Design & Development of e-Turbo™ for SUV and Light Truck Applicaitons

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Garrett Engine Boosting Systems

Diesel Engine Emissions Reduction Conference

August, 2003

Presentation Outline

- Preliminary System Benefits Quantified & Configuration Identified
- "Go/No-Go" Technical Feasibility Established
- System Modeling Tools for EBS have been Developed
- Sensitivity Analysis has been Performed to Set Development Targets
- Key Technical Targets and Challenges have been Defined
- Feasible Technical Solutions have been Identified
- Conclusions and Next Steps

Presentation includes gasoline and diesel engine data and analysis

It also includes e-Charger and e-Turbo results

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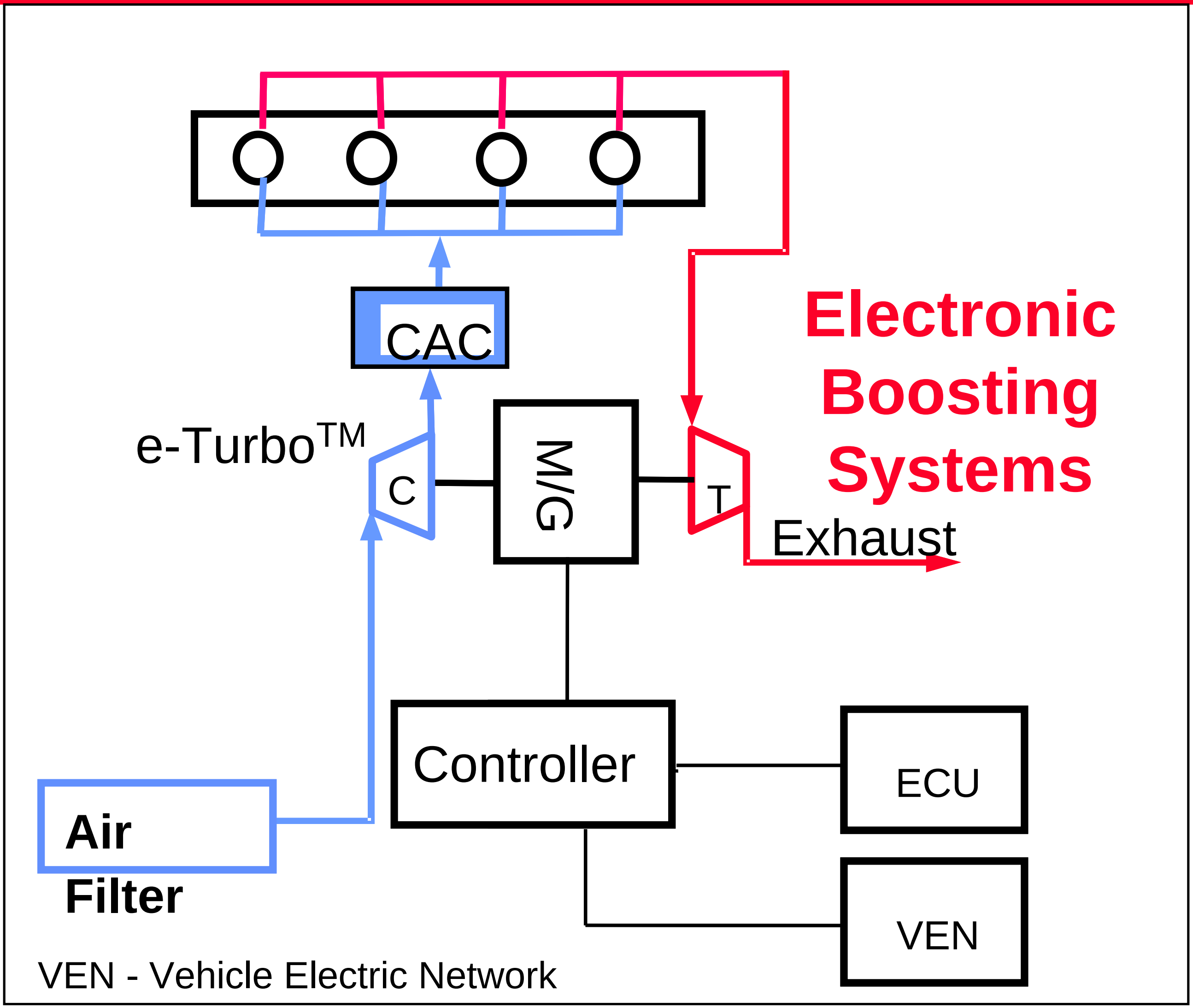
e-Turbo™: Electrically-Assisted Turbocharger



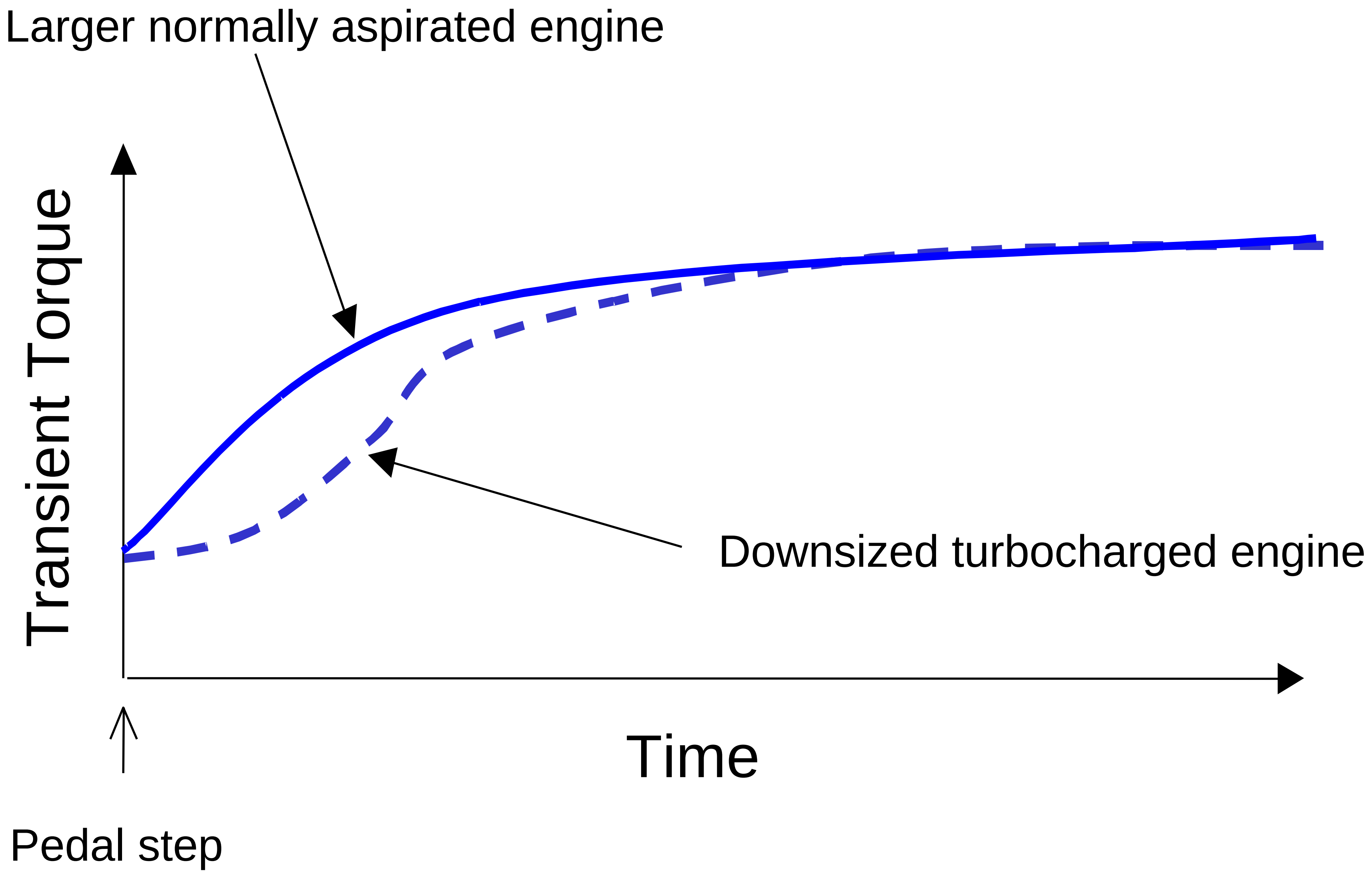
Three Levels of System Benefits

- **Performance - Eliminate Turbolag**
- **Aggressive Engine Downsizing**
- **Air Management System - Synergy with EGR, Fuel Injection, Aftertreatment, Vehicle Power Demands**

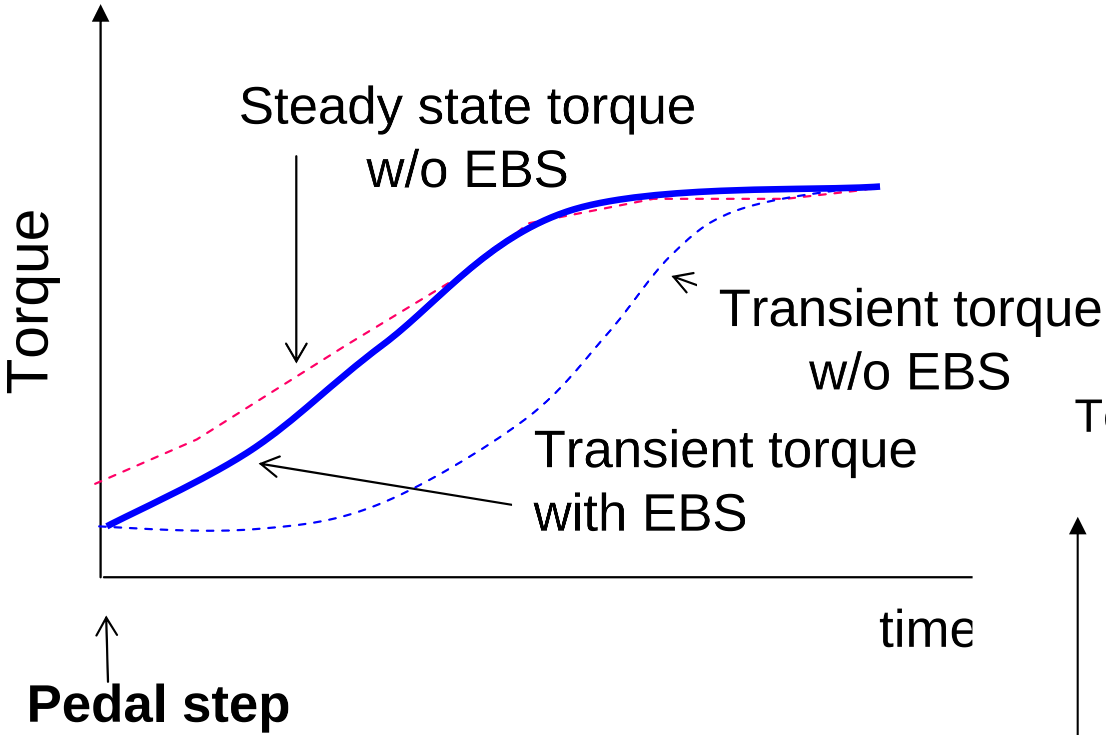
M/G - Supplier Developed 12 V DC Input 2 kW Induction Motor/Generator

