{p_{scav}V_{scav}}((O_{exh} - O_{scav})\dot{m}_{egr}T_{egr}.. + (O_{comp} - O_{scav})\dot{m}_{comp}T_{scav})$$

Exhaust receiver

$$\frac{d}{dt}p_{exh} = \frac{R_e}{V_{exh}}T_{exh}(\dot{m}_{engOut} - \dot{m}_{egr} - \dot{m}_{turb})$$

$$\frac{d}{dt}O_{exh} = \frac{R_e T_{exh}}{p_{exh}V_{exh}}(O_{eng} - O_{exh})\dot{m}_{engOut}$$

Cylinders

$$\dot{m}_{EngIn} = A_{eng}\frac{p_{scav}}{\sqrt{R_a T_{scav}}}\sqrt{\frac{2\gamma_a}{\gamma_a - 1}\left[\Pi_{eng}^{\frac{2}{\gamma_a}} - \Pi_{eng}^{\frac{\gamma_a+1}{\gamma_a}}\right]}$$

$$\dot{m}_{EngOut} = \dot{m}_{EngIn} + \dot{m}_{Fuel}$$

$$u_{load} = Y\omega_{shaft}k_{load}$$

$$\dot{m}_{fuel} = Y\omega_{shaft}$$

$$T_{exh} = \eta_{sc}\Pi_{eng}^{1-1/\gamma_a}r_c^{1-\gamma_a}x_p^{1/\gamma_a - 1}\ldots \left(q_{in}\left(\frac{1-x_{cv}}{c_{pa}} + \frac{x_{cv}}{c_{Va}}\right) + T_1 r_c^{\gamma_a - 1}\right)$$

$$x_p = 1 + \frac{q_{in}x_{cv}}{c_{Va}T_1 r_c^{\gamma_a - 1}}$$

$$q_{in} = \frac{\dot{m}_{fuel}q_{HV}}{\dot{m}_{engIn} + \dot{m}_{fuel}}(1 - x_r)$$

$$x_r = \frac{\Pi_e^{1/\gamma_a}x_p^{-1/\gamma_a}}{r_c x_v}$$

$$T_1 = x_r T_e xh + (1 - x_r)T_{scav}$$

$$x_v = 1 + \frac{q_{in}(1 - x_{cv})}{(q_{in}x_{cv}/c_{Va}) + T_1 r_c^{\gamma_a - 1}}\frac{1}{c_{pa}}$$

$$O_{eng} = \frac{\dot{m}_{engIn}O_{scav} - \dot{m}_{fuel}OF_s O_{comp}}{\dot{m}_{engIn}\dot{m}_{fuel}}$$

EGR string

$$\dot{m}_{egr} = u_{egr}A_{egrmax}\frac{p_{blow}}{\sqrt{R_e T_{scav}}}\sqrt{\frac{2\gamma_e}{\gamma_e - 1}\left[\frac{p_{scav}}{p_{blow}}^{\frac{2}{\gamma_e}} - \frac{p_{scav}}{p_{blow}}^{\frac{\gamma_e+1}{\gamma_e}}\right]}$$

$$\Gamma_{blow} = \ldots$$

$$\Psi_{blow} = \frac{2c_{pe}T_{egr}}{R_{blow}^2 u_{blow}^2}\left(\frac{p_{blow}}{p_{exh}}^{1-\frac{1}{\gamma_e}} - 1\right)$$

$$c_{\Phi 1} = c_{\omega\Phi_{blow}}\left[u_{blow}^2 \; u_{blow} \; 1\right]^T$$

$$c_{\Psi 1} = c_{\omega\Psi_{blow}}\left[u_{blow}^2 \; u_{blow} \; 1\right]^T$$

Turbine/Compressor

$$u_{vgt,FB} = \frac{1}{\tau_{vgt}}(u_{vgt,SP}(t - d\tau_{vgt}) - u_{vgt,FB})$$

$$\dot{m}_{turb} = k_{vgt}(u_{vgt})f_{turb}(\Pi_t, \omega_t)$$

$$f_{turb}(\Pi, \omega_t) = \sum_{n=0}^{4}\sum_{m=0}^{4}T_{mass}(n,m)\omega_t^n\Pi_t^m$$

