Control Strategy for a Dual Loop EGR System to Meet Euro 6 and Beyond

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Our Beliefs

Respect
Collaboration
Excellence
Integrity
Community

BorgWarner

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  - Thermodynamic Analysis
- **Control System Overview**
  - Structure
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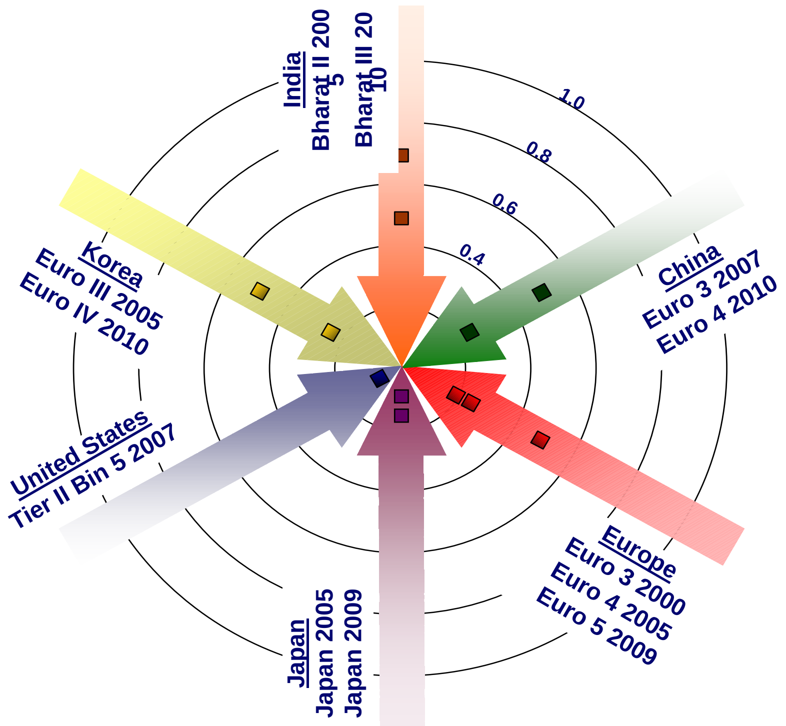
Motivation