Controller - Supplier Developed

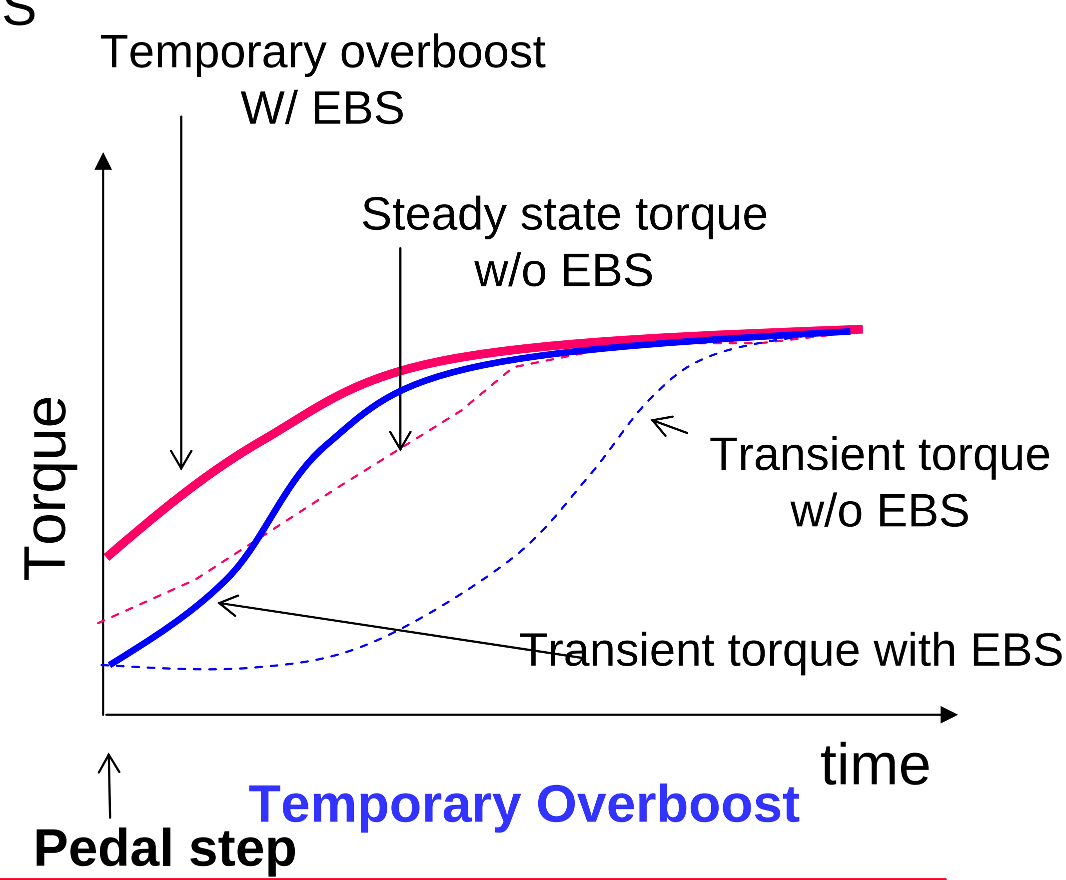
Problem Statement for EBS



Performance Benefits – Transient Torque

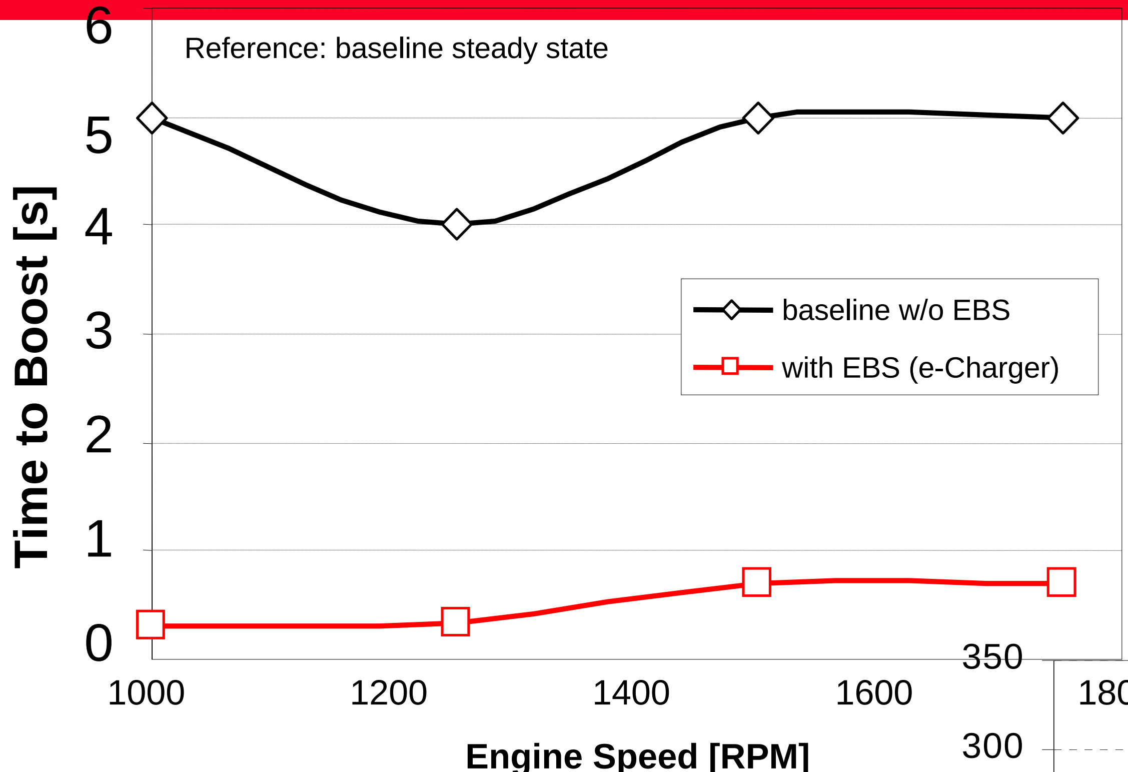


Transient Time-to-Boost Improvement



Temporary Overboost

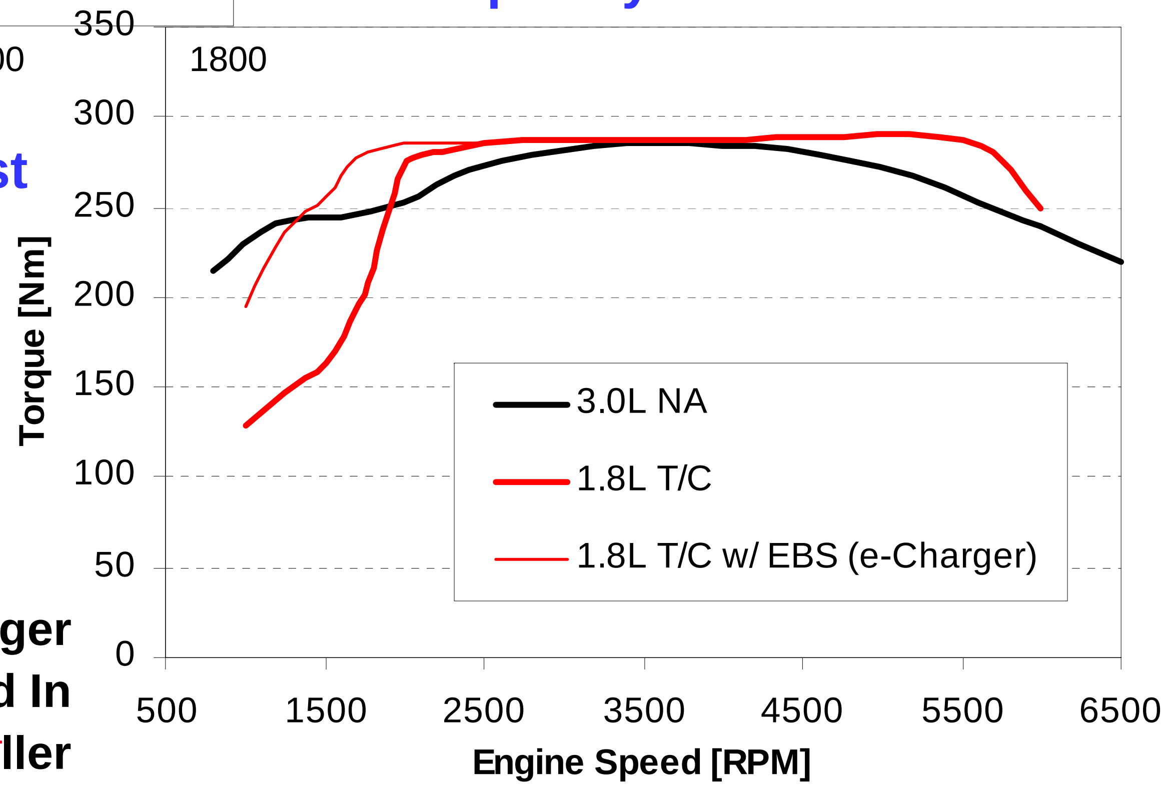
Example of Benefits - Engine Test Results



Transient Time-to-Boost Improvement

- **In-House Design e-Charger**
- **Permanent Magnet System**
- **1.8 L European Gasoline Engine**
- **Testing at European Consultancy**

Temporary Overboost



Proof of Concept Using e-Charger and Gasoline Engine

Garrett in-house design e-Charger with Permanent Magnet Motor and In house controller

Garrett

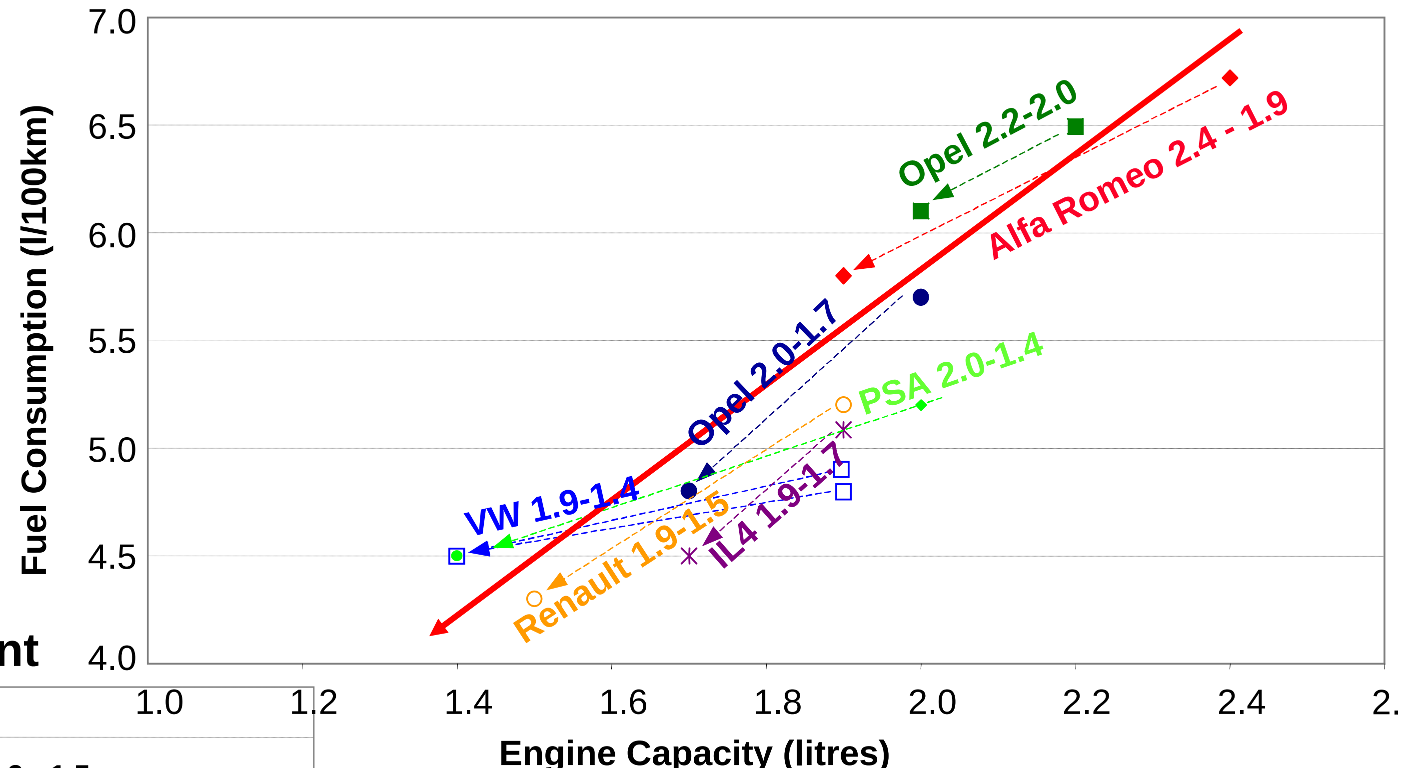
Diesel Engine Turbocharging & Downsizing

