Modeling and Optimal Control for Dynamic Driving of Hybridized Vehicles with Turbocharged Diesel Engines

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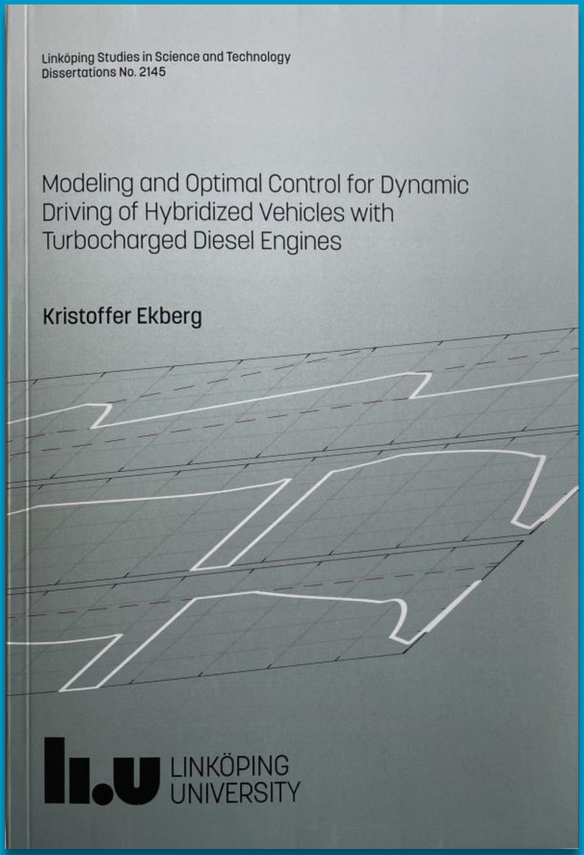

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Introduction

- Majority of road freight transported by trucks [1]
- Diesel powered 98% [1]
- Diesel emissions [2]:
  - Hydro carbons
  - Particulate emissions (soot)
  - Carbon monoxide
  - Nitrogen oxides and dioxides (NO_x).

A better fuel economy of produced vehicles will reduce the amount of needed fuel, and consequently the release of CO_2.

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1. *Trucks What are trucks fact sheet*
2. *Heywood 2018, Internal Combustion Engine Fundamentals*

Trends

- Electrification of powertrains

Results in:

- Increase in system complexity
- More difficult engineering problem, choice of technology and its controls

Inserting electric machines in the powertrain:

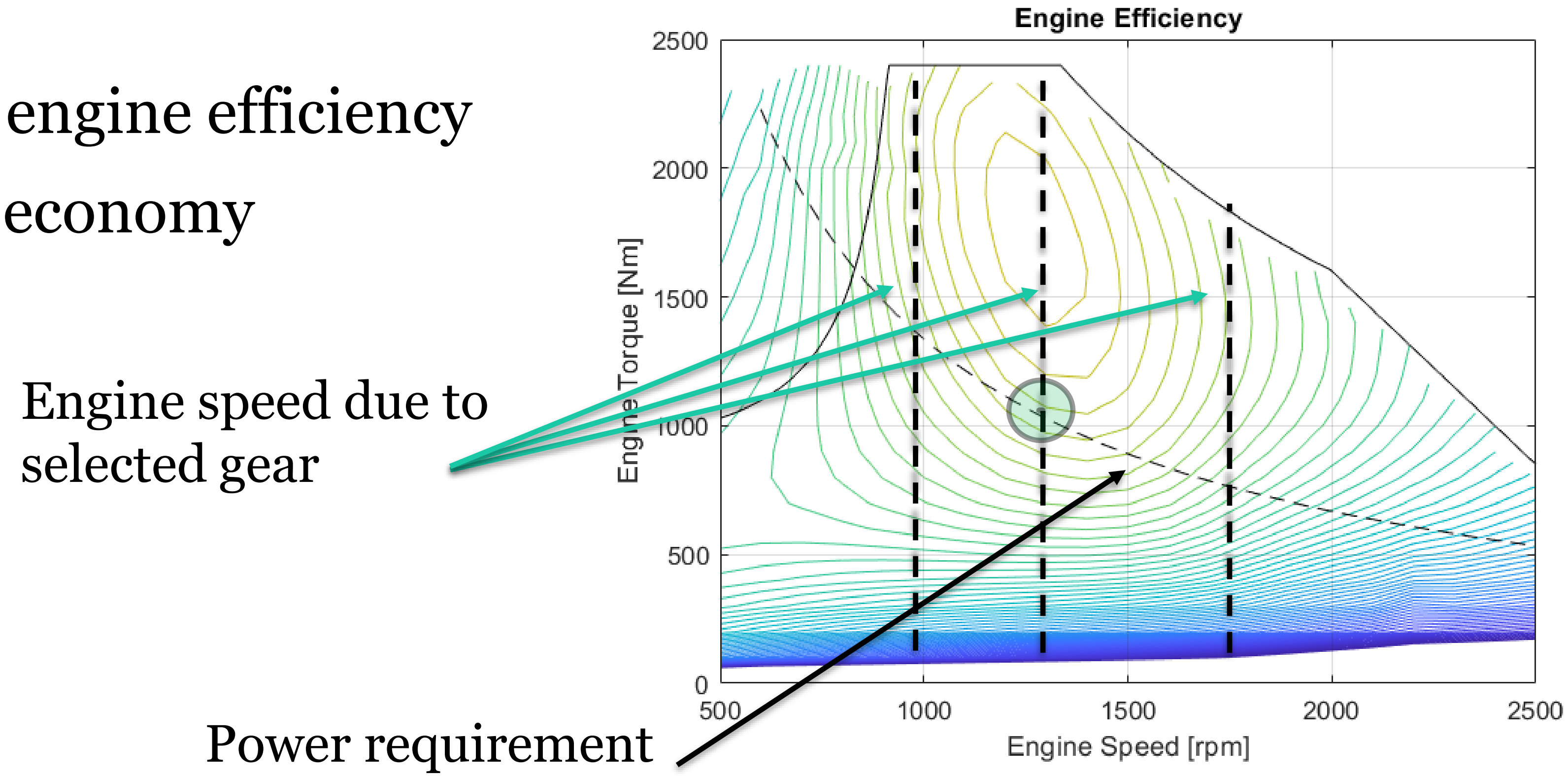
  - Electric crank shaft motor
  - Electric turbocharger

Thesis Aim

- Reduce the energy needed for accelerating and driving commercial vehicles.
- Methods that solve these problems.
- Knowledge about the relative importance of electric turbocharging and hybrid propulsion technologies on the system performance.

Propulsion - Achieving improvements

- Diesel engine control
- Load point dependent engine efficiency
- Gear selection for fuel economy



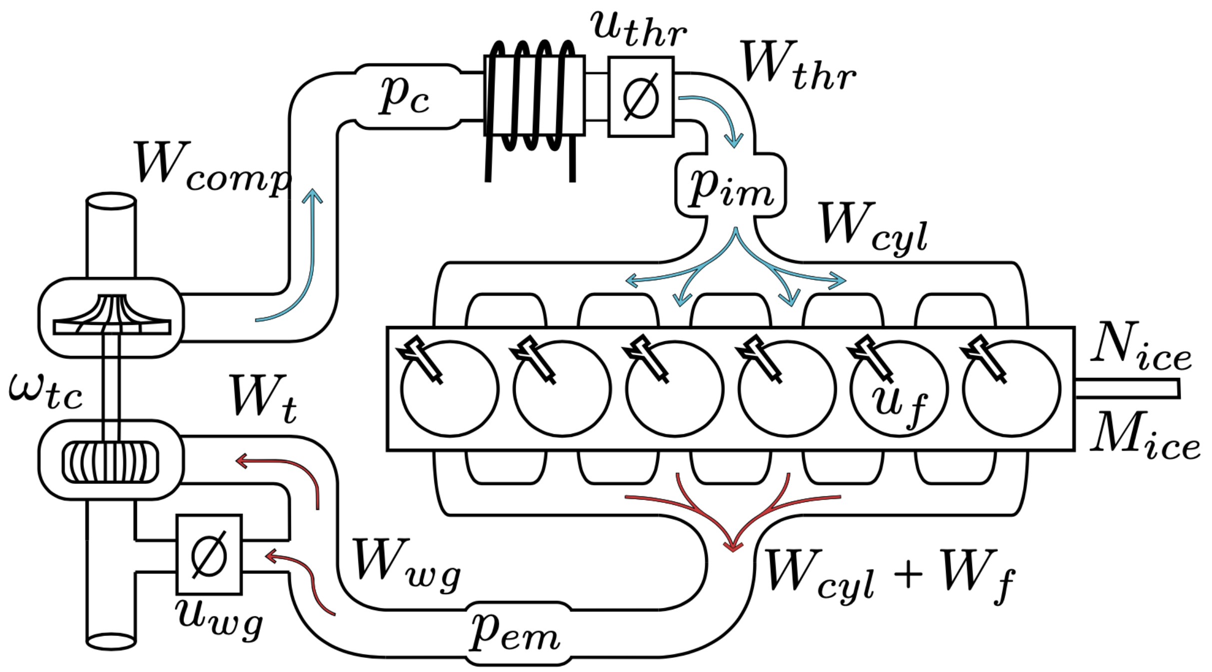
Turbocharged Compression Ignited (CI) Engine