$$k_{vgt}(u_{vgt}) = au_{vgt}^2 + bu_{vgt} + c$$

$$\eta_t = v_{turb}(h_{turb}(\Pi_t, \omega_t), u_{vgt})$$

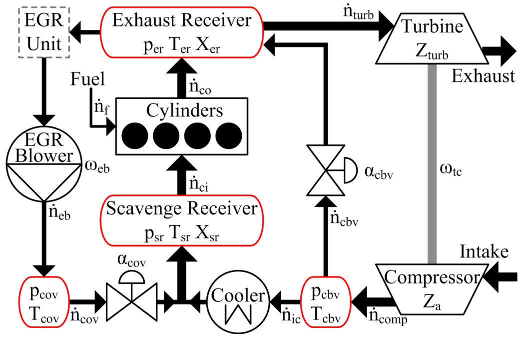
$$h_{turb}(\Pi_t, \omega_t) = \sum_{n=0}^{4}\sum_{m=0}^{4}T_h(n,m)\omega_t^n\Pi_t^m$$

$$\sum^{4}\sum^{4} T_{\ldots}(n,m)h_{turb}^n u_{vgt}^m$$

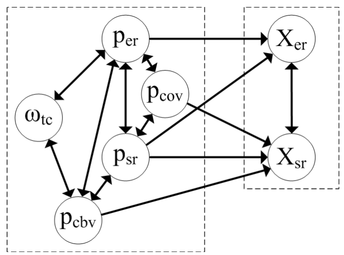
$$P_t = \eta_t\dot{m}_{turb}c_{pe}T_{exh}\left(1 - \frac{p_{amb}}{p_{exh}}^{\ldots}\right)$$

$$P_c = \frac{\dot{m}_{comp}c_{pa}T_{amb}}{\eta_c}\left(\frac{p_{scav}}{p_{amb}}^{1-\frac{1}{\gamma_a}} - 1\right)$$

Simplified the Model Shamelessly!
- Enables synthesis with our tools.
- Loss of generality.



View as two cascaded submodels.



Separate oxygen level sub model and apply model reduction. Control Oriented Model - COM

$$\tau\dot{O}_{sr} = -O_{sr} + O_a - \frac{\left(1 + \frac{y}{4}(O_a + 1)\right)\dot{n}_f\dot{n}_{egr}}{\left(\dot{n}_{ic} + \frac{y}{4}\dot{n}_f\right)\left(\dot{n}_{ic} + \dot{n}_{egr}\right)}$$

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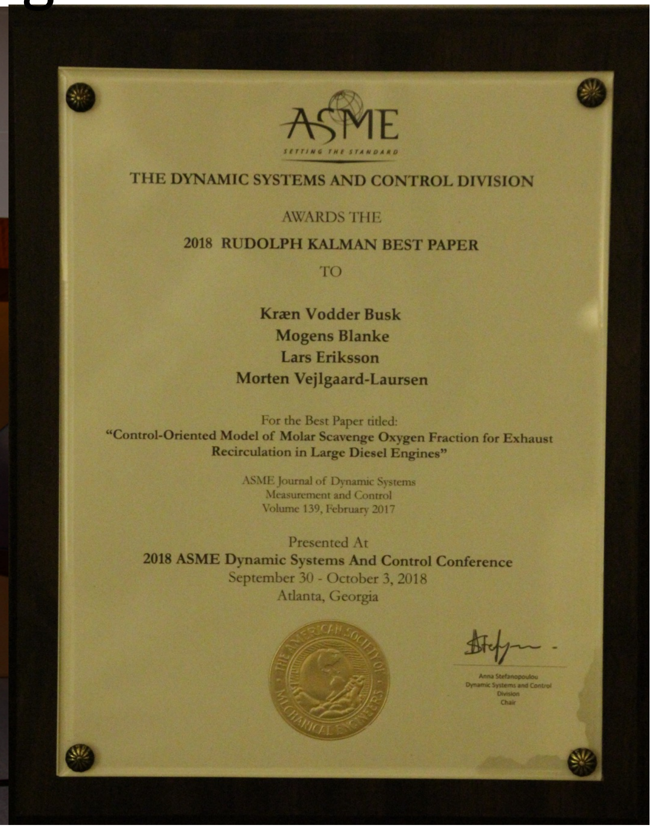
Control-Oriented Model of Molar Scavenge Oxygen Fraction for Exhaust Recirculation in Large Diesel Engines.
Kraen Vodder Nielsen, Mogens Blanke, Lars Eriksson, and Morten Vejlgaard-Laursen (2017).
In: *ASME Journal of Dynamic Systems, Measurement, and Control*, 139(2).