European

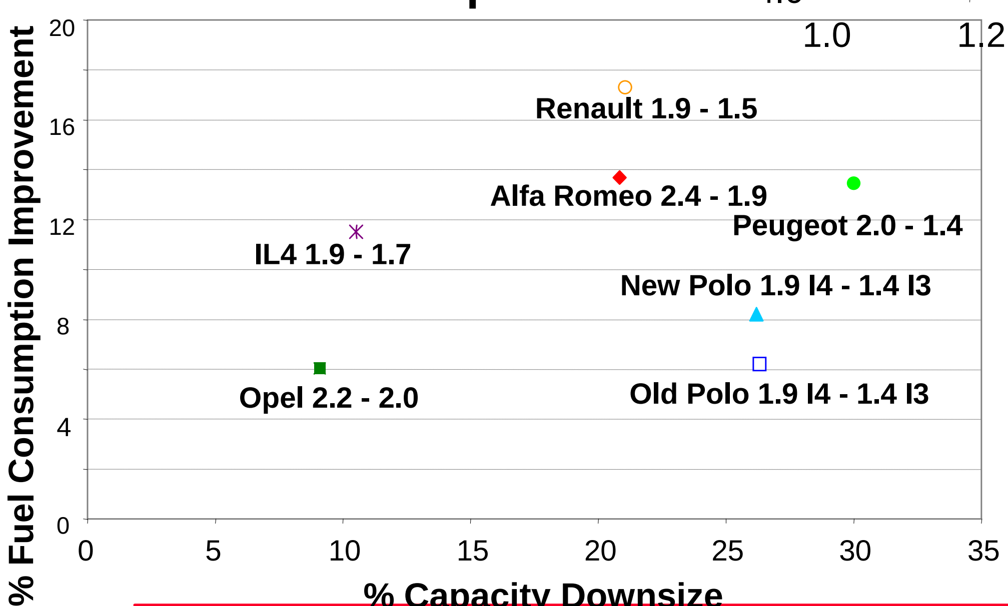
Production Models

Same Vehicle

Effect of Downsizing on Fuel Consumption



% FC Improvement

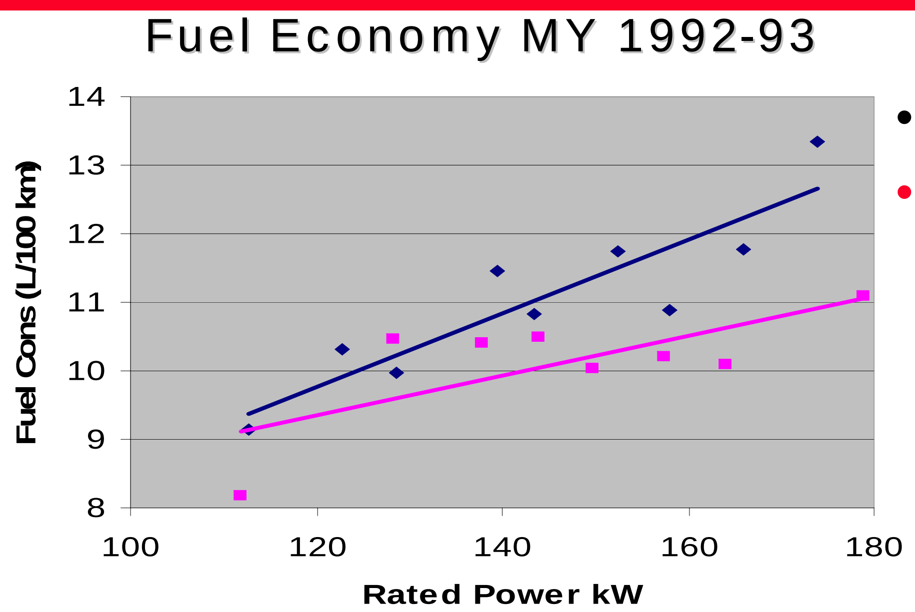


10-30% Downsizing

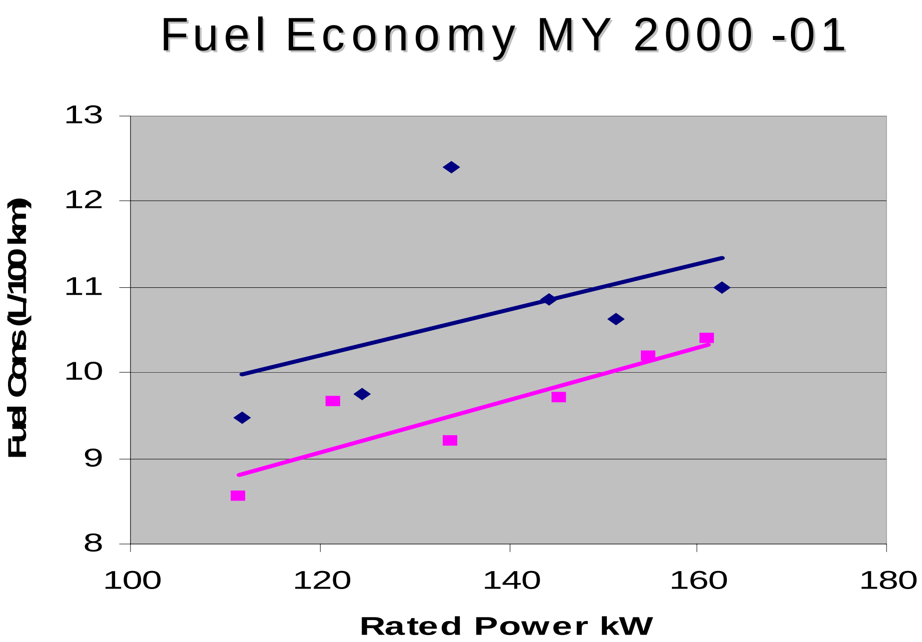
6-17% Fuel Economy Improvement

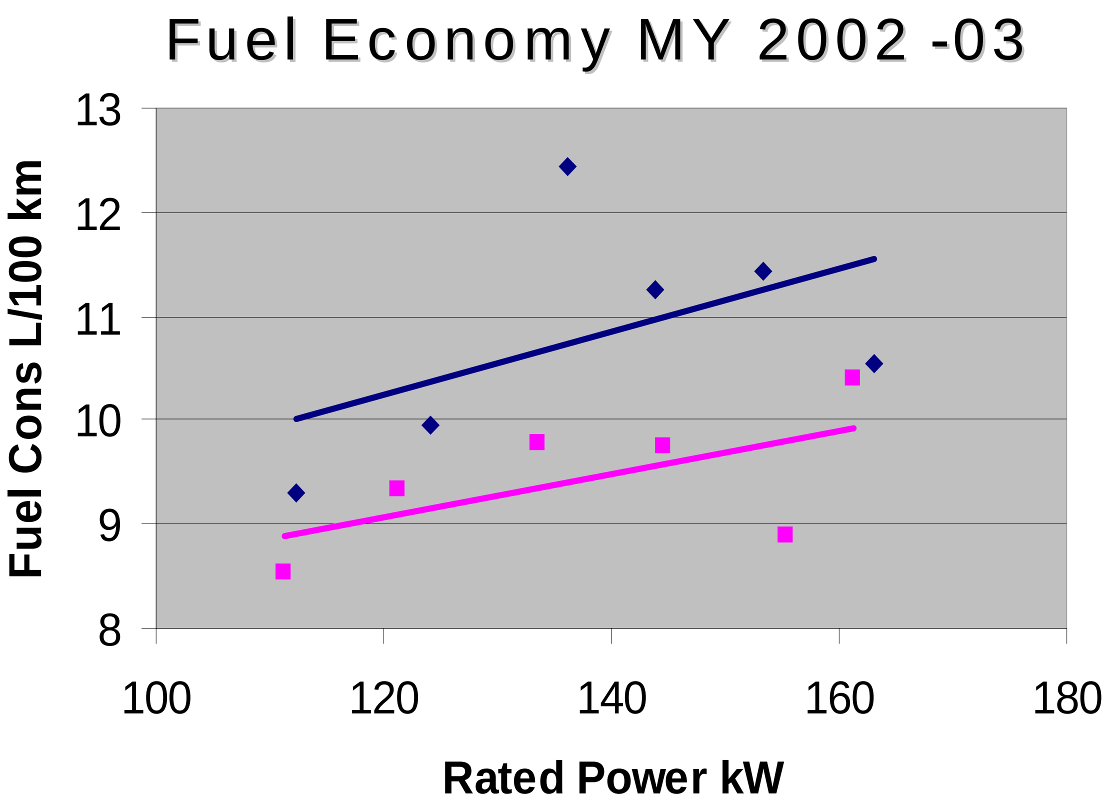
Credits RICARDO

Gasoline Engine Downsizing & Turbocharging



- Units litres/100 km - lower is better
- Turbocharged downsized engines show 8-10% better fuel economy than non-turbocharged engines over 10 years of production vehicles





NA TC Linear (TC) Linear (NA)

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Critical “Go/No-Go” Technical Feasibility Criteria

- High-speed motor/controller system to provide up to 1.4kW mechanical power at speeds up to 175kRPM total system efficiency > 70%.
- Turbocharger bearing system to carry the extra mass and length while still retaining acceptable shaft rotor-dynamic behavior up to 225kRPM.
- Turbocharger and motor cooling system to protect the motor from the extreme turbocharger thermal environment as well as from self-heating.
- Compressor aerodynamics to deliver the extra boost without suffering from surge (“stall”) during the transient.

Designs Successfully Establish Feasibility

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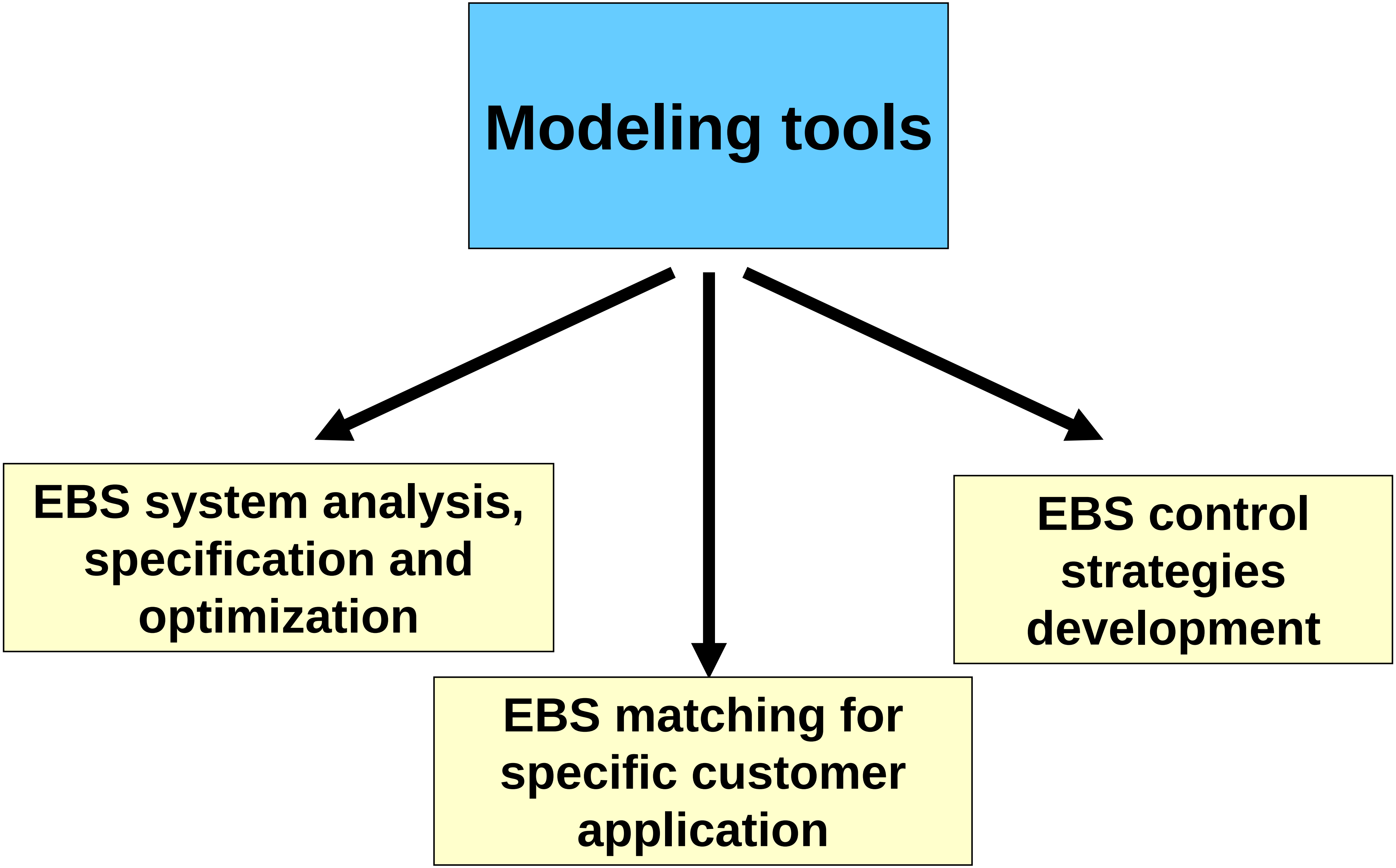
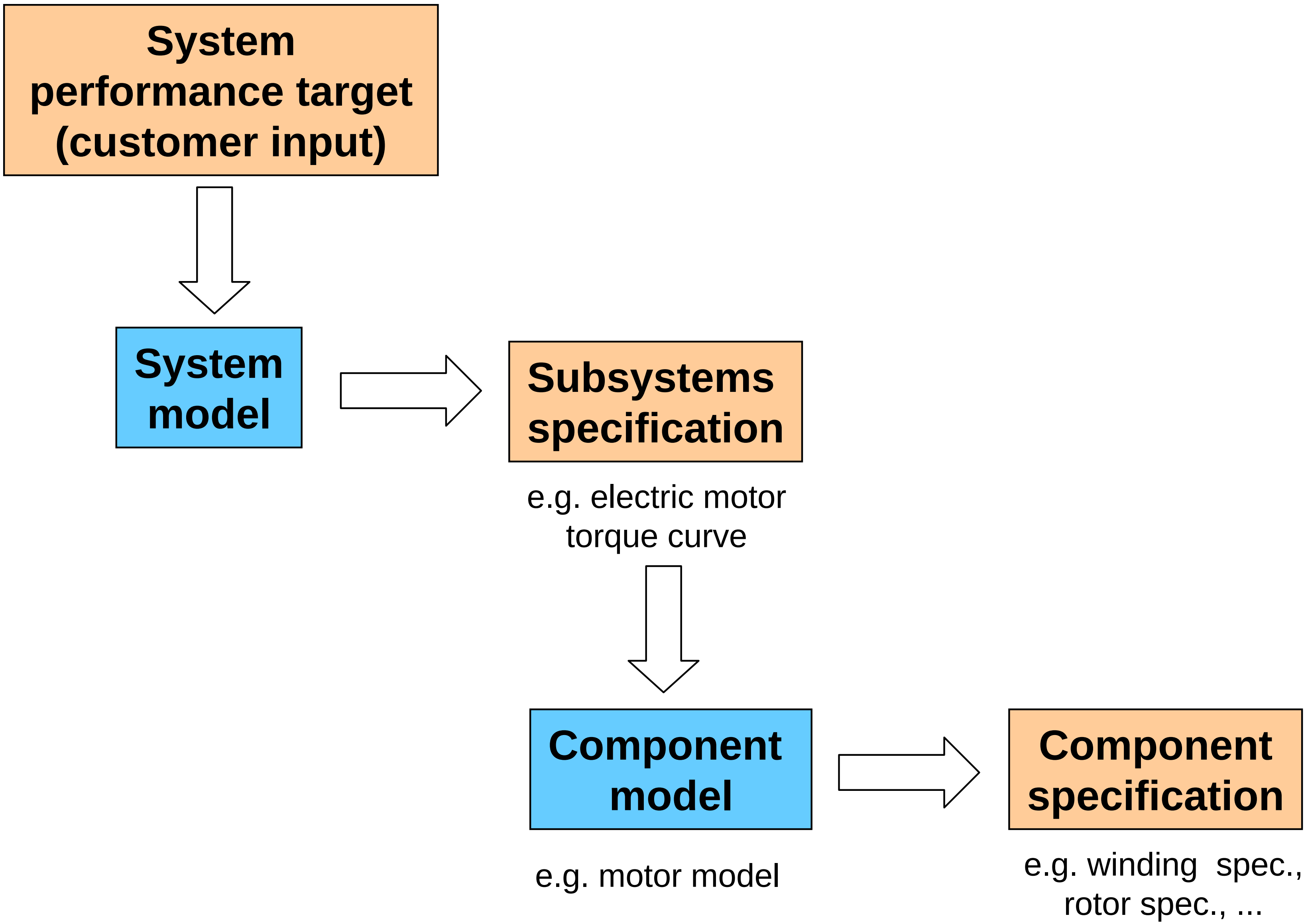
Modeling for EBS