- Air Fuel Ratio

$$\lambda = \frac{W_{cyl}}{AF_s\, W_f}$$

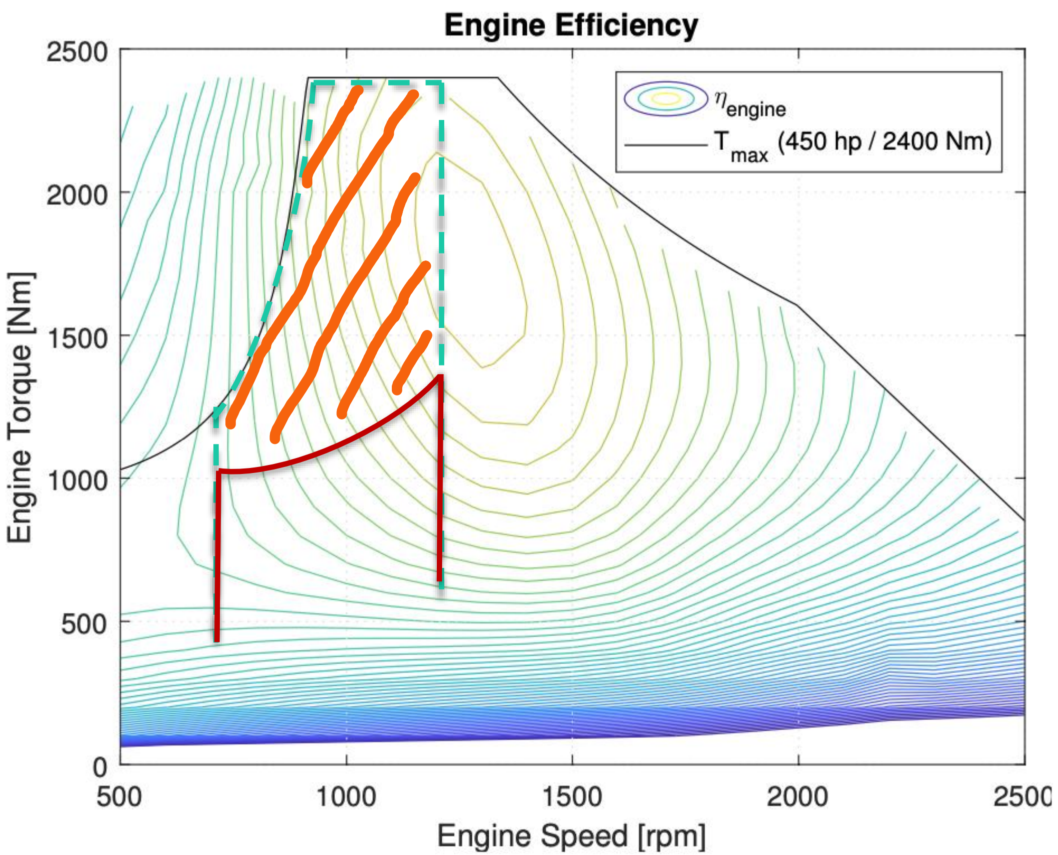
- Restricted due to smoke formation

$$\lambda_{min} < \lambda$$



Turbocharger Lag

- Transient response
- Risk of black smoke[1]



1. Rakopoulos and Giakoumis 2009, Diesel Engine Transient Operation

Paper I

PAPER I

Improving Fuel Economy and Acceleration by Electric Turbocharger Control for Heavy Duty Long Haulage [1]

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[1] Reprinted, with permission, from Kristoffer Ekberg and Lars Eriksson (2017). "Improving Fuel Economy and Acceleration by Electric Turbocharger Control for Heavy Duty Long Haulage." In: *IFAC-PapersOnLine* 50.1. 20th IFAC World Congress, pp. 11052–11057. ISSN: 2405-8963. DOI: https://doi.org/10.1016/j.ifacol.2017.08.2486. The formating is restricted to adjusting the appearance of the text, figures, tables, and the reference style without changing their content.

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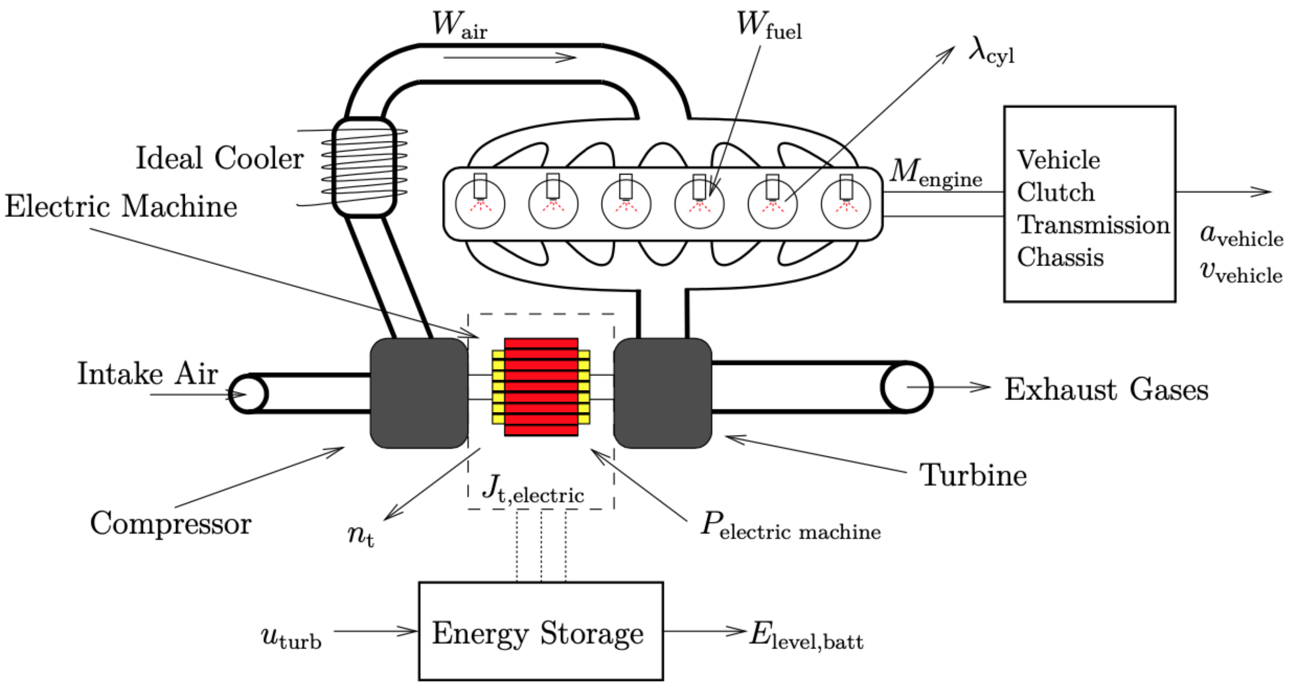
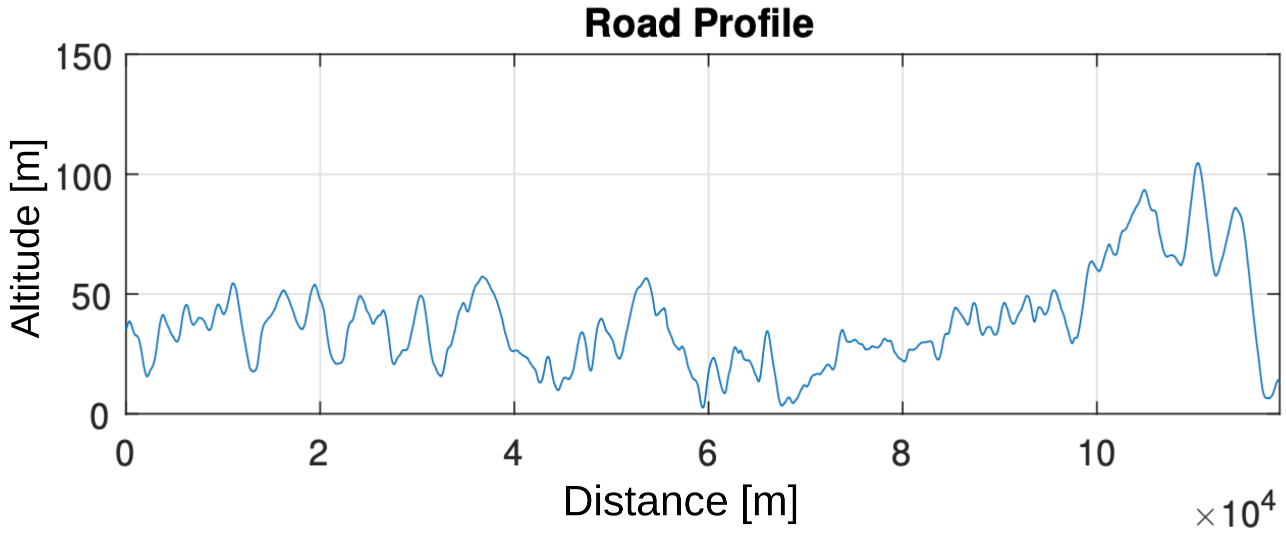
Electric Topologies for Boost Control

- Extra power input
- Regeneration



Paper I – Results – Long Haulage Driving

- With electric turbocharger: 37.48 l/100km
- Without electric turbocharger: 37.82 l/100km
- 0.9% fuel saving for the undulated driving mission



Optimal Control

- Mathematical way to find system controls to minimize a defined cost
- Different methods
  - Dynamic Programming
  - Numerical method - Direct collocation
- Model requirements

Paper II

PAPER II

Optimal Control of Wastegate Throttle and Fuel Injection for a Heavy-Duty Turbocharged Diesel Engine During Tip-In [1]

Kristoffer Ekberg, Viktor Leek, and Lars Eriksson
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[1] Reprinted, with permission, from Kristoffer Ekberg, Viktor Leek, and Lars Eriksson (2019). "Optimal Control of Wastegate Throttle and Fuel Injection for a Heavy-Duty Turbocharged Diesel Engine During Tip-In." In: *SIMS 2017, Reykjavik, Island*. DOI: http://dx.doi.org/10.3384/ecp17138317. The formating is restricted to adjusting the appearance of the text, figures, tables, and the reference style without changing their content.