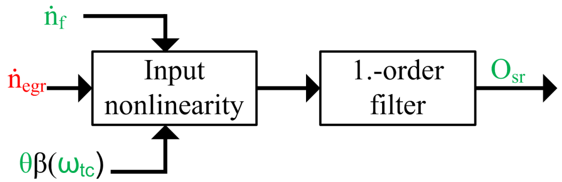
2018 – Rudolph Kalman Best Paper Award
MAN D&T – The Extended Engine Model



Control-Oriented Model of Molar Scavenge Oxygen Fraction for Exhaust Recirculation in Large Diesel Engines.
Kraen Vodder Nielsen, Mogens Blanke, Lars Eriksson, and Morten Vejlgaard-Laursen (2017).
In: *ASME Journal of Dynamic Systems, Measurement, and Control*, 139(2).

MAN D&T – Model-Based Estimation and Control

Structure of COM: 1st-order Hammerstein.



Input nonlinearity from COM:

$$O_{sr} = O_a - \frac{\left(1 + \frac{y}{4}(O_a + 1)\right)\dot{n}_f \dot{n}_{egr}}{\left(\theta\beta(\omega_{tc}) + \frac{y}{4}\dot{n}_f\right)\left(\theta\beta(\omega_{tc}) + \dot{n}_{egr}\right)}$$

Inverted input nonlinearity:

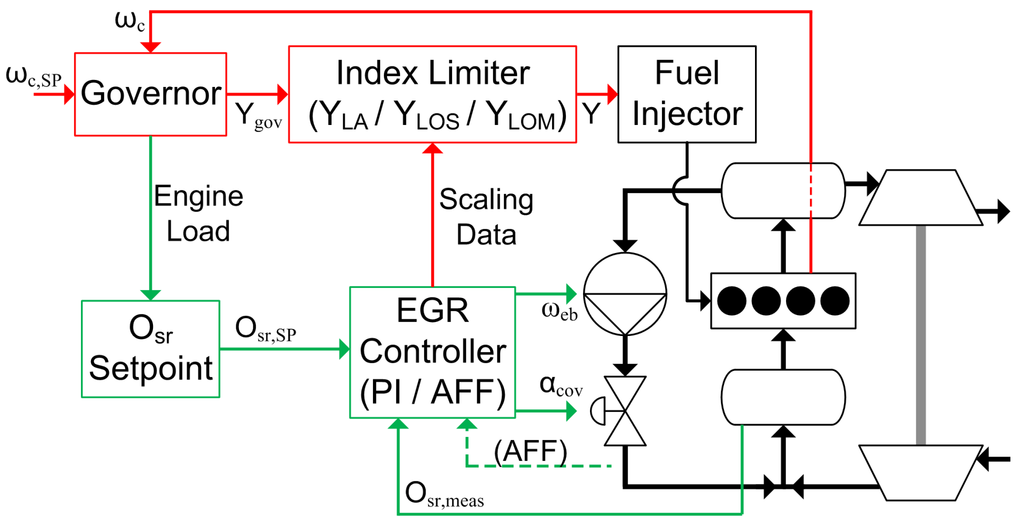
$$\dot{n}_{egr} = \frac{\theta\beta(\omega_{tc}) \cdot (O_a - O_{sr})}{O_{sr} - \frac{\theta\beta(\omega_{tc}) \cdot O_a - \dot{n}_f \cdot \left(1 + \frac{y}{4}\right)}{\theta\beta(\omega_{tc}) + \frac{y}{4} \cdot \dot{n}_f}}$$

Adaptive Feed Forward Controller (AFF)

Exponential convergence – Obs. & Con.