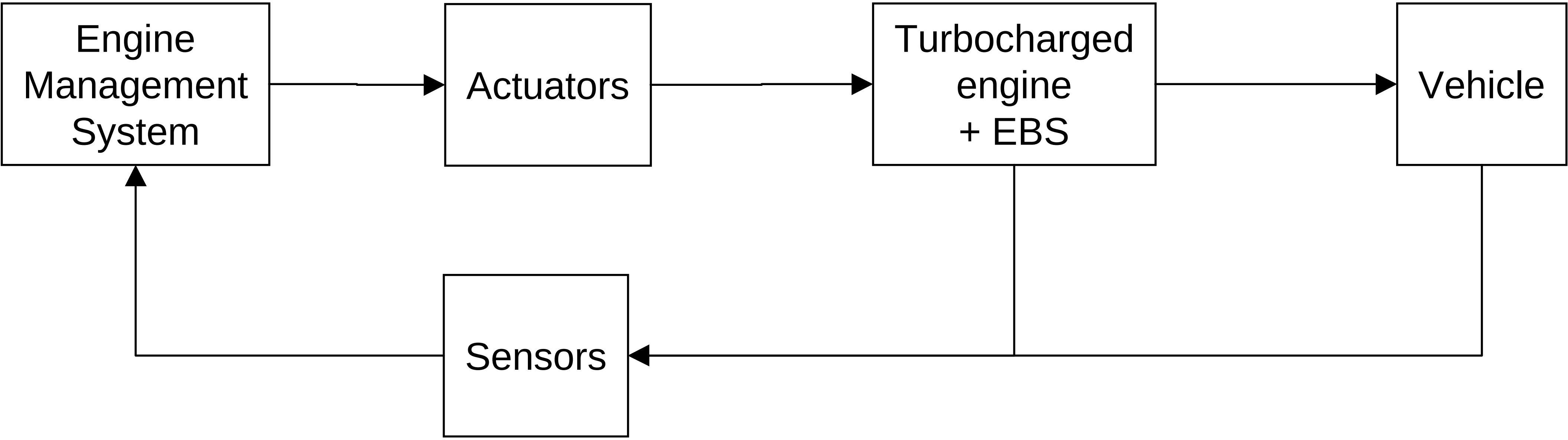


EBS System Analysis

High level to low level specification



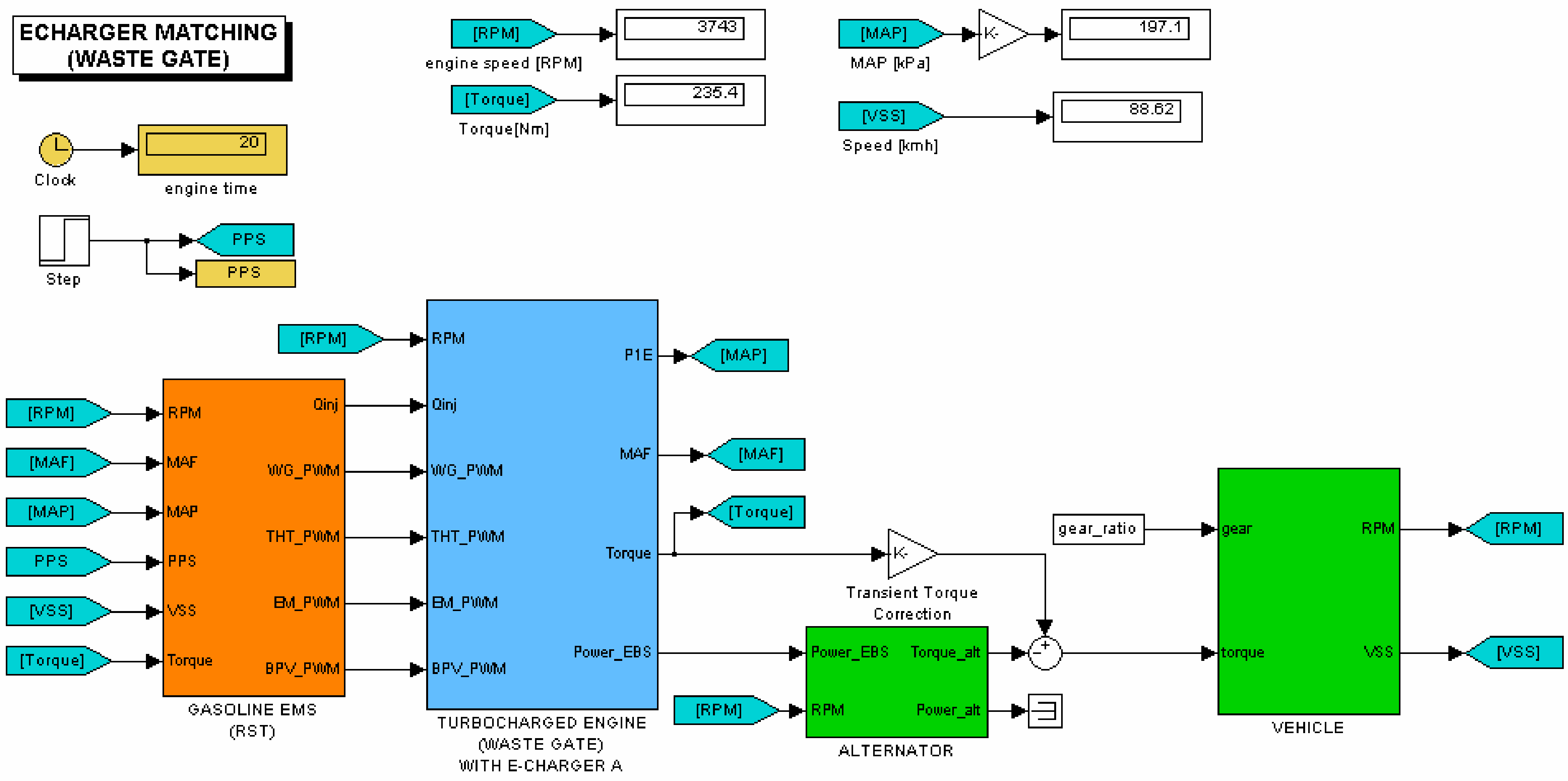
System Model Schematic



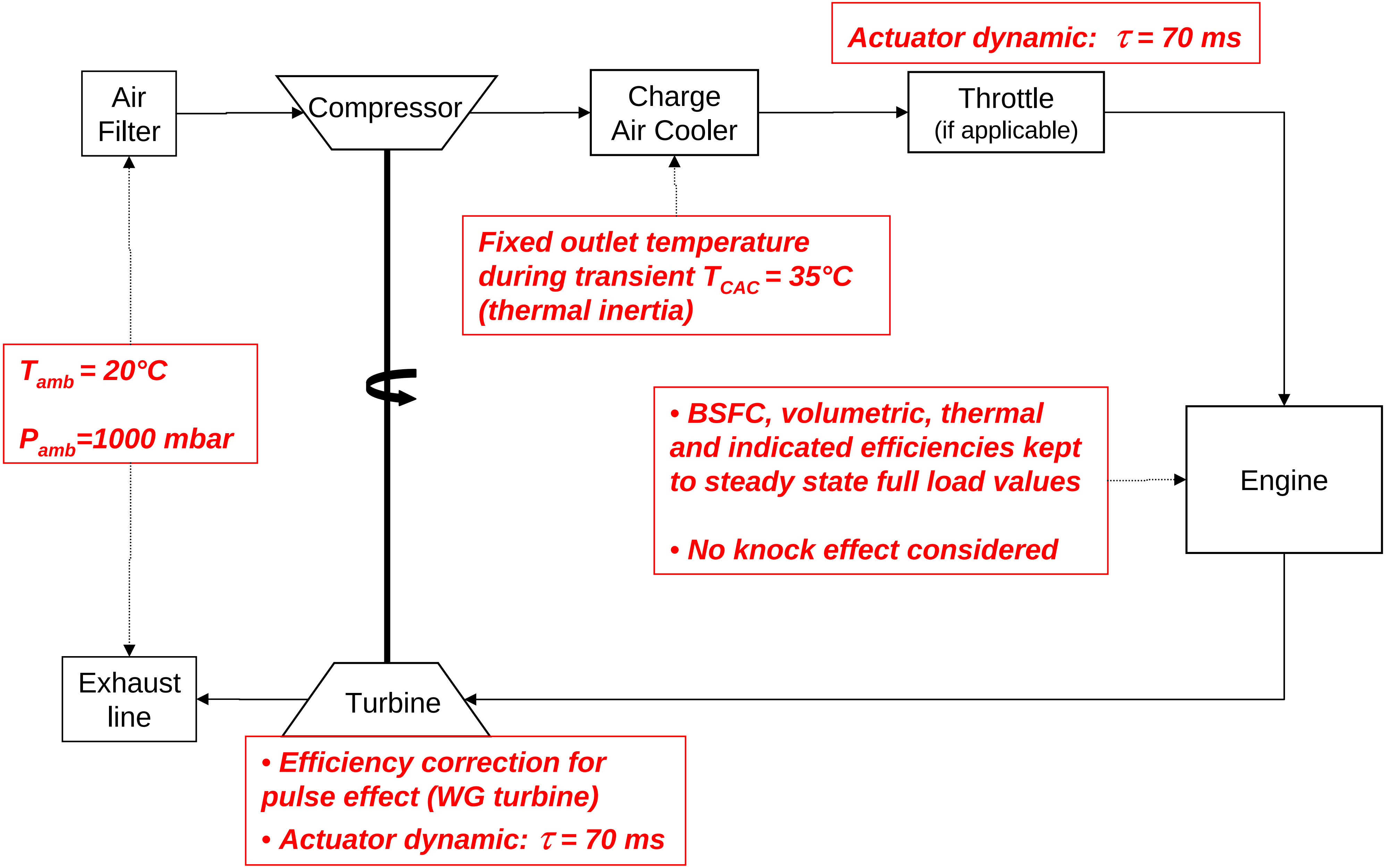
Engine mean value model (diesel and gasoline)

- **Thermodynamics/mechanical model of turbocharged engine**
- **Validated against steady state and transient engine data**