Paper II – Optimal Control

- Find a stationary point at a defined engine speed and delivered torque, which is fuel optimal.
- Find the least time consuming control to perform a Tip-In, from the stationary point, to a point where the requested torque is available.

$$\min_{x(t),u(t)} t_f,$$

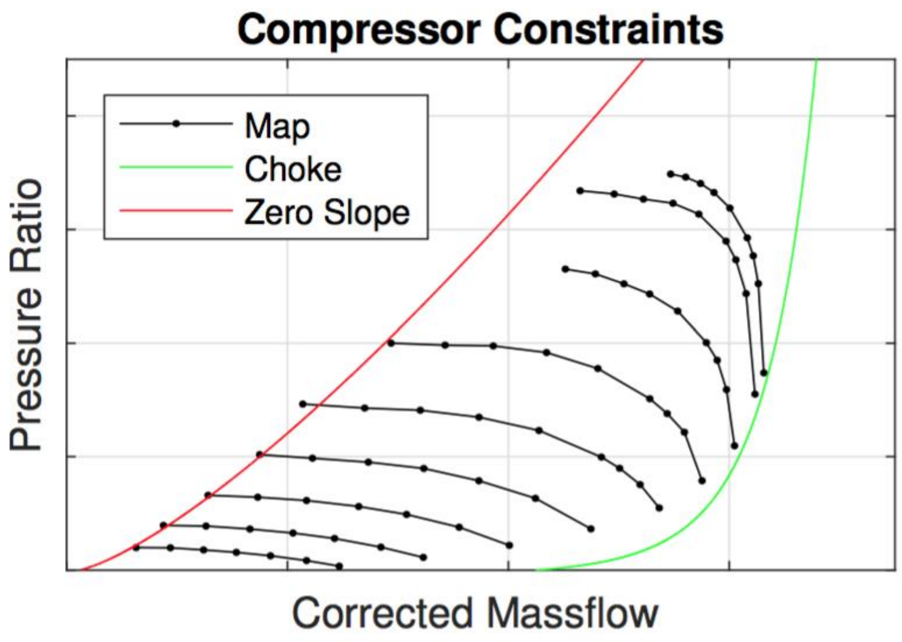
$s.t.$

$$
\begin{aligned}
&\dot{x}(t) = f(x(t), u(t)) \\
&x_{min} \leq x(t) \leq x_{max} \\
&u_{min} \leq u(t) \leq u_{max} \\
&0 \leq \phi(t) \leq 1/\lambda_{min} \\
&BSR_{min} \leq BSR(t) \leq BSR_{max} \\
&\dot{m}_c(t) \geq \dot{m}_{zsl}(N_t) \\
&\dot{m}_c(t) \leq \dot{m}_{ch}(N_t) \\
&N_t(t) \geq c_{22} \quad \text{(from Equation (11c))} \\
&N_e(t) = N_{e,fixed}
\end{aligned}
$$

Paper II – Constraints

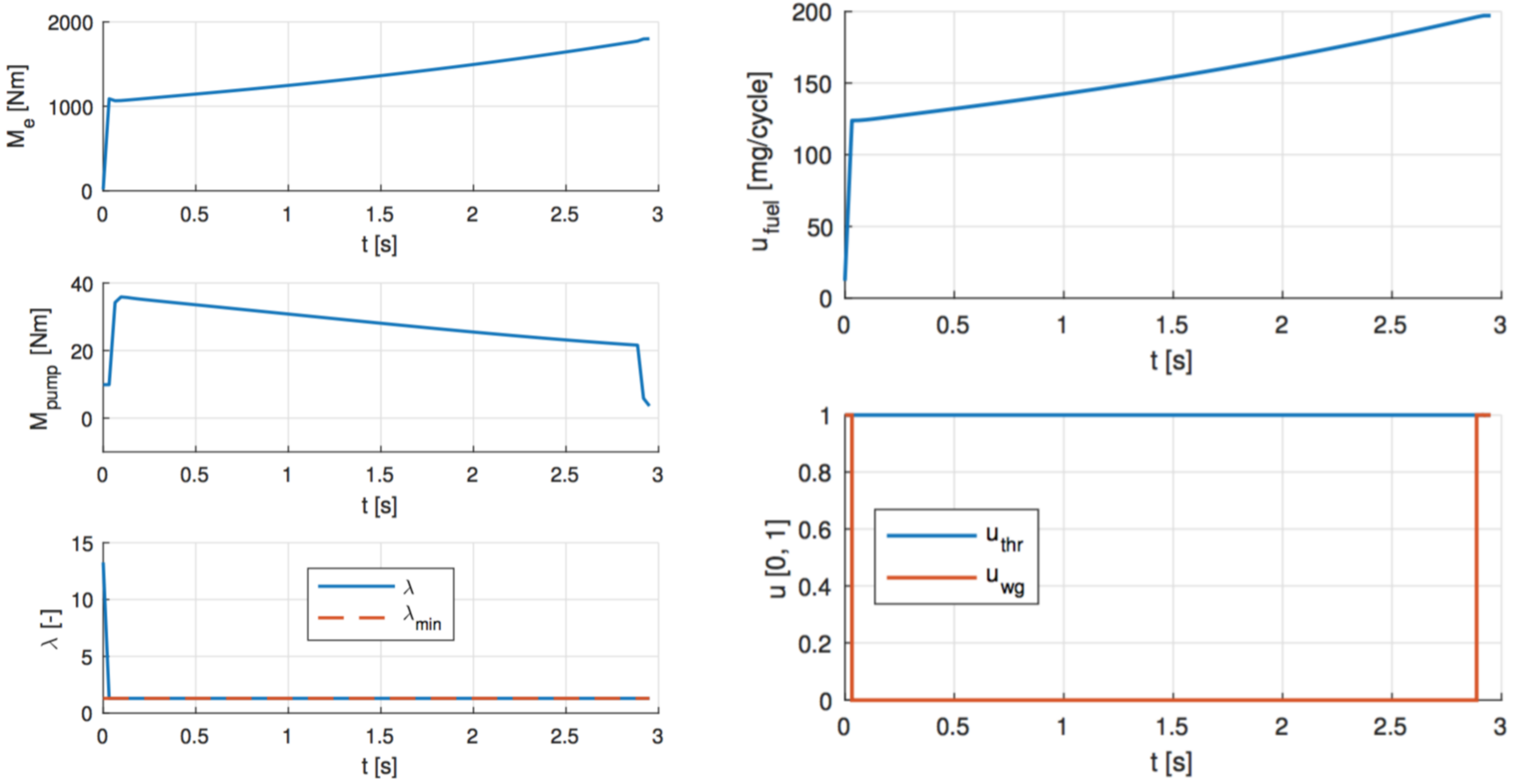
The problem constraints are formulated in the following way

$$\dot{x}(t) = f(x(t), u(t))$$
$$x_{min} \leq x(t) \leq x_{max}$$
$$u_{min} \leq u(t) \leq u_{max}$$
$$0 \leq \phi(t) \leq 1/\lambda_{min}$$
$$BSR_{min} \leq BSR(t) \leq BSR_{max}$$
$$\dot{m}_c(t) \geq \dot{m}_{zsl}(N_t)$$
$$\dot{m}_c(t) \leq \dot{m}_{ch}(N_t)$$
$$N_t(t) \geq c_{22} \quad \text{(from Equation (11c))}$$
$$N_e(t) = N_{e,fixed}$$



Paper II – Results – Optimal Control

Time optimal Tip-In at fixed engine speed



$$x(0) = x_0$$
$$u(0) = u_0$$
$$M_e(t_f) = M_{e,des},$$

Paper III

PAPER III

Modeling and Validation of an Open-Source Mean Value Heavy-Duty Diesel Engine Model [1]

Kristoffer Ekberg, Viktor Leek, and Lars Eriksson
Department of Electrical Engineering
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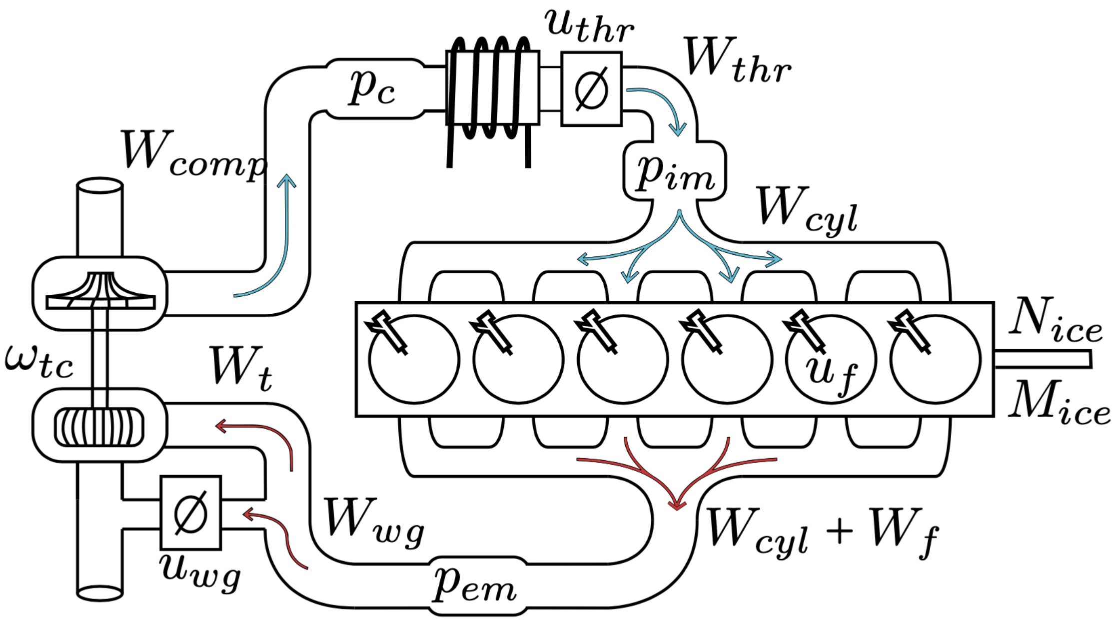
[1] Reprinted, with permission, from Kristoffer Ekberg, Viktor Leek, and Lars Eriksson (Dec. 2018). "Modeling and Validation of an Open-Source Mean Value Heavy-Duty Diesel Engine Model." In: *Simulation Notes Europe* 28(4), pp. 197–204. ISSN: 2306-0271. DOI: https://doi.org/10.11128/sne.28.tn.10451. The formating is restricted to adjusting the appearance of the text, figures, tables, and the reference style without changing their content.

Paper III – Contributions

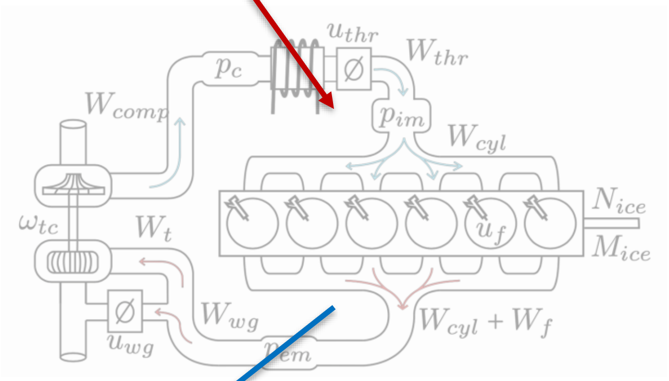
- Models and validates a model of a 13 liter CI engine and release the model as open source.
- Load dependent engine efficiency.