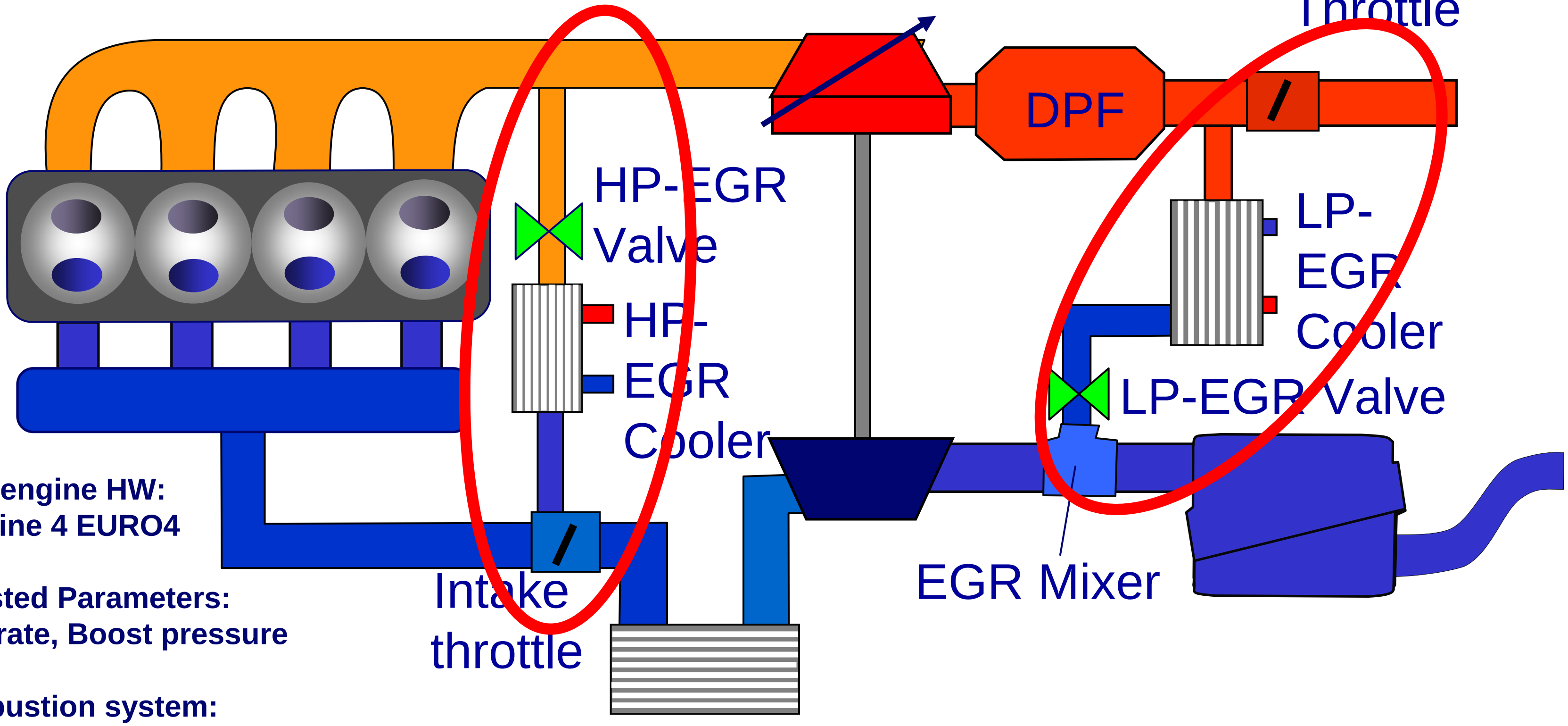
- Reduce the cost and lower emissions of diesel engines in an ever tightening regulatory world
  - Focus on EGR and Boost Systems

NOx Emissions Regulation (g/km)



EGR & Turbo Charging System Architecture
Base "Dual Loop" EGR system Layout

I4 diesel engine, common rail



Base engine HW:
2L Inline 4 EURO4

Adjusted Parameters:
EGR-rate, Boost pressure

Combustion system:
standard Diesel (diffusive)