System Model: Matlab/Simulink Implementation



Summary of Main Modeling Assumptions



Summary of Main Modeling Assumptions

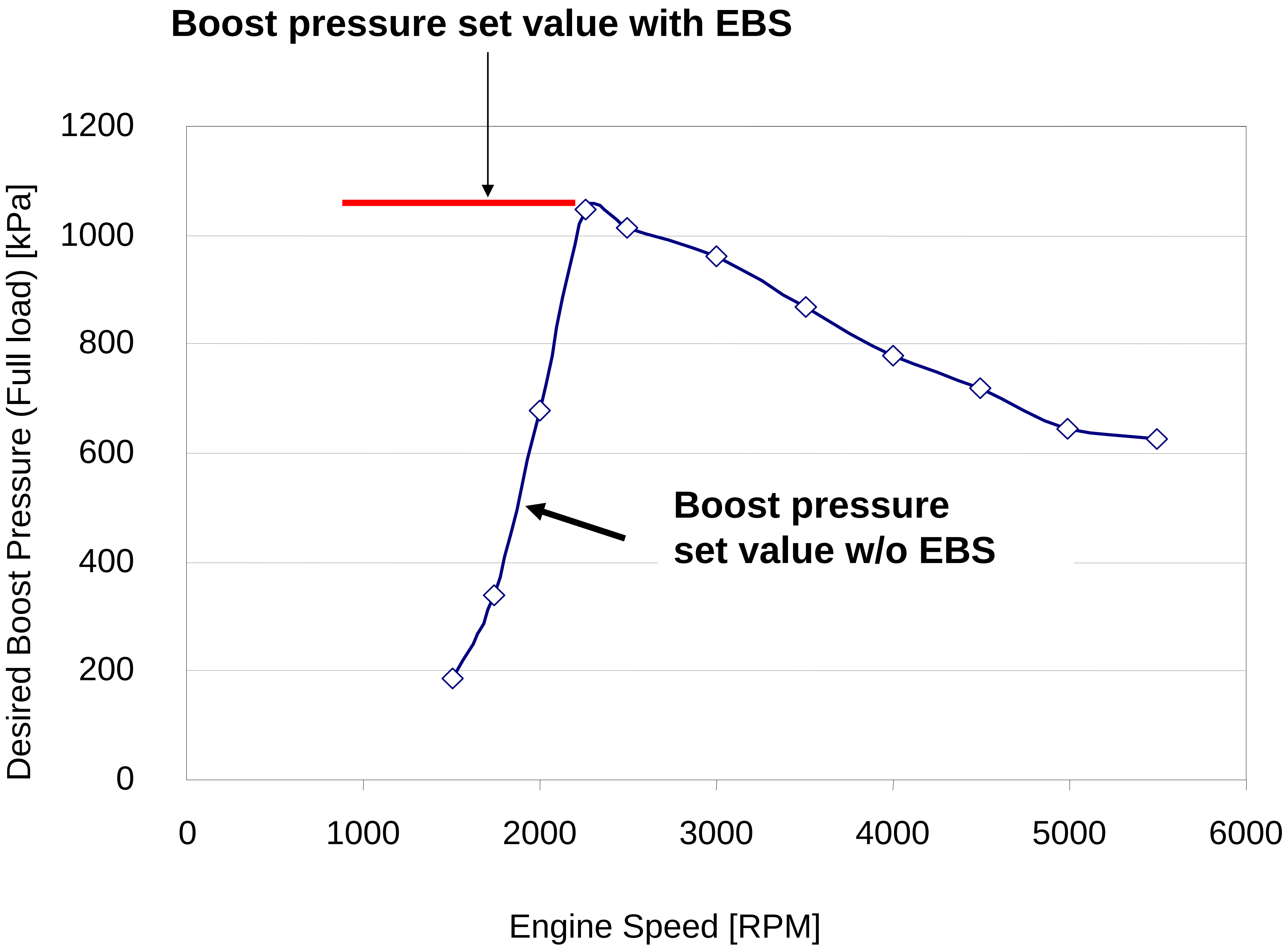
During transient simulation:

Goal: Reach & Maintain Boost Pressure Set Value

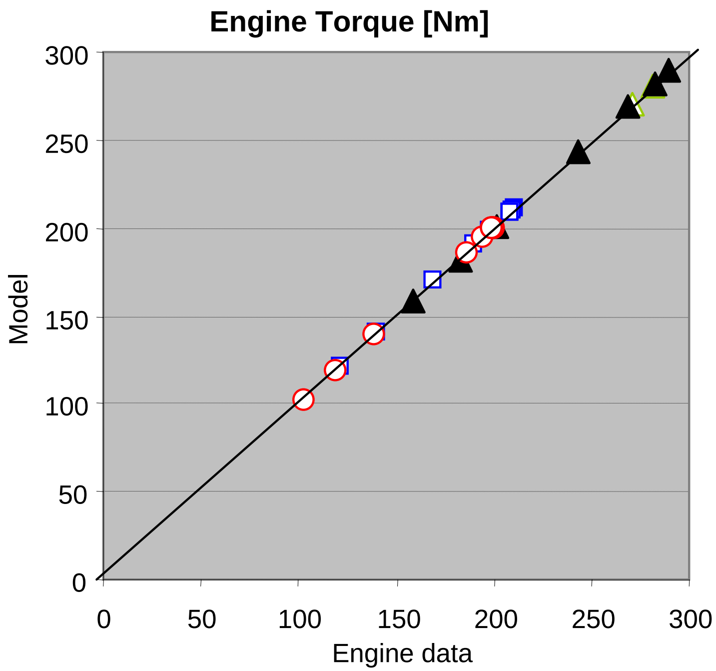
- **Throttle (if applicable) Control:**
  - Fast opening at PPS step (instantaneous 100 % DC command)
- **WG/VNT Control:**
  - Open at part load (0% DC command)
  - Fast closing at PPS step (instantaneous 100 % DC command)
  - Kept closed if electric motor activated, regulation mode afterward
- **Electric Motor Control:**
  - Fast starting at PPS step (instantaneous 100 % DC command)
  - Regulation mode afterward
- **Boost Pressure Set Value:**
  - If EBS is activated, desired boost pressure set to maximum full load boost

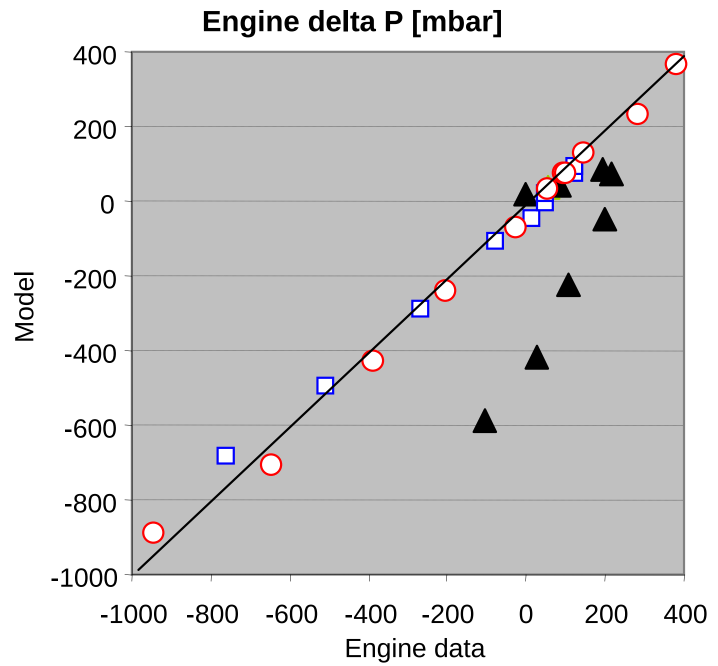
PPS-Pedal Position Sensor
WG for Gasoline and VNT for Diesel

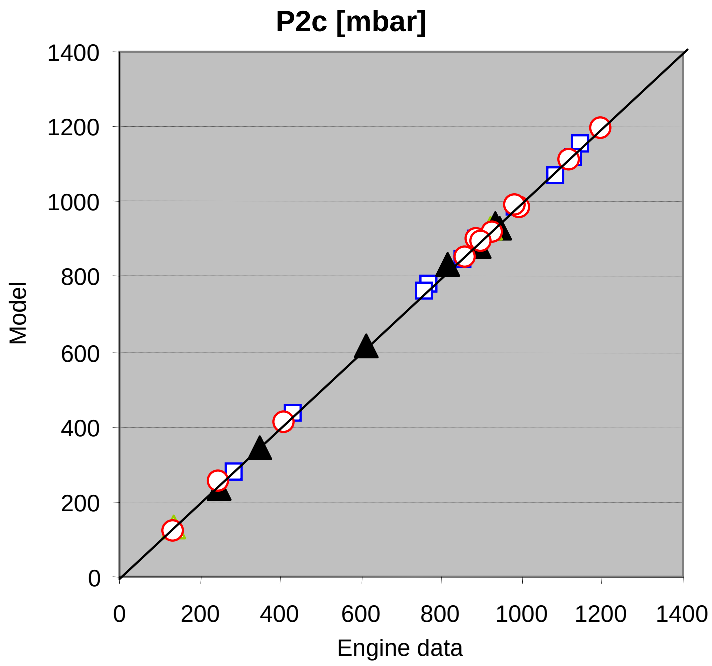
Summary of Main Modeling Assumptions

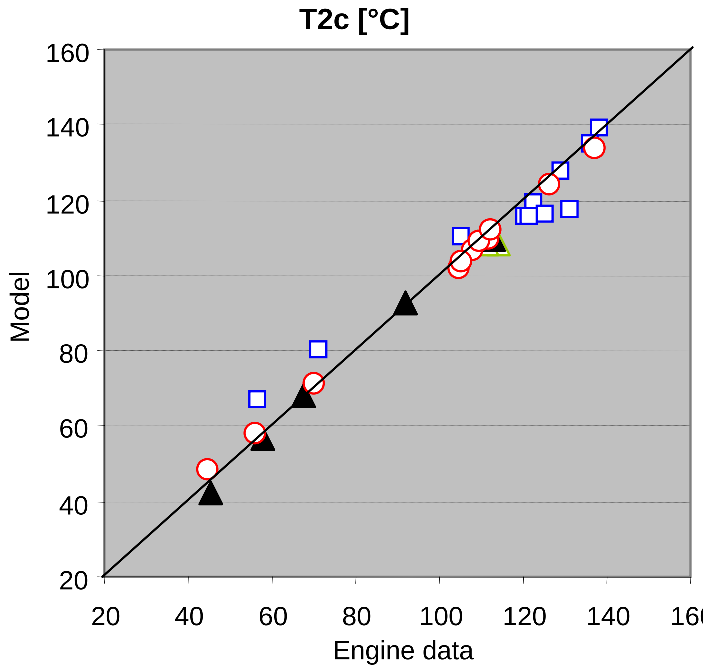


Steady-State Model Validation





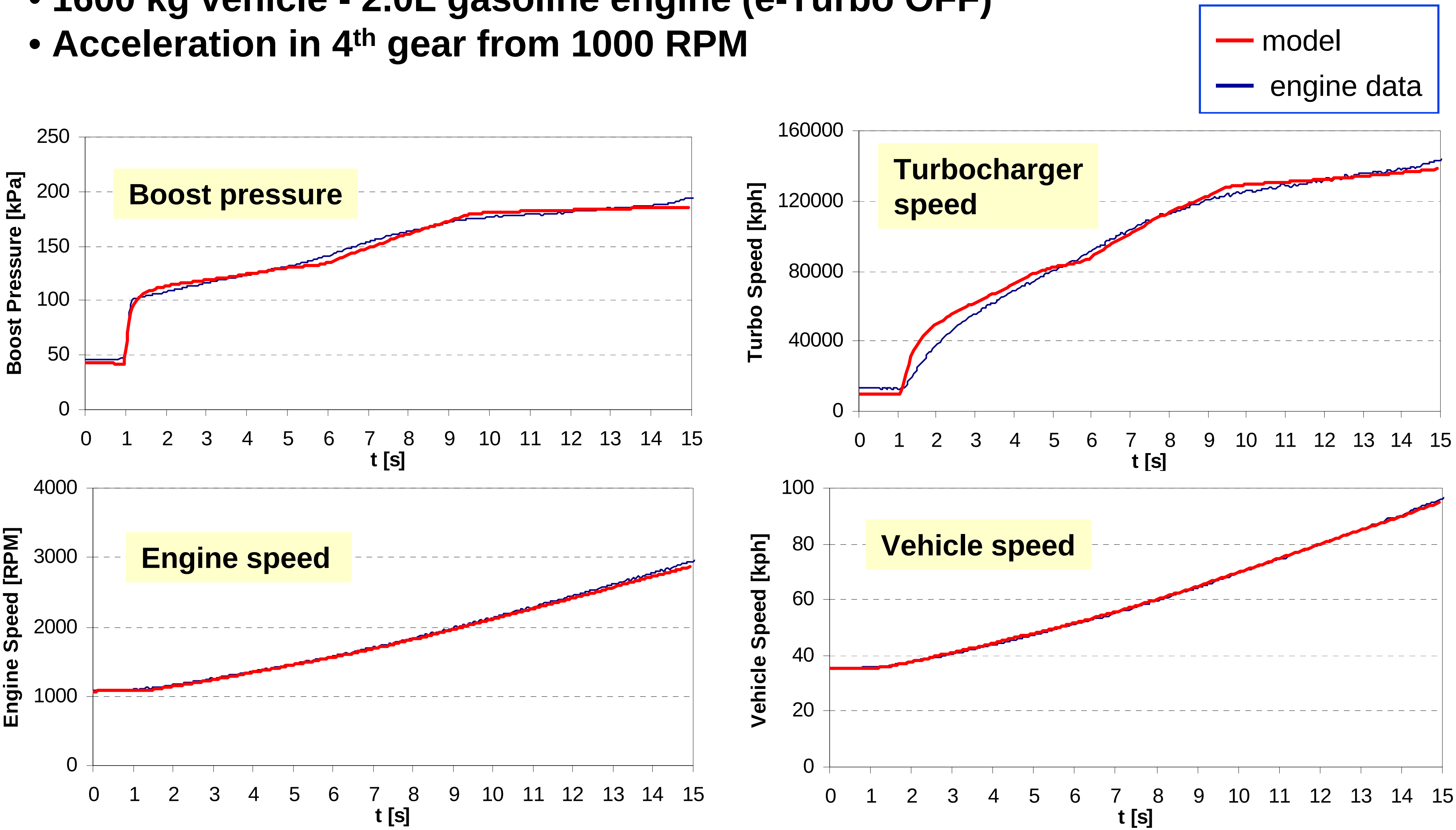




Garrett

Transient Model Validation

- **1600 kg vehicle - 2.0L gasoline engine (e-Turbo OFF)**
- **Acceleration in 4th gear from 1000 RPM**