Paper III – Available Data

Dataset
A. Stationary measurement data
B. GT Power Simulation
C. Compressor map
D. Turbine map
E. Dynamic measurement data
F. Throttle effective area

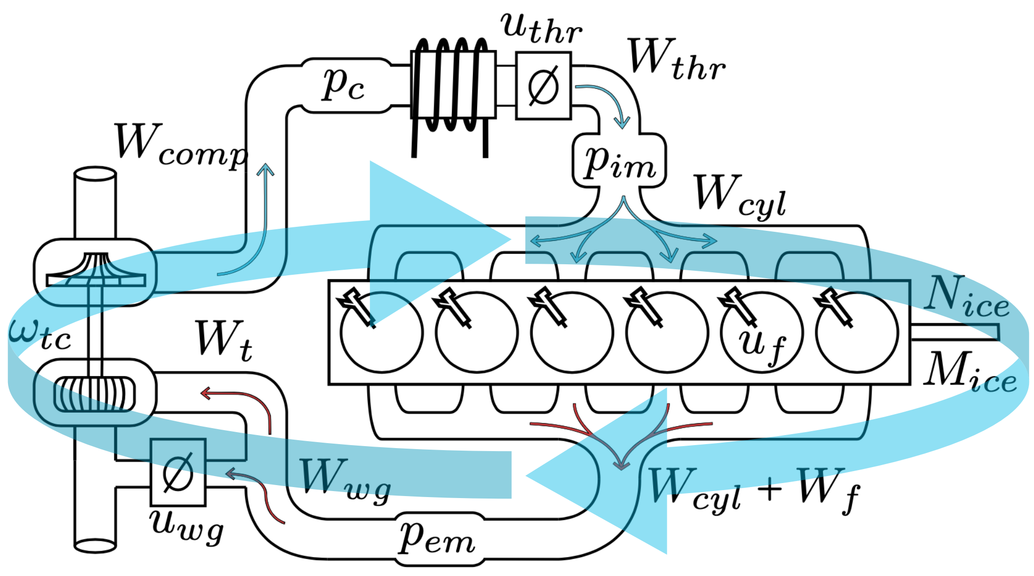
Parametrization



Validation

Paper III – Model Parametrization

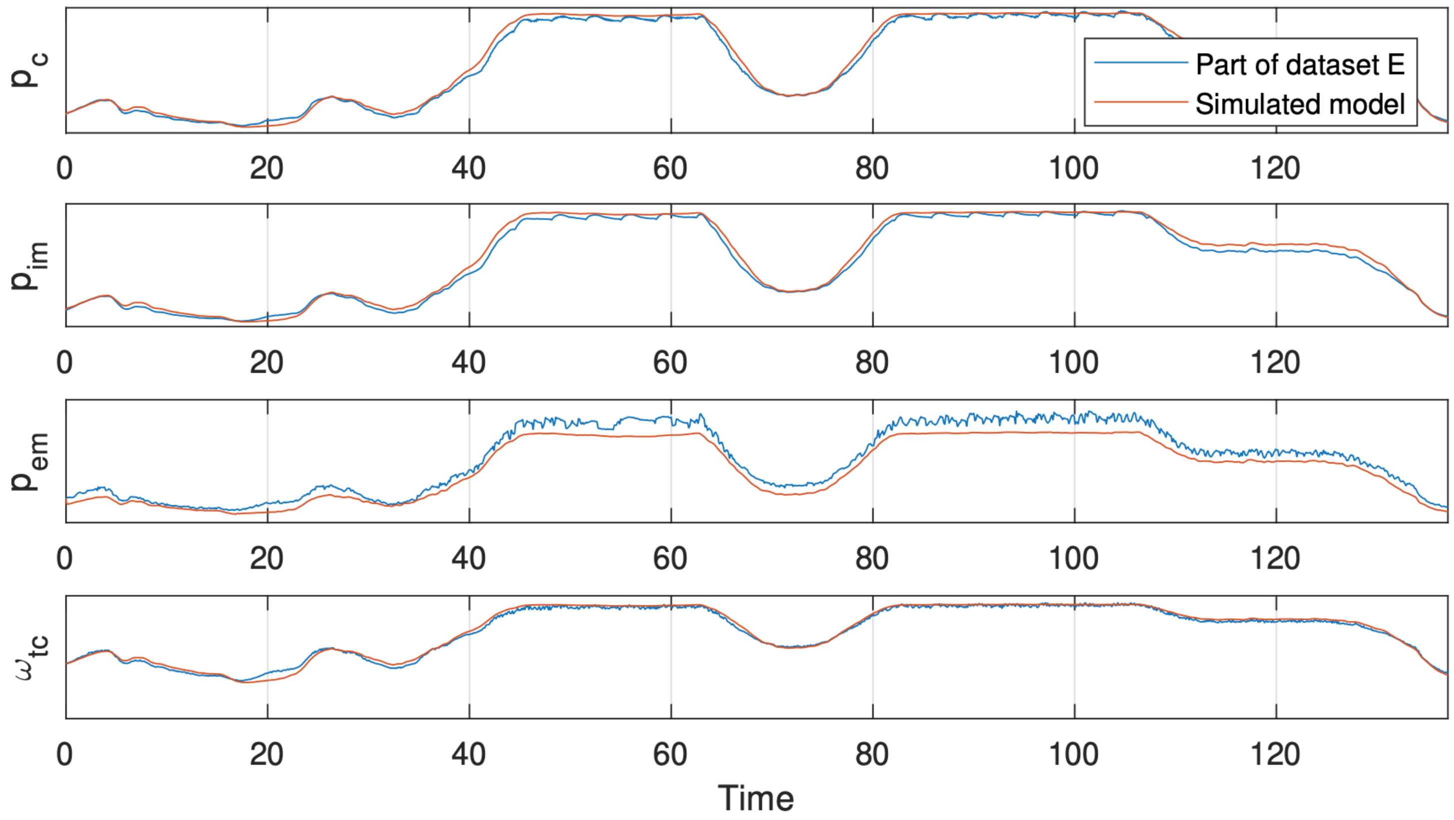
- Closed loop model (stationary)
  - Controlling the wastegate.
  - Individual cost to update sub-model parameters.



$$\theta^\star = \arg\min_\theta \Big(\sum_{k=1}^{K} e_k^2(\theta) + C \sum_{i=1}^{I} \big(\mu_i \frac{\theta_i^* - \theta_i}{\theta_i^*}\big)^2 \Big)$$

Paper III – Dynamic Validation

- Stationary and dynamic levels are well represented.



Paper IV

PAPER IV

Development and Analysis of Optimal Control Strategy for Gear Changing Patterns During Acceleration [1]

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[1] Reprinted, with permission, from Kristoffer Ekberg and Lars Eriksson (2019). "Development and Analysis of Optimal Control Strategy for Gear Changing Patterns During Acceleration." In: *IFAC-PapersOnLine* 52.5. 9th IFAC Symposium on Advances in Automotive Control AAC 2019, pp. 316–321. ISSN: 2405-8963. DOI: https://doi.org/10.1016/j.ifacol.2019.09.051. The formating is restricted to adjusting the appearance of the text, figures, tables, and the reference style without changing their content.

Paper IV – Contribution

Method for solving fuel optimal accelerations, while simultaneously solving for gear shifts and engine dynamics.

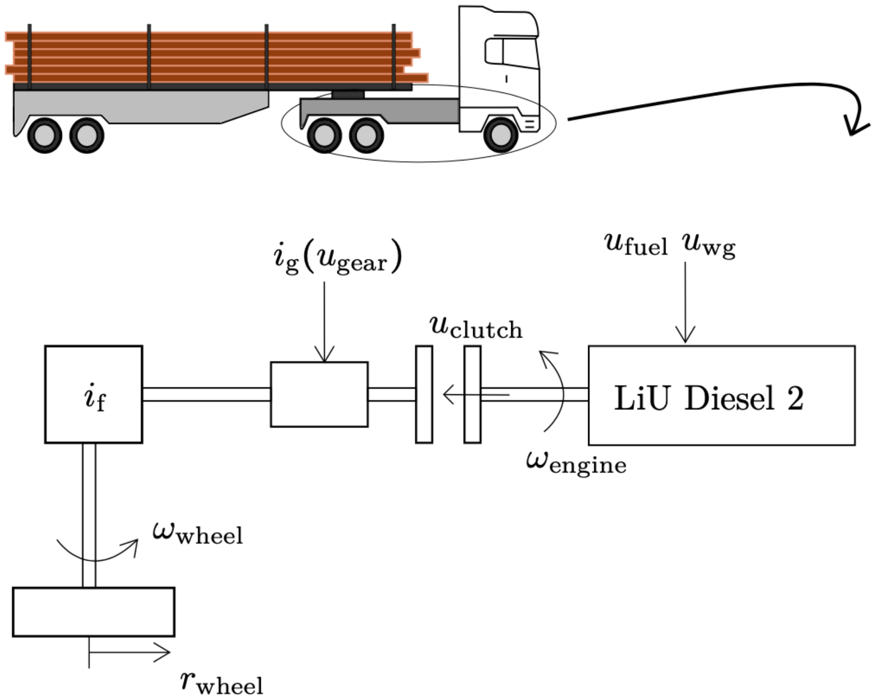
Scenario:

Accelerate a vehicle from slow rolling speed, to a pre-defined target speed (30 km/h) to the least fuel cost.

Paper IV – Model

Table 7.1: Model states and control signals.