EGR Controller

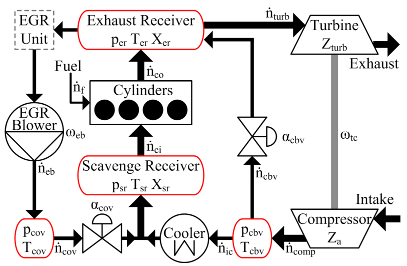
Fuel Controller (Index Limiter)

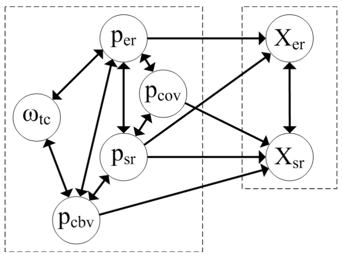


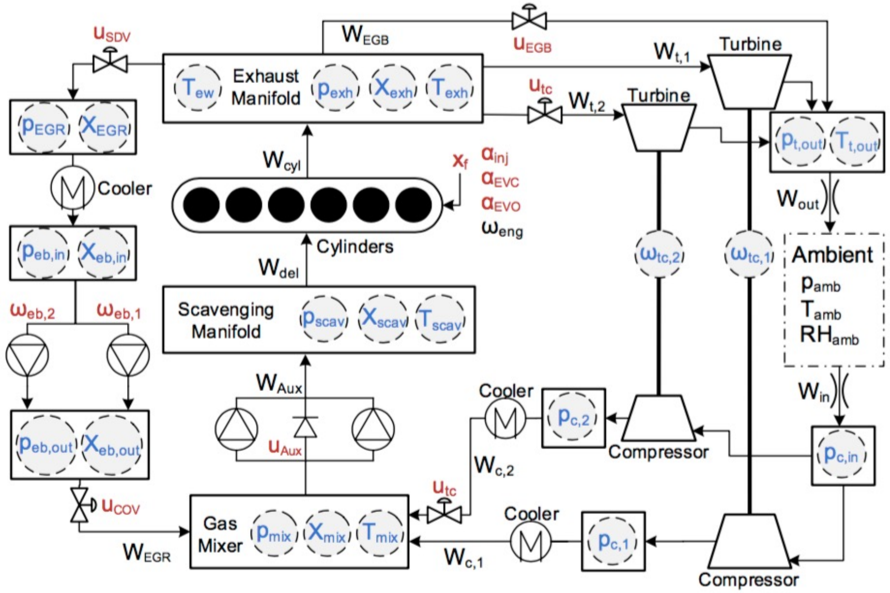
Adaptive feedforward control of exhaust recirculation in large diesel engines
Kræn Vodder Nielsen, Mogens Blanke, Lars Eriksson, Morten Vejlgaard-Laursen
Control Engineering Practice, Volume 65, Pages 26-35, August 2017

Do the Simplifications stand the Test?

- Adaptive control design on the simplified model
- Test the design on a full model in dynamic ship operation
- Robustness to parameter changes and measurement errors







$$\tau \dot{O}_{sr} = -O_{sr} + O_a - \frac{\left(1 + \frac{y}{4}(O_a + 1)\right)\dot{n}_f \dot{n}_{egr}}{\left(\dot{n}_{ic} + \frac{y}{4}\dot{n}_f\right)\left(\dot{n}_{ic} + \dot{n}_{egr}\right)}$$

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Modeling and Control of EGR on Marine Two-Stroke Diesel Engines.
Xavier Llamas (2018).
PhD thesis, No. 1904, Linköping University.