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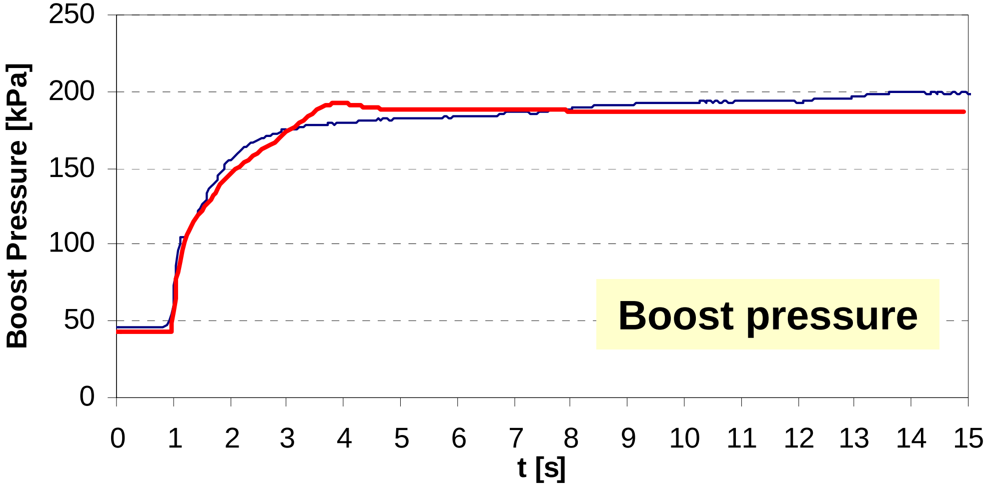
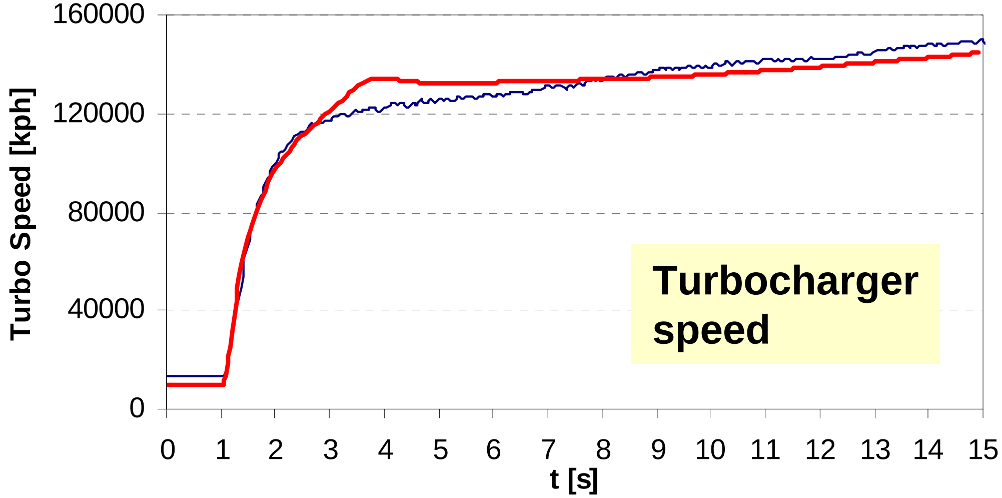
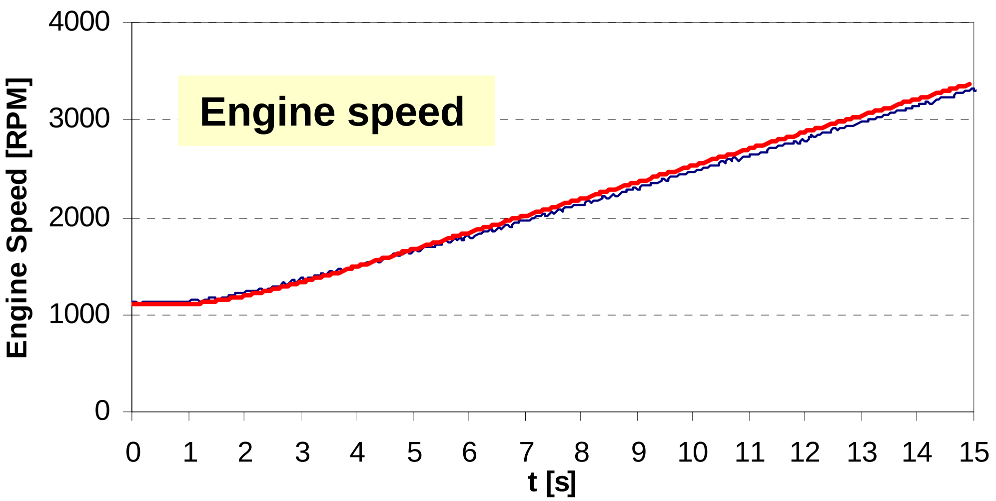
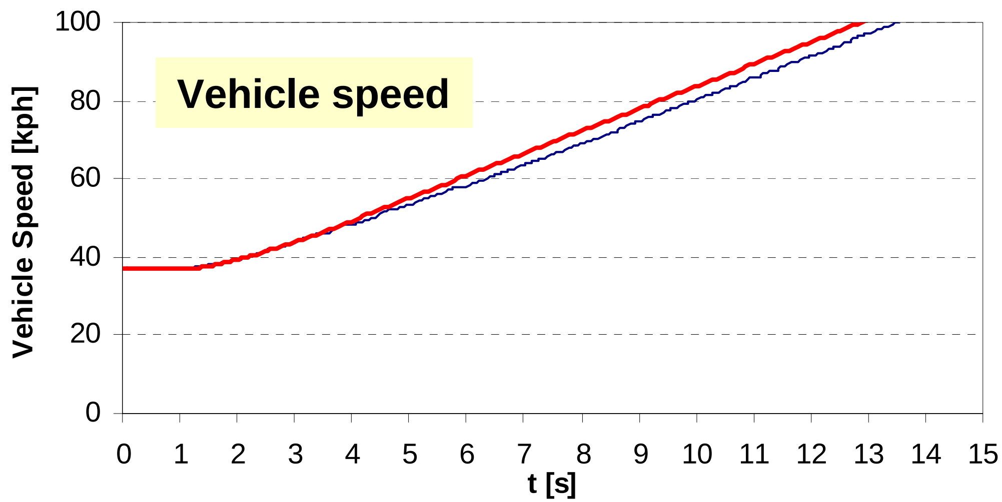
model
engine data









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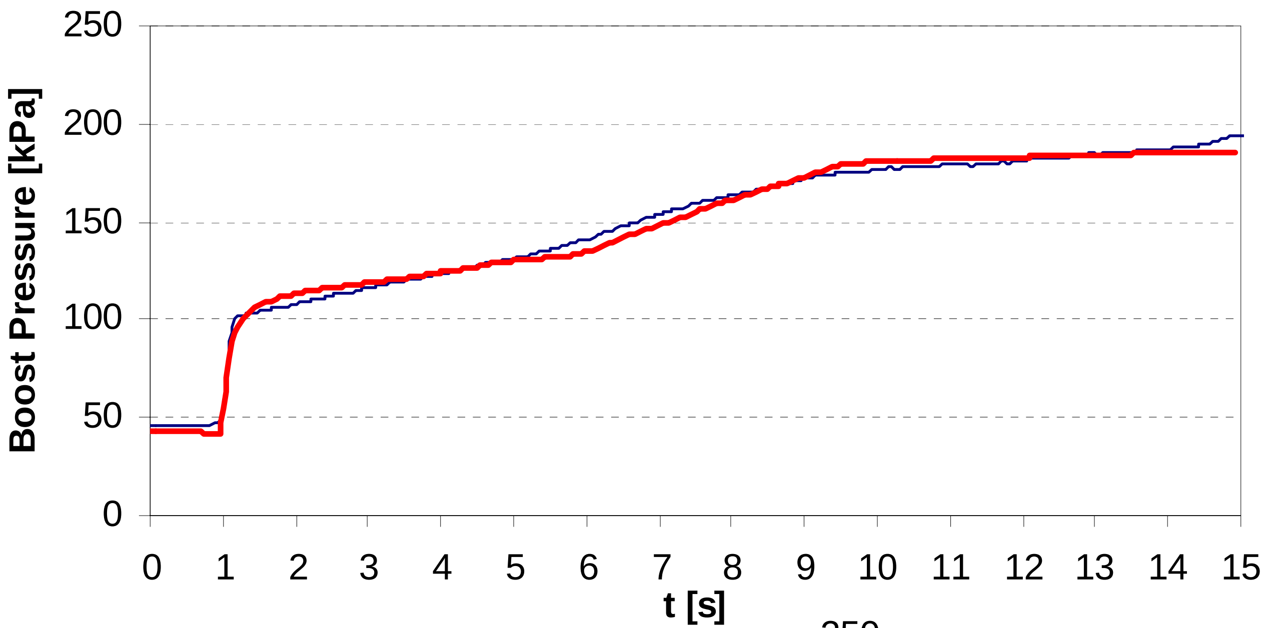
1600 kg vehicle - 2.0L gasoline engine

• Acceleration in 4th gear from 1000 RPM

(e-Turbo OFF)



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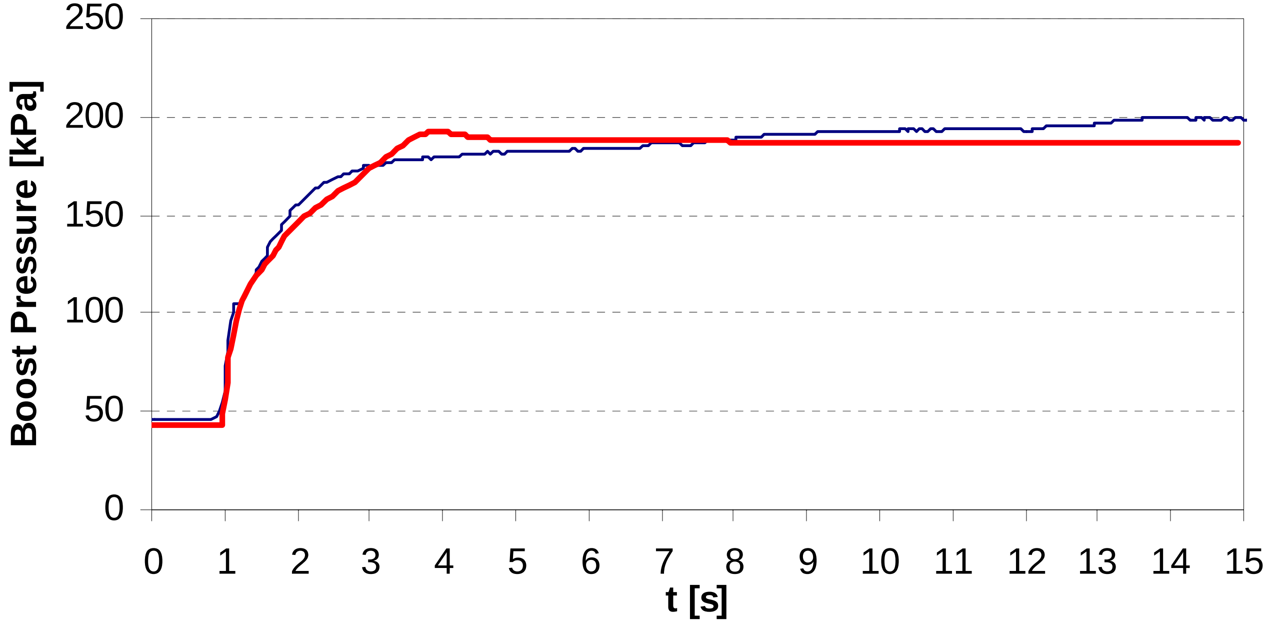