State	Description
p_{im}	Intake manifold pressure
p_{em}	Exhaust manifold pressure
ω_{tc}	Turbocharger rotational speed
ω_{engine}	Engine rotational speed
ω_{wheel}	Wheel rotational speed
X_{distance}	Driven distance
Control	**Description**
u_{fuel}	Fuel injection
u_{wg}	Wastegate position
u_{clutch}	Clutch torque
u_{gear}	Selected gear



Paper IV – Results - All Gears

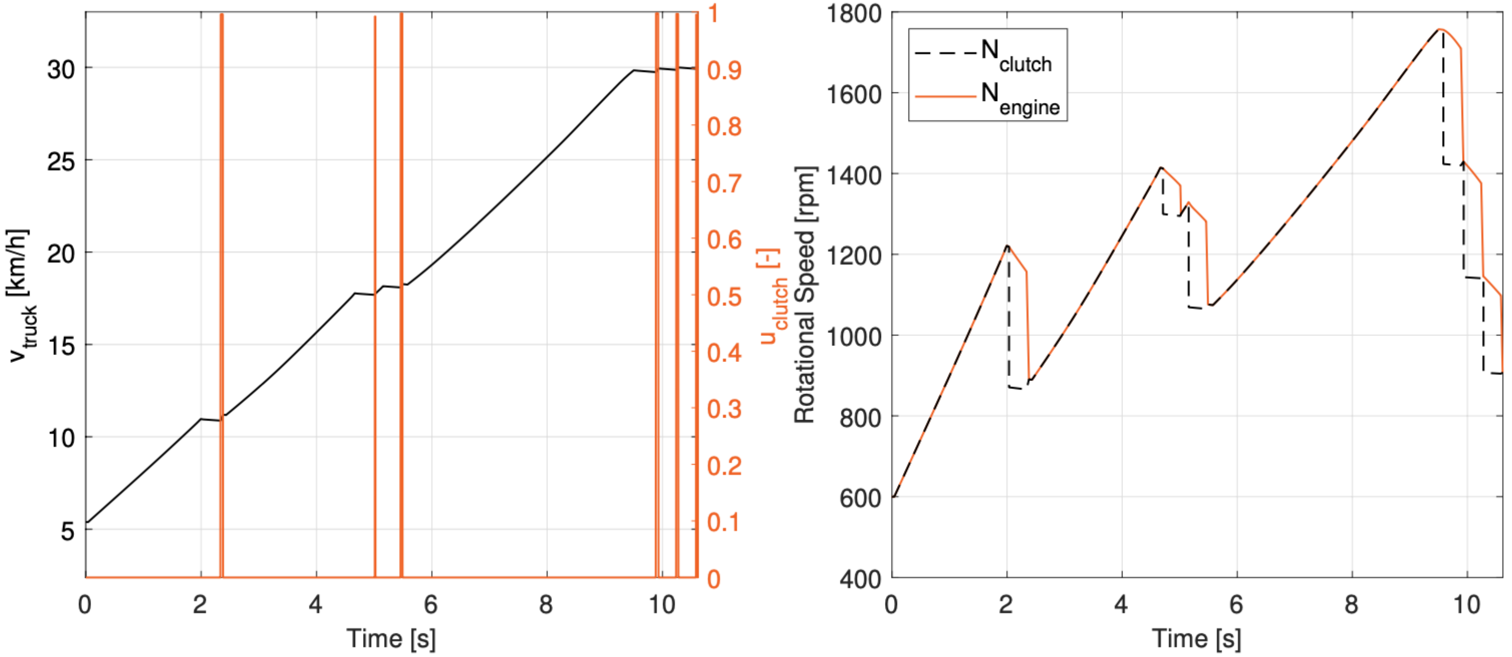


Figure 7.4: Acceleration from 5 to 30 km/h, where all the gears between 4 and 10 has to be used.

Paper IV – Results – Optimal Gears

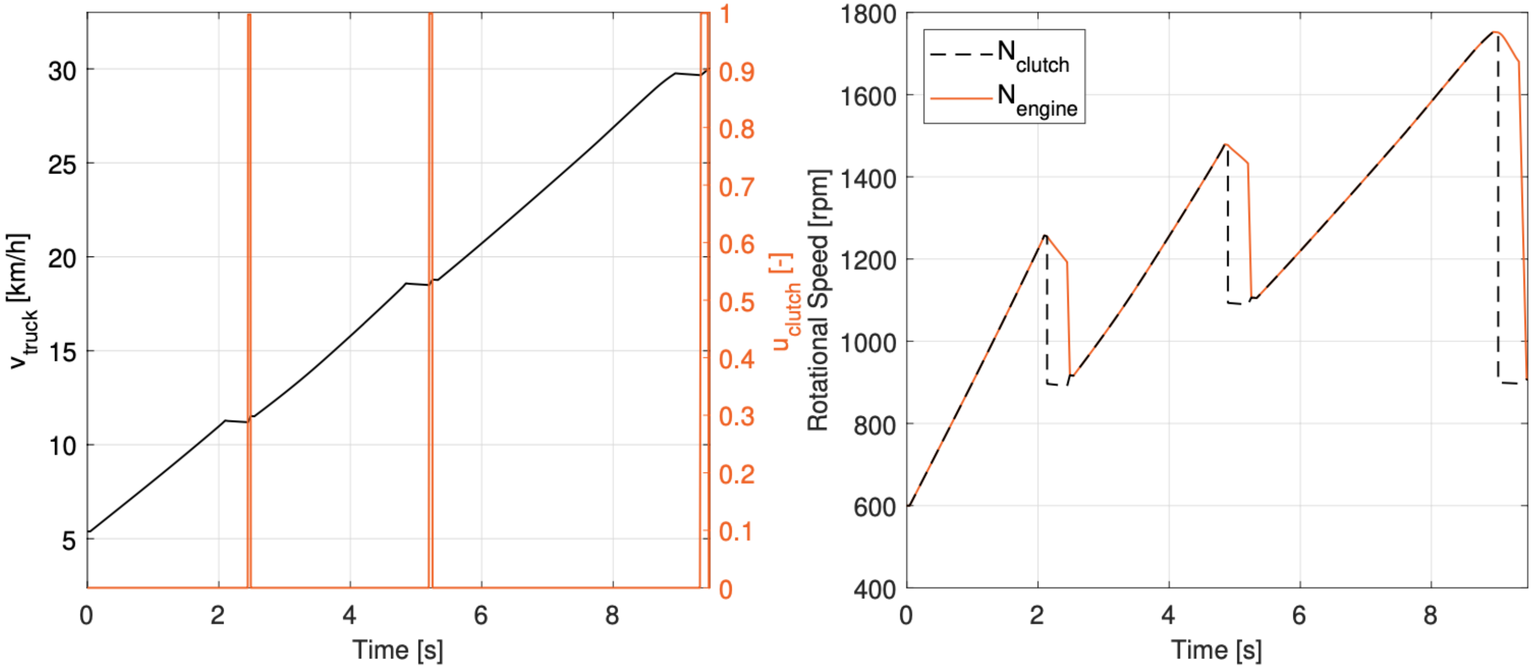


Figure 7.5: Acceleration from 5 to 30 km/h, where the non-used gears are removed from the set of active gears.

Paper V

PAPER V

A Comparison of Optimal Gear Shifts for Stiff and Flexible Driveshafts During Accelerations [1]

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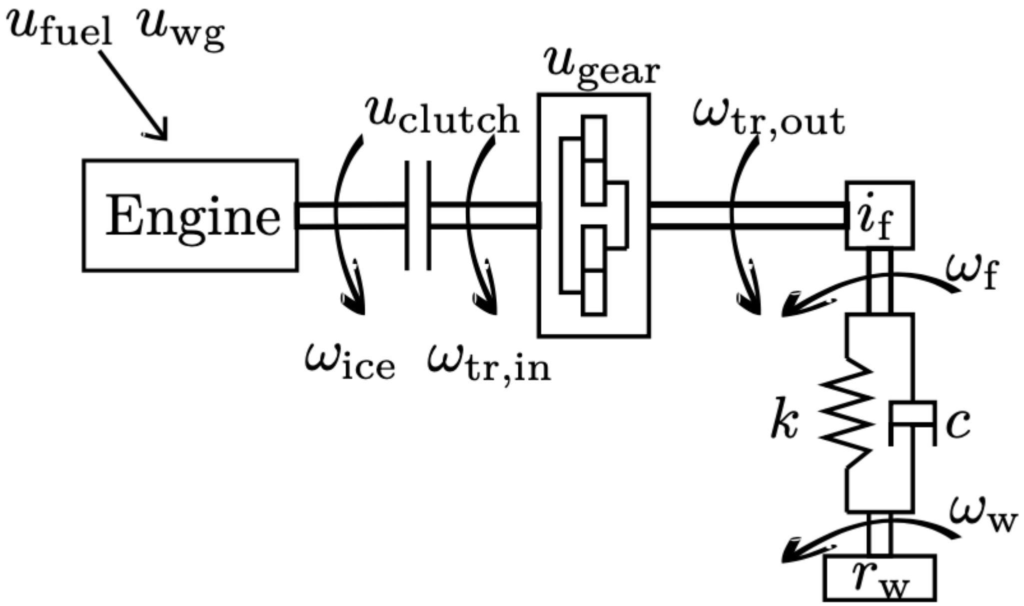
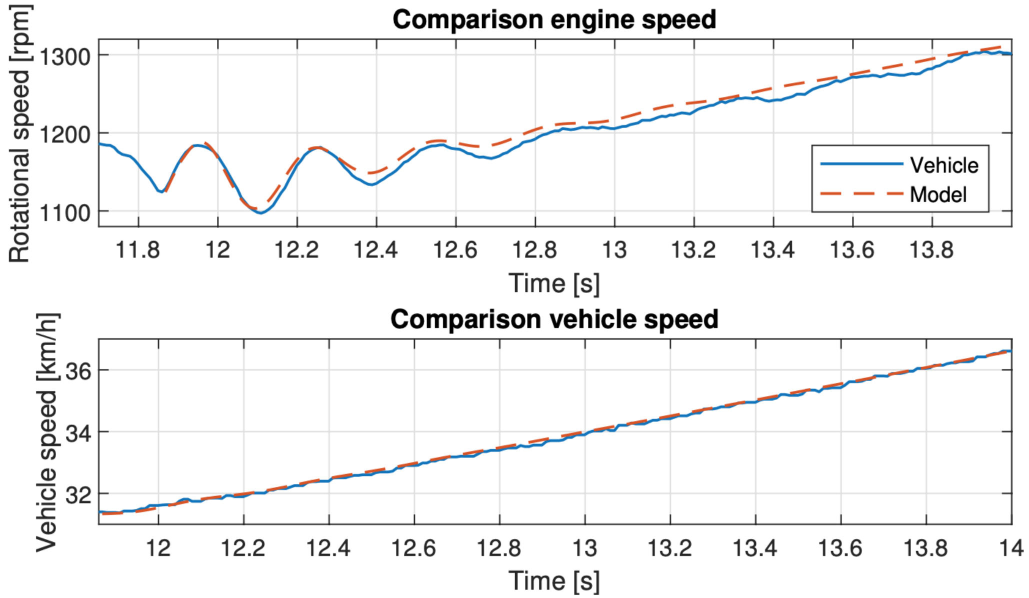
[1] Reprinted, with permission, from Kristoffer Ekberg and Lars Eriksson (2020). "A Comparison of Optimal Gear Shifts for Stiff and Flexible Driveshafts During Accelerations." In: *IFAC-PapersOnLine* 53.2. 21th IFAC World Congress, pp. 14413–14419. ISSN: 2405-8963. DOI: https://doi.org/10.1016/j.ifacol.2020.12.1410. The formating is restricted to adjusting the appearance of the text, figures, tables, and the reference style without changing their content.