EGR-system:
cooled HP-EGR, cooled LP-EGR

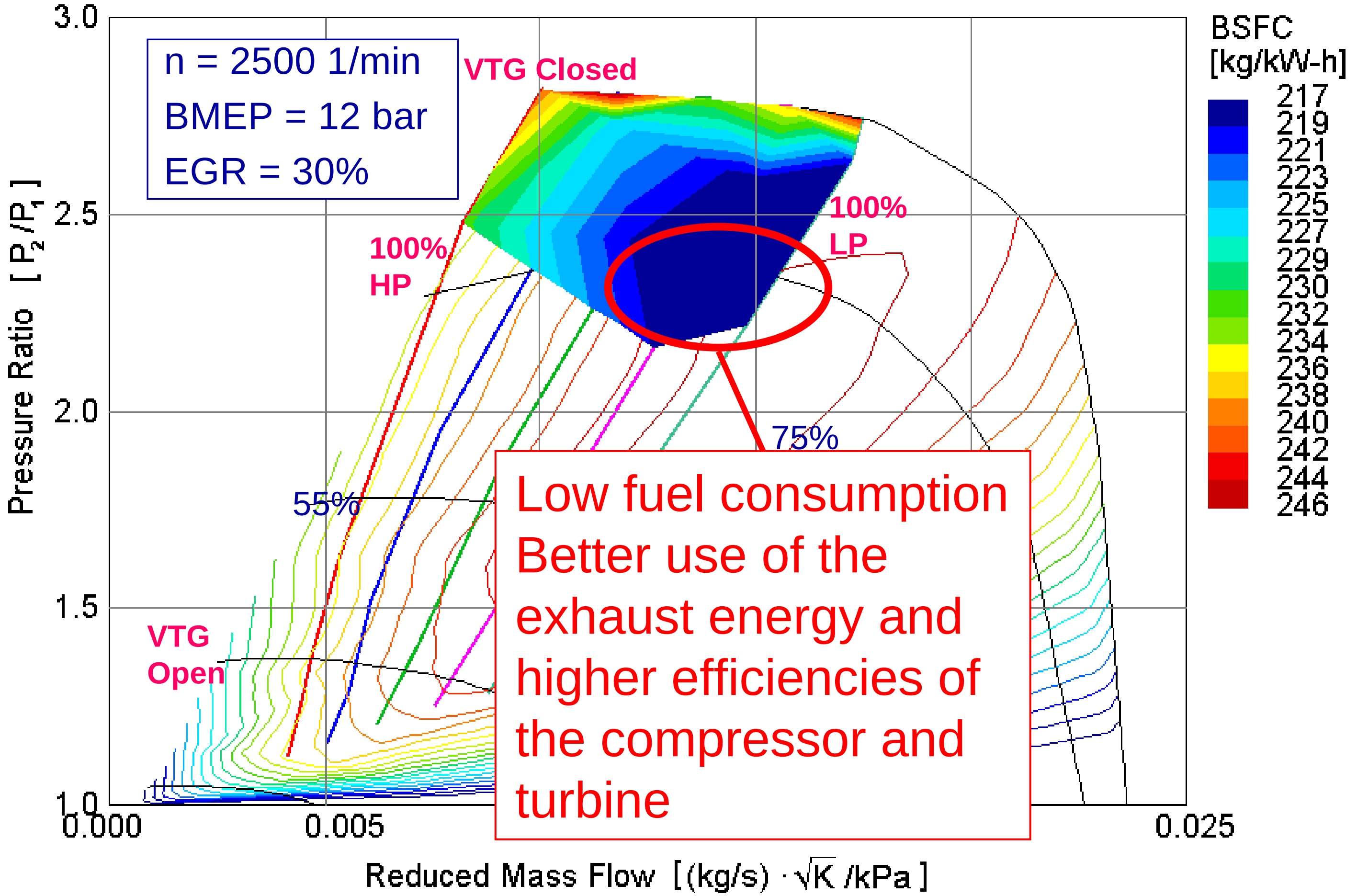
Boosting system:
1-stage VTG

Last year conclusions

- **A Dual Loop EGR System offers significant advantages to reduce emissions and fuel consumption and can meet future emission requirements**
  - **Mostly due to improved turbocharger operating efficiency**
  - **Charge Air Temperature Reduced**
  - **Up to 4% improvement in BSFC in steady state**
  - **More EGR can be driven without performance sacrifice**
- **Dynamic engine performance can be improved with a dual loop EGR system**
- **Transient controls need to be developed and improved *(focus of today's presentation)***