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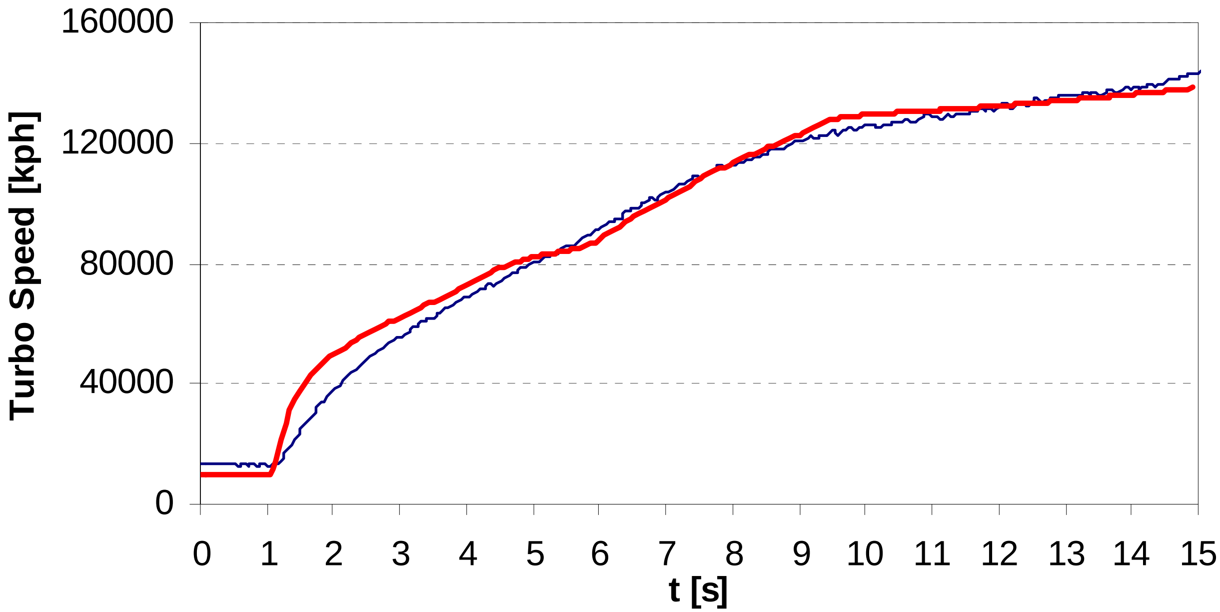

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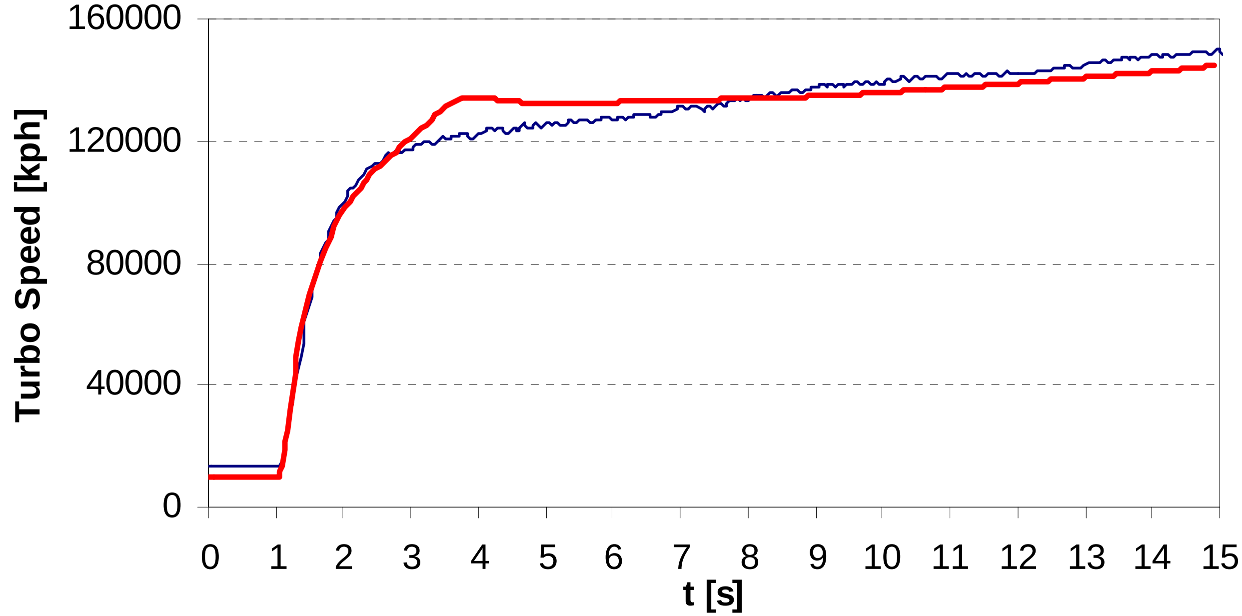

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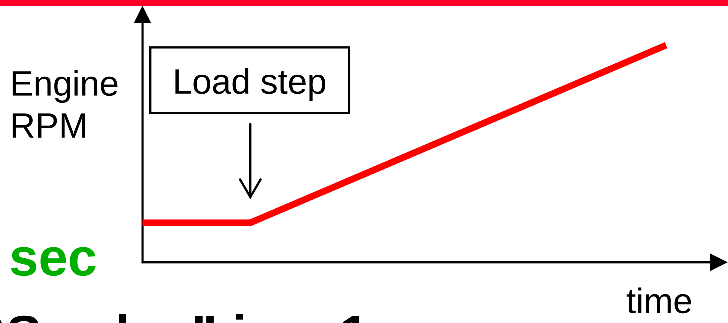
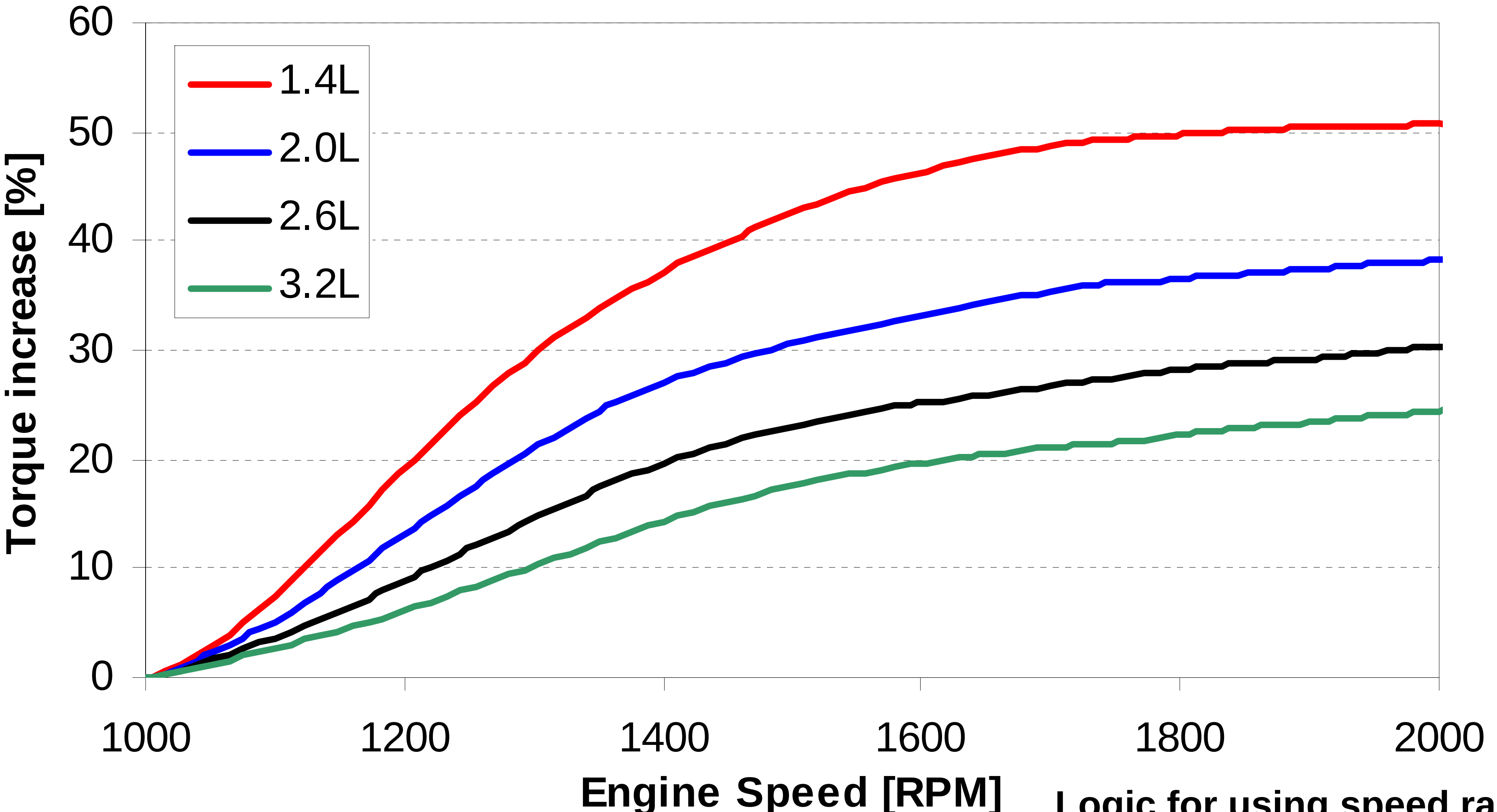
Sensitivity Analysis Example: Displacement

- Fixed RPM ramp after load step (400 engine RPM/s)
- Electric motor mechanical power: 1250 W
- Relative value compared to transient w/o EBS
- Diesel Engine Modeling - % increase in torque in ~ 1 sec



Transient torque increase over “no-EBS value” in ~ 1 sec



Logic for using speed ramp

Sensitivity Analysis Example: Power

- Fixed RPM ramp after load step (400 engine RPM/s)
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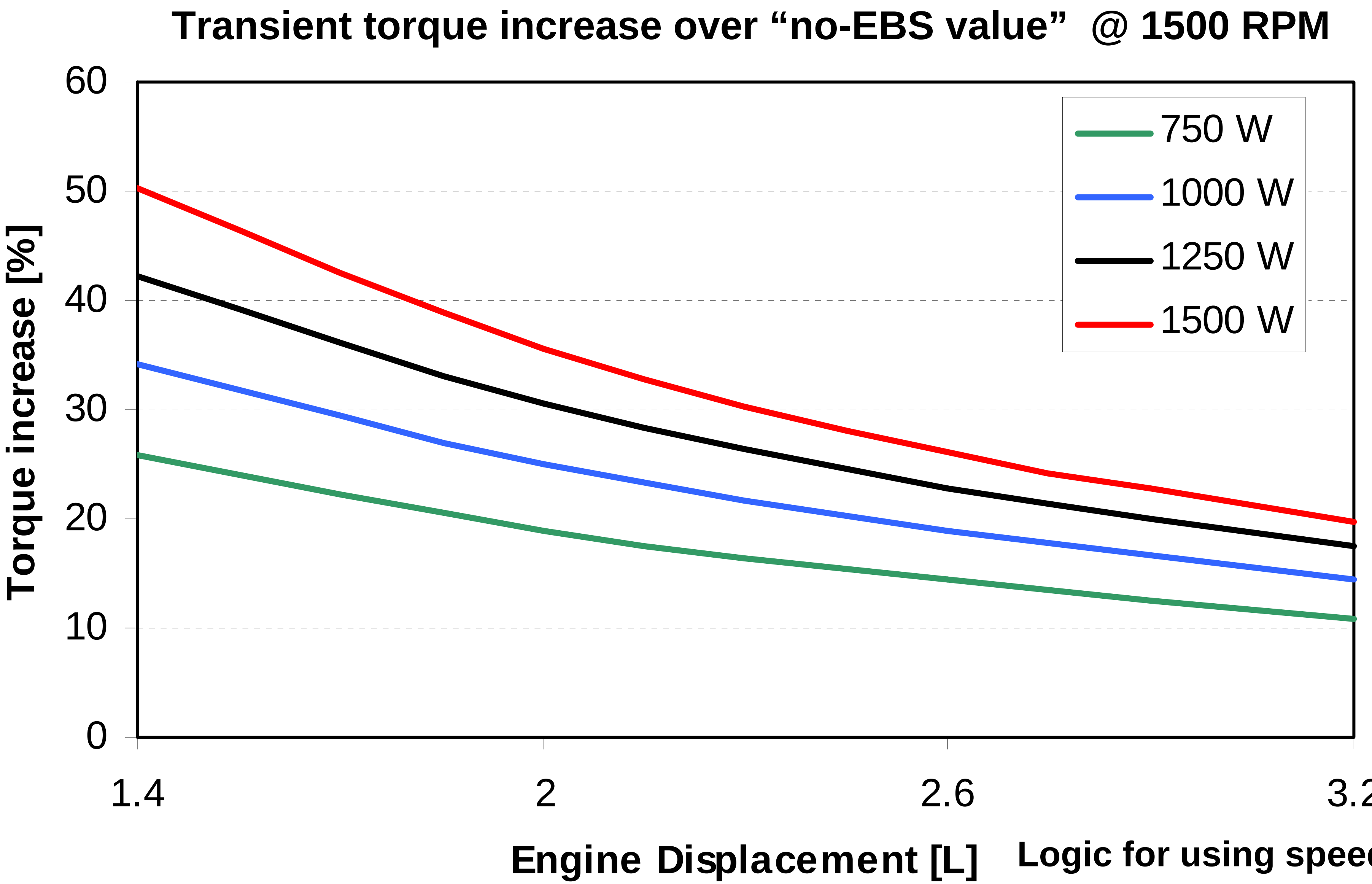
- Diesel Engine Modeling - % increase in torque in ~ 1 sec