Paper V – contribution

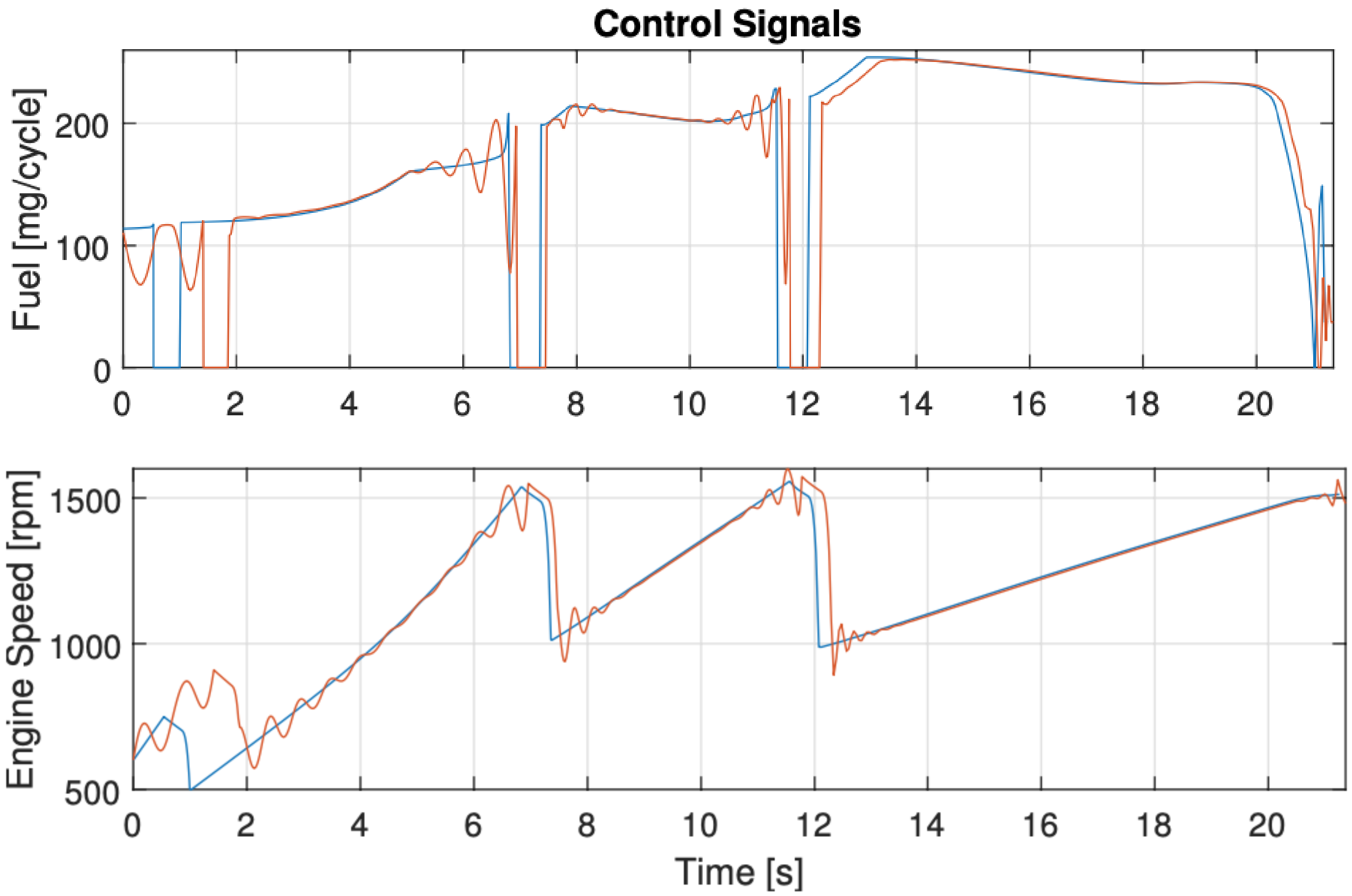
- Impact of a flexible driveshaft when solving acceleration missions for fuel optimal controls





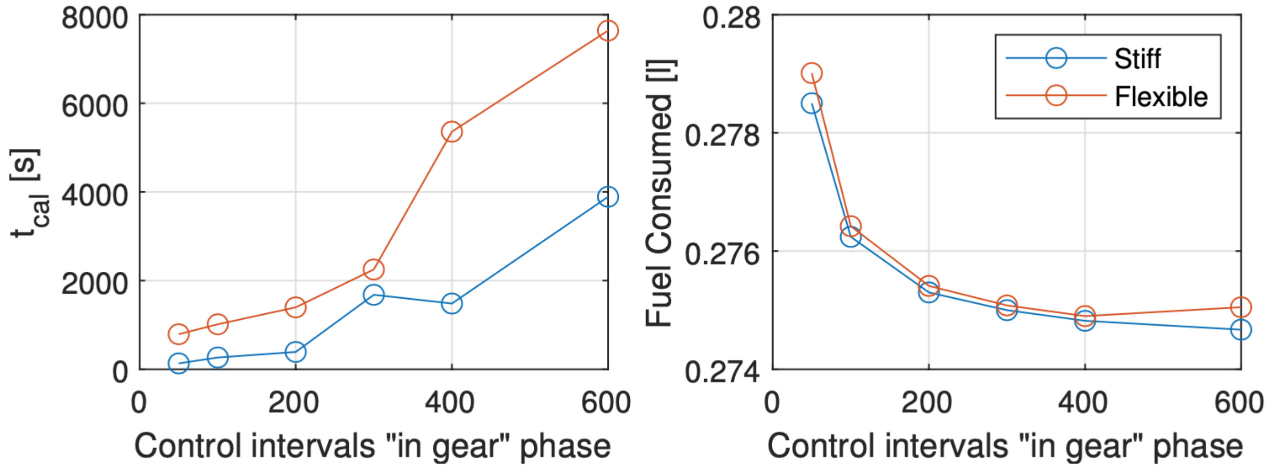
Paper V – Comparison of the two driveline representations

Fuel optimal acceleration
- Blue: Stiff driveshaft
- Red: Flexible driveshaft



Paper V – Sensitivity Analysis

- Change of control signal intervals "in gear": resolution of the discretization when formulating the optimal control problem.



Paper VI

PAPER VI

Electrification of a Heavy-Duty CI Truck—Comparison of Electric Turbocharger and Crank Shaft Motor [1]

Kristoffer Ekberg, Lars Eriksson, and Christofer Sundström
Department of Electrical Engineering
Division of Vehicular Systems
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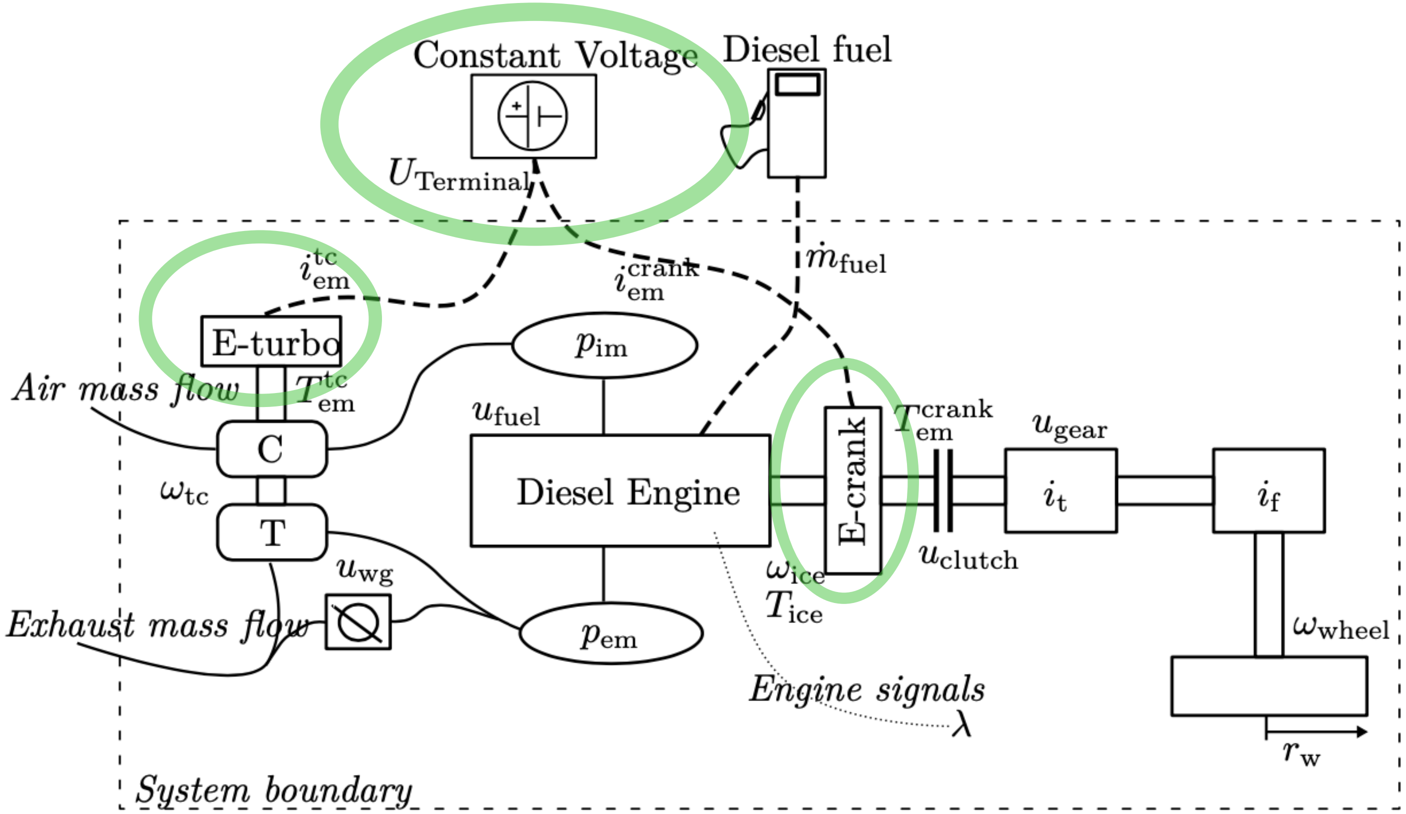
[1] Reprinted, with permission, from Kristoffer Ekberg, Lars Eriksson, and Christofer Sundström (2021). "Electrification of a Heavy-Duty CI Truck—Comparison of Electric Turbocharger and Crank Shaft Motor." In: *Energies* 14.5. Licenced under CC-BY. ISSN: 1996-1073. DOI: 10.3390/en14051402. The formating is restricted to adjusting the appearance of the text, figures, tables, and the reference style without changing their content.