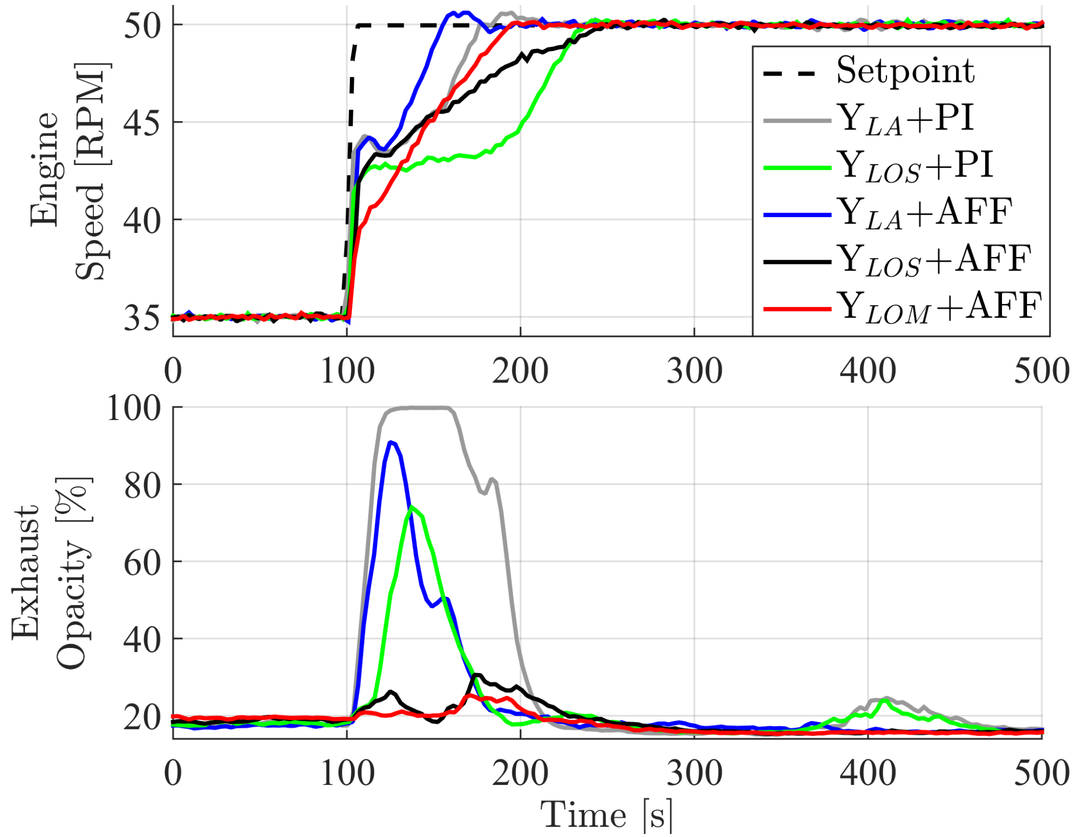
Robustness Analysis of Dual Actuator EGR Controllers in Marine Two-Stroke Diesel Engines.
Lars Eriksson, and Xavier Llamas (2020).
In: *Journal of Marine Engineering & Technology*, 19(sup. 1):17--30.

MAN D&T – Controller Demonstrations

Existing:
Y_{LA}+PI

Improved:
Y_{LA}+AFF

Final:
Y_{LOM}+AFF



Danish Innovation Award

- Kraen Vodder Busk
  - PhD Thesis March 2017
  - Decision for production spring
  - Implementation and integration in the production code Summer 2017
  - Installation and testing at customer October 2017
  - Innovation Award as Industrial researcher January 2018 Handed over by Sören Pind, Minister of Education and Research

- Available open source models was a critical enabler for this high pace of innovation

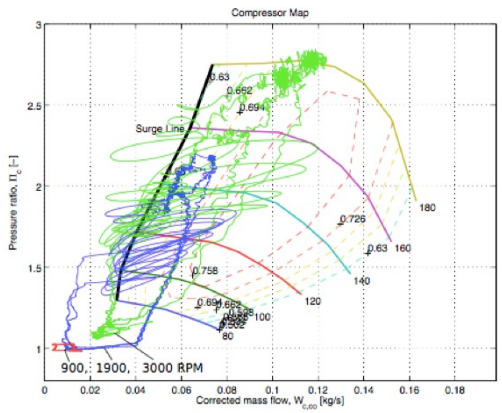
Controller Implementation in Production

- Adaptive Control based on the Model Implemented and Tested in Ships
- In-Production:
  First commissioning in October 2017 meeting and exceeding IMO NECA Legislations