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Key Technical Challenges and Targets (2.0L)

- Maintain baseline turbocharger speed = 225kRPM
  - Challenge for rotor bearing subsystem to carry motor
    - Extra length of shaft
    - Overhung weight of motor
  - Challenge for motor mechanical stress
    - Durability at high speed
- Motor performance
  - Acceptable performance on 12V network and < 2kW electric input
    - Torque and mechanical power necessary for boost benefit
    - Efficiency to minimize electric input power requirement
- Compressor aerodynamics to deliver full benefits of motor boost
  - Good efficiency at low flow, low pressure ratio
  - Good range to avoid surge during overboost
- Temperature capability and cooling: motor < 180C
- Protection of motor at severe “off” conditions (e.g. soakback)
  - Unconstrained duty cycle operation at typical operating conditions
  - Partial duty cycle operation at worst-case operating conditions
    - 850C turbine inlet
    - 110C cooling water
    - 150C oil temperature

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Solutions Require Integrated Approach

e-Turbo Design Parameters	Turbocharger Size	Motor Mechanical Speed Limit	Compressor Range/Surge	Motor Torque	Rotor Diameter	Bearing Type	Rotordynamic Stability	Shaft Motion	Bearing Length	Bearing Diameter	Rotor/Stator Air Gap	Motor Length	Oil System	Cooling System	Motor Efficiency	Motor Power	Stator Diameter	Compressor Packaging	Motor Motoring Speed Limit	Turbine Packaging
Turbocharger Size																				
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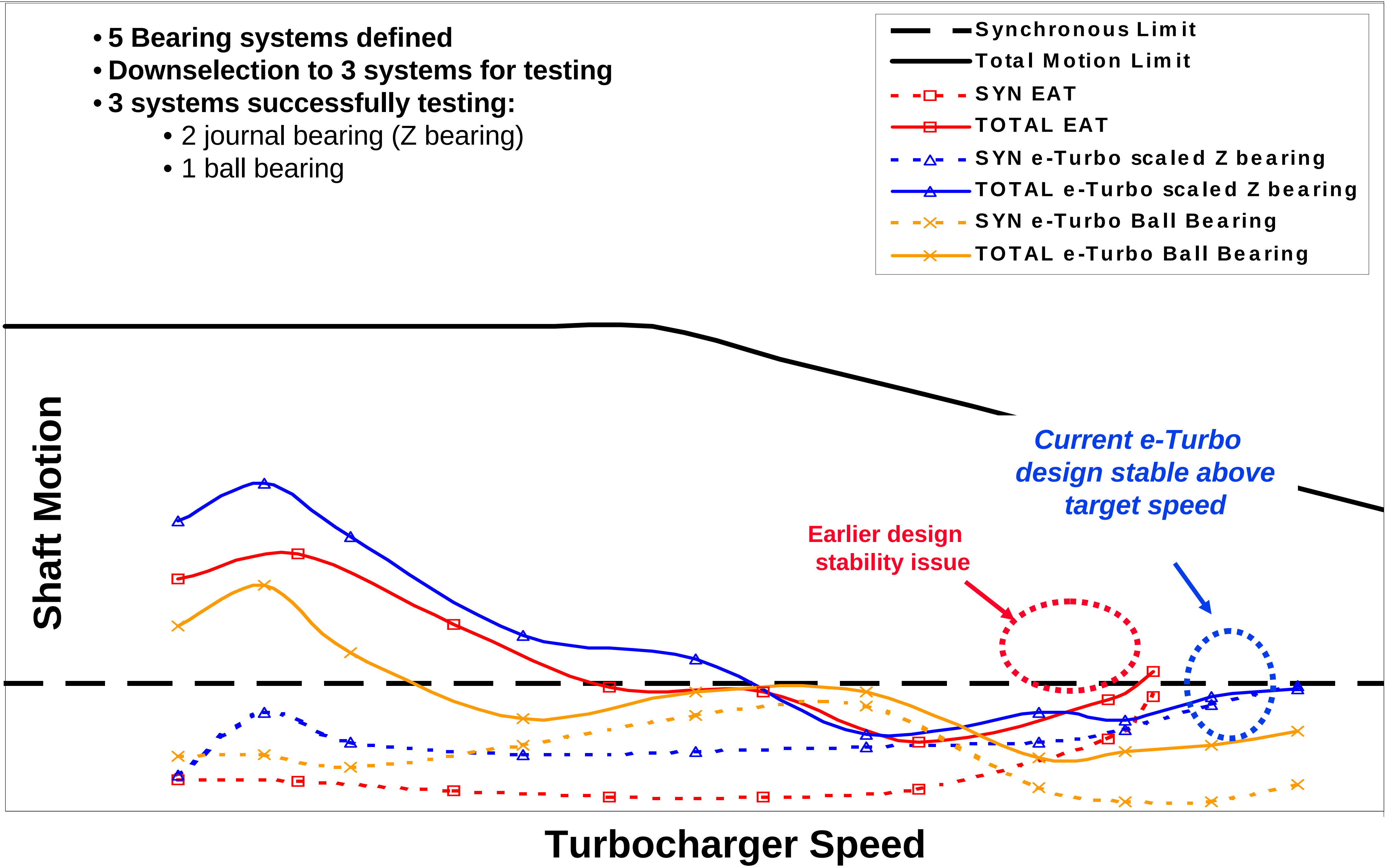
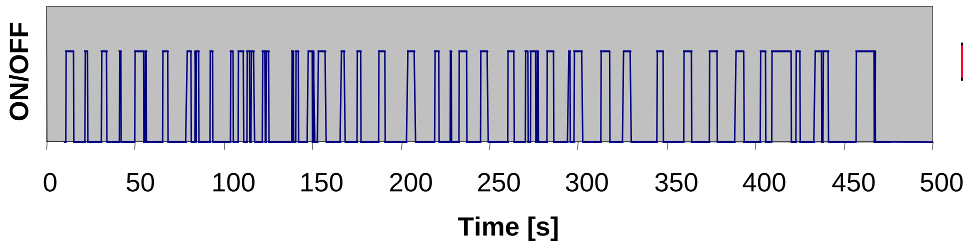
Rotor Bearing Subsystem

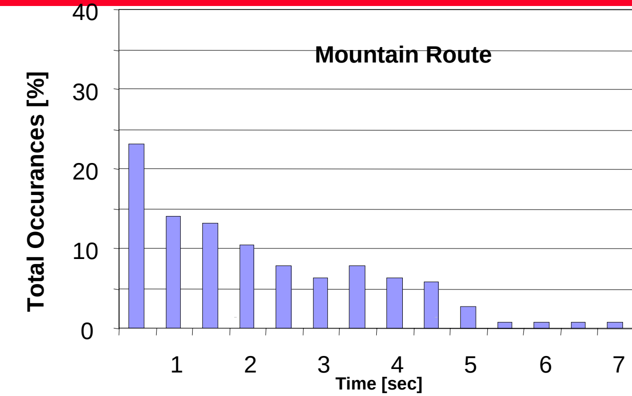
- **5 Bearing systems defined**
- **Downselection to 3 systems for testing**
- **3 systems successfully testing:**
  - 2 journal bearing (Z bearing)
  - 1 ball bearing



Cooling Subsystem

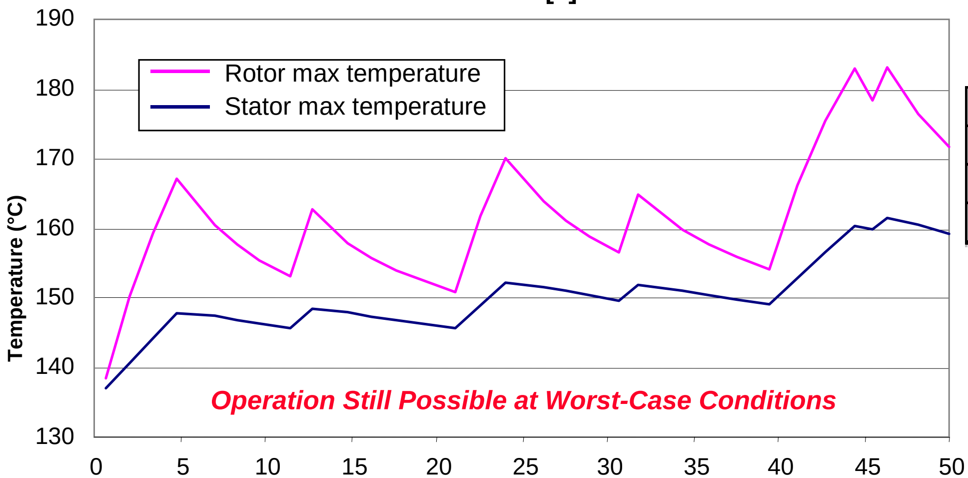
Vehicle Duty-Cycle Recording @ Several Conditions



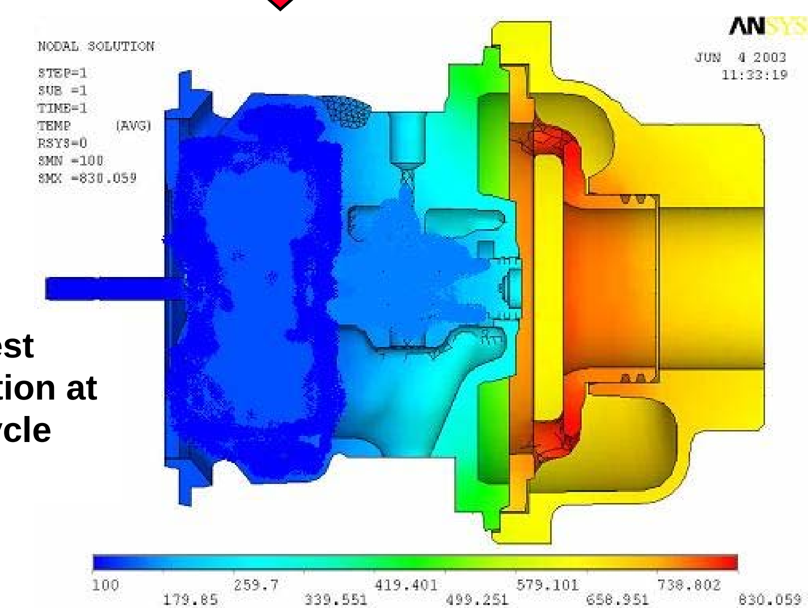


Statistical Analysis

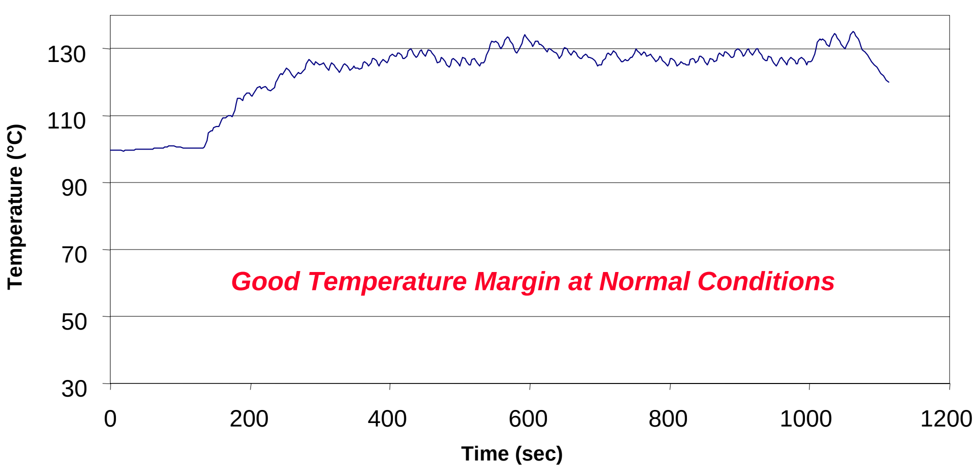
	City	Mountain	Highway	Country Road
Duty Cycle (%)	7%	19%	3%	6%
Average ON time (sec)	1.1	2.2	1.5	1.3
% ON > 2 sec	91%	58%	83%	86%



3D Transient Thermal Modeling to Optimize Cooling



e-Turbo Bench Test and Model Validation at Mountain Duty Cycle Conditions



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Conclusions and Next Steps

Conclusions

- System models have been developed, validated, and used to set development targets
- Testing and simulation has validated the potential for engine downsizing using EBS
- Key technical challenges have been identified and solutions have been found: rotor bearing subsystem, cooling system, motor, aerodynamics
- Next Steps
- Develop next-generation prototype encompassing latest technical solutions and performance targets
- Perform engine and vehicle testing to validate performance and downsizing potential
- Assess total installed system cost and packaging
- Scale up to SUV Size Engine