Paper VI – System Description & Contribution

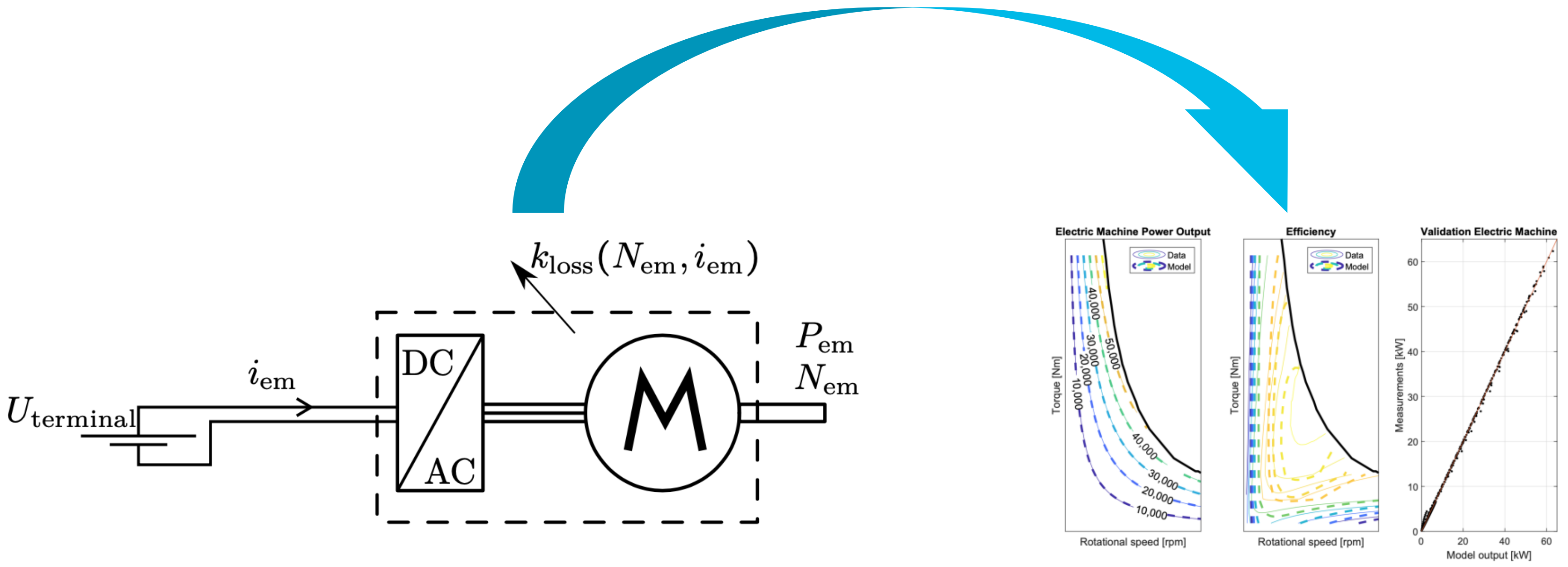
- Developing a method to enable comparisons of electrification architectures



$$J = \dot{m}_{fuel}\, Q_{LHV} + \beta\, U_{Terminal}\, i_{motor}$$

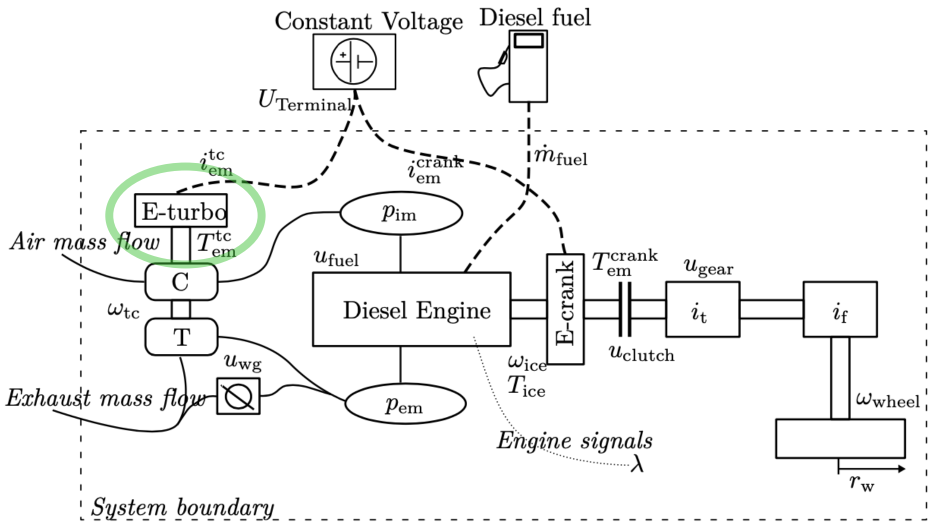
Paper VI – Electric Motor Model

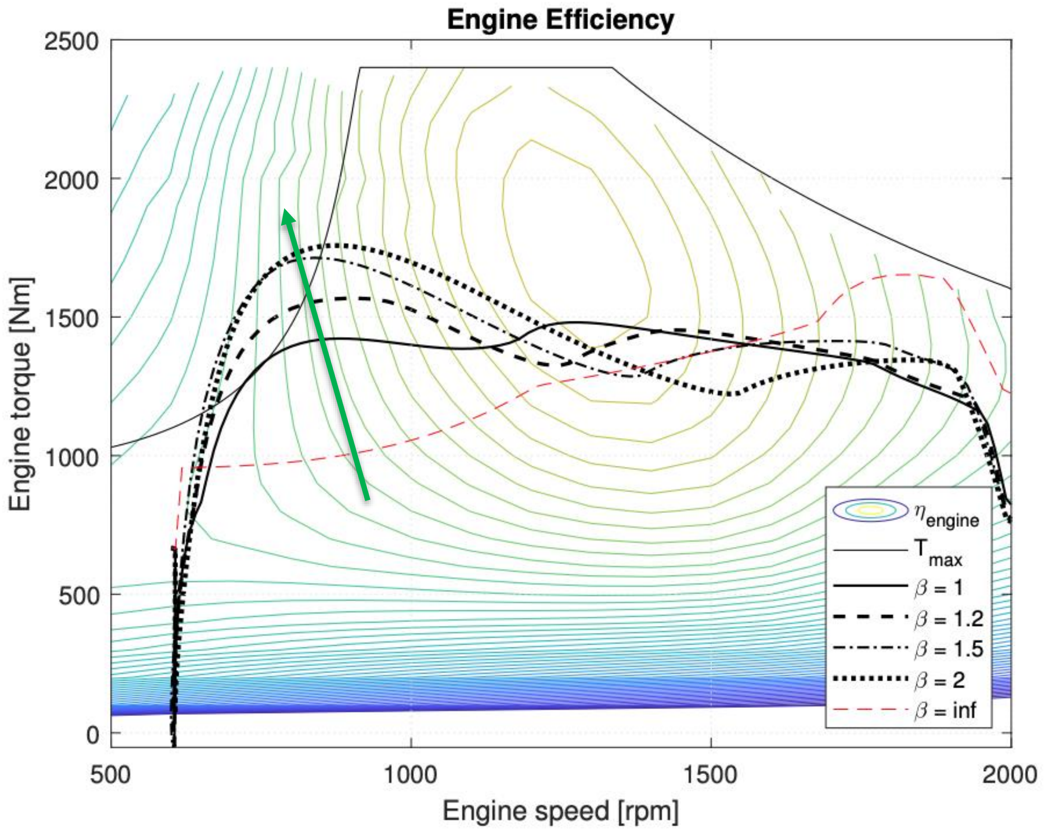
- Development of reference model
- Scaling the model to the size of either propulsion or E-turbo motor.



Paper VI – Electric Turbocharger

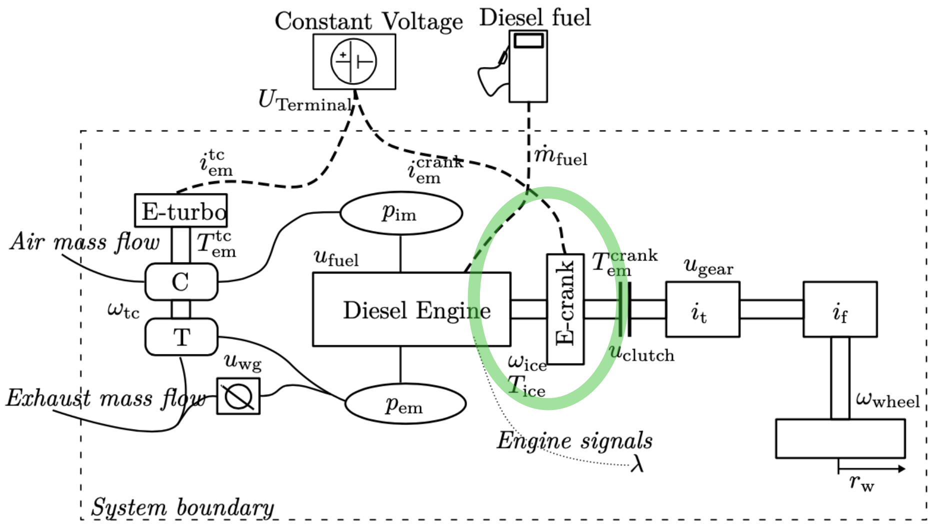
- Using the E-turbo results in an increase of output torque at low engine speeds.