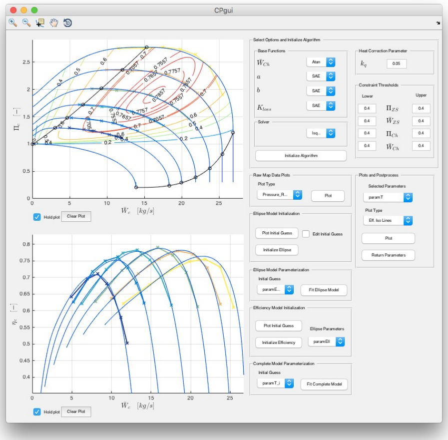
- **Adaptive feedforward control of exhaust recirculation in large diesel engines**
  Kræn Vodder Nielsen, Mogens Blanke, Lars Eriksson, Morten Vejlgaard-Laursen
  Control Engineering Practice, Volume 65, Pages 26-35, August 2017

Awarded:
Control Engineering Practice Paper Price at IFAC World Congress 2020 in Berlin

Turbo modeling outside The Box



- Performance map extrapolation
  - Start & all low load
  - Low load marine
  - Extrapolation based on physics

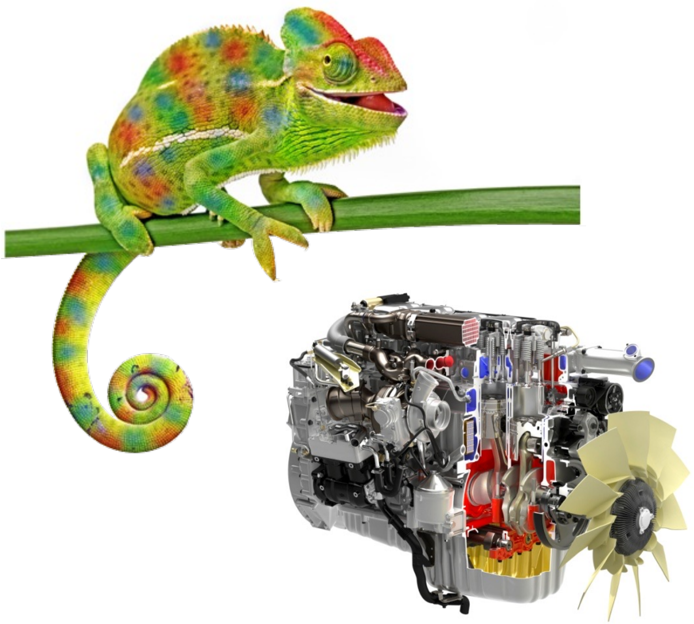


- Ellipse model
  - SCANIA CV AB
  - MAN D&T Augsburg
  - Toolbox
- Modeling expertise
  - SAAB Aeronautics
    - Cooling system for the Gripen Fighter Aircraft Radar System

Control-Oriented Compressor Model with Adiabatic Efficiency Extrapolation.
Xavier Llamas, and Lars Eriksson (2017).
In: SAE International Journal of Engines, 10(4).

Family Tree with a Solid Root and Several Offsprings

Shape Shifting Chameleon
– That has Travelled the World and the Seven Seas
– While Adapting to a Wide Range of Applications



- Cummins
- Ford
- MAN D&T
- SAAB AB
- Scania
- Volkswagen
- Volvo Trucks
- Volvo Busses
- Volvo CE
- Toyota

- Austria
- Australia
- China
- Japan
- Germany
- Spain
- Sweden
- Italy
- USA

- Optimal Control
- MPC
- Diagnosis and Supervision
- Non-linear Control
- Control Lyapunov Functions
- Benchmark
- Driving analysis
- Diesel Electric
- Electrification
- Hybridization

Core points for the success

- Research on the right problem
  - Collaboration with industry
- Models that are of general nature
  - Component- and Physics-based models
  - Systematic approach to modeling and tuning
- Transparency and open source of the resulting model
- Good timing matching the societal needs
- Find the essence in the problem and simplify shamelessly

Once you get the physics right,
the rest is mathematics.
-- Rudolf E. Kalman

Hope you have enjoyed the story of an evolving model!

Thank you!

Lars.Eriksson@LiU.SE

http://www.fs.isy.liu.se/Software

http://users.isy.liu.se/en/fs/larer/?__publications

www.liu.se

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DTU

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MAN

VOLVO