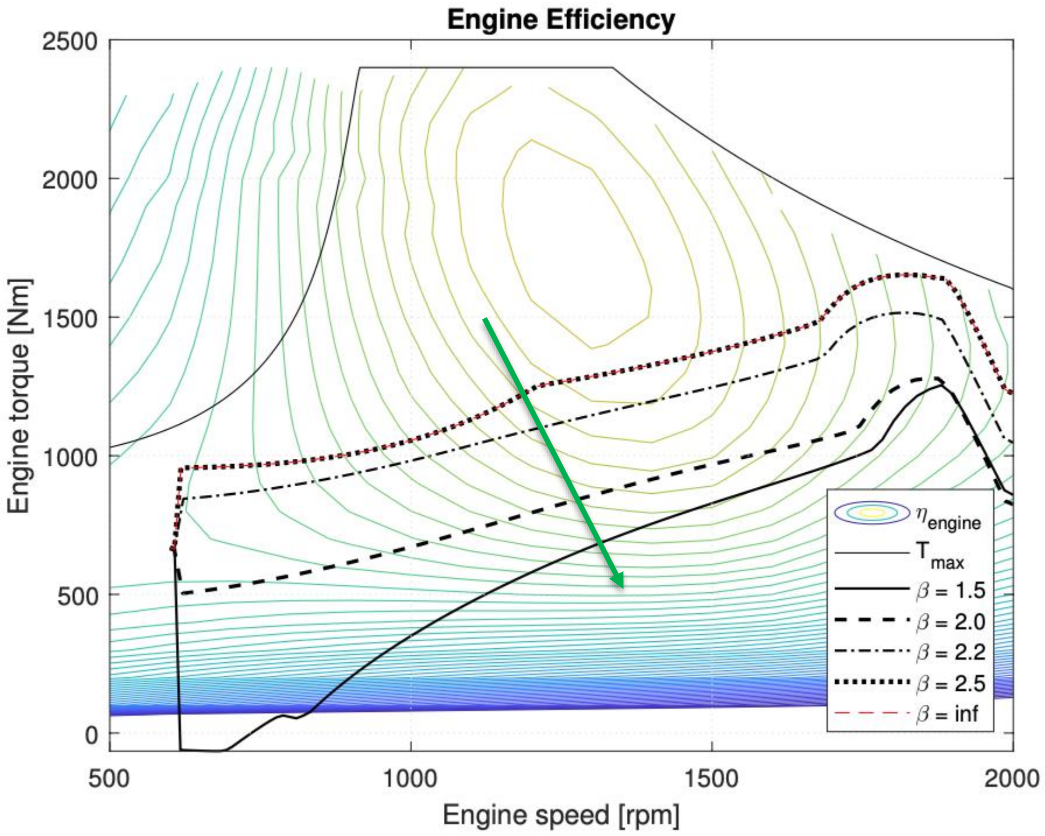




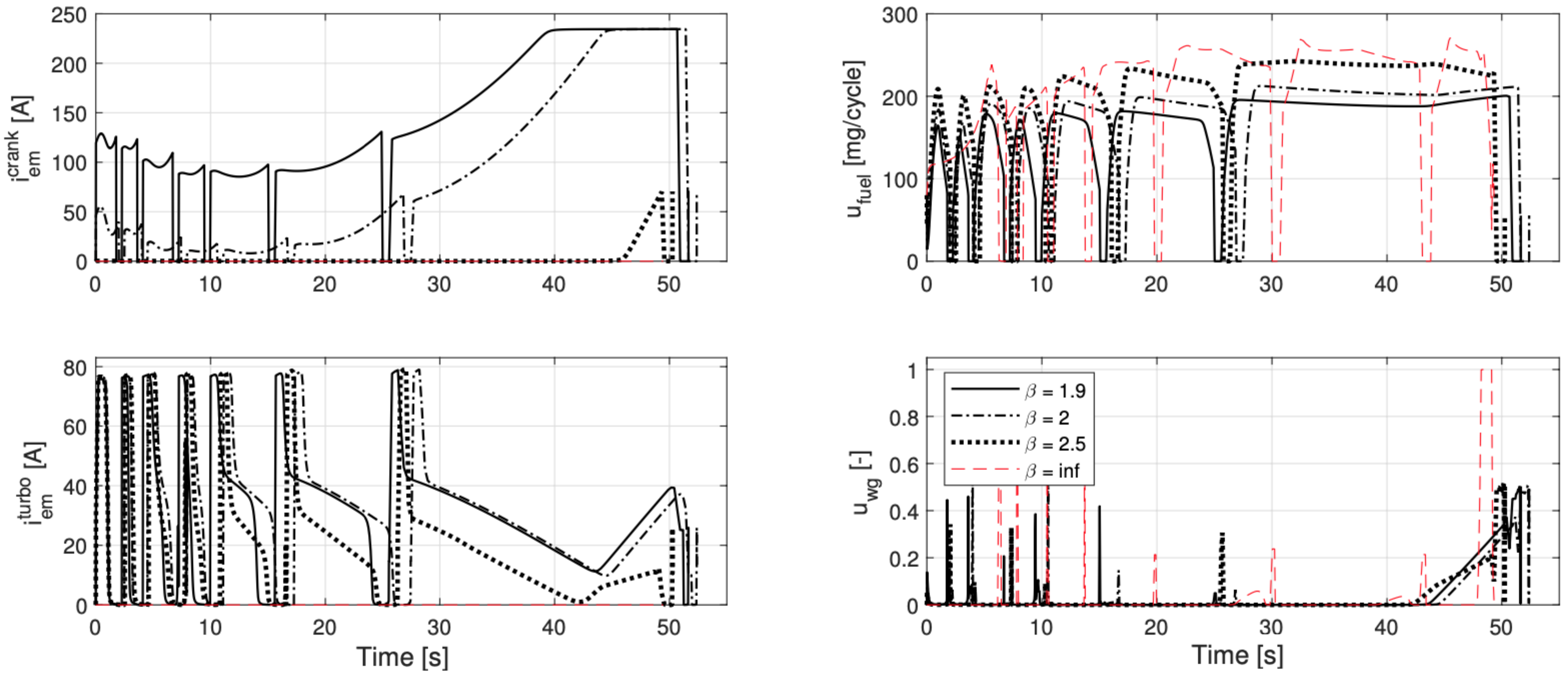
Paper VI – Electric Crank Shaft Motor

- Using the E-crank results in a reduction of output torque from the diesel engine



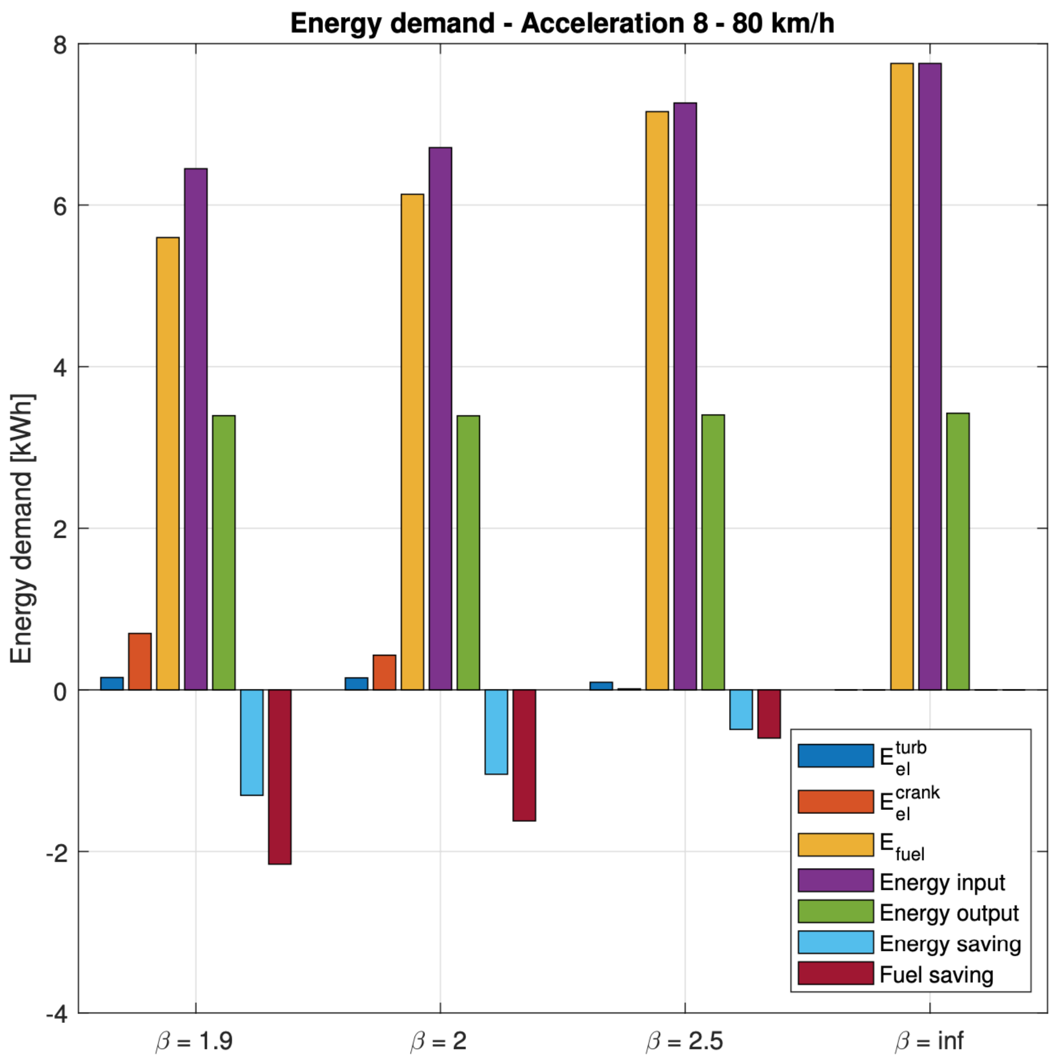


Paper VI – Acceleration 8-80 km/h



Paper VI – Consumed Energy

- Lower β – Higher utilization of E-crank
- Higher β – Higher utilization of E-turbo in comparison to E-crank.



Thesis Contributions

Thesis Contributions

- Controller for E-turbo
- Turbine model taking speed-lines into account
- Load dependent efficiency model for a CI engine
- Validated MVEM engine model released open source
- Method to investigate gear shifts for fuel optimal accelerations
- Analyzed impact of flexible driveline
- Electric motor model suitable for optimal control
- Optimal power split in HEV with multiple electric motors

Questions

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