Thermodynamic Analysis HP&LP Loop

Specific fuel consumption at different HP/LP-EGR-splits



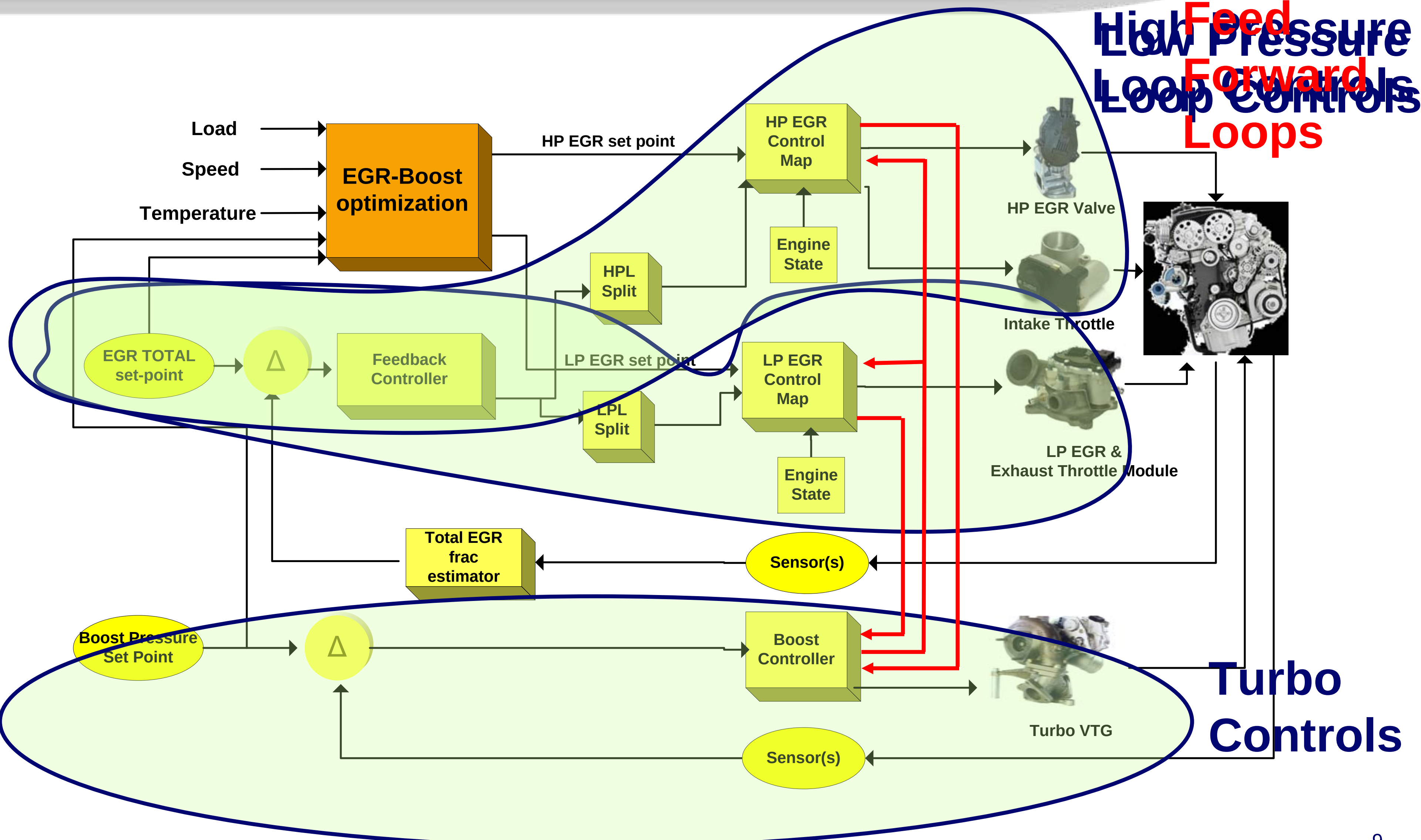
Development Process

- Modeling of Production Baseline
  - Full GT-Power Model
  - Real time capable mean value model (MVM)
- Development of controller in Simulink
- Controller Verification and calibration with GT-Power MVM in Simulink
- Dynamometer testing and final calibration using same Simulink code
- Verification on Dyno simulating NEDC Cycle

Previous Controller Options

- Separate EGR and Boost Controllers
  - Stability achieved by maintaining open loop or slow dynamic controls
- Decoupled EGR and Boost Controllers
  - Loop interference reduced but slow response and overshoots still an issue
- In both cases, NOx and PM control compromised during transients

Air Controller System Architecture



BW Coordinated Controller Features

- **Negative coupling is eliminated and positive coordination is added to improve response and control**
  - **Dual Loops and VTG help each other to achieve higher efficiency**
- **Static EGR Estimation Improvement**
  - **Achieves requested EGR rate more accurately**
- **EGR Boost Optimization Block**
  - **Determines EGR loop split**
  - **Calculated dynamically for best efficiency**
- **Utilization of EGR path which is most capable and efficient of achieving the set-point**
  - **statically (actuator saturation (virtual or actual))**
  - **dynamically (slower loop dynamics)**
- **Improved Dynamic Control**
  - **Coordinated EGR and boost system to adjust on the fly with closed loop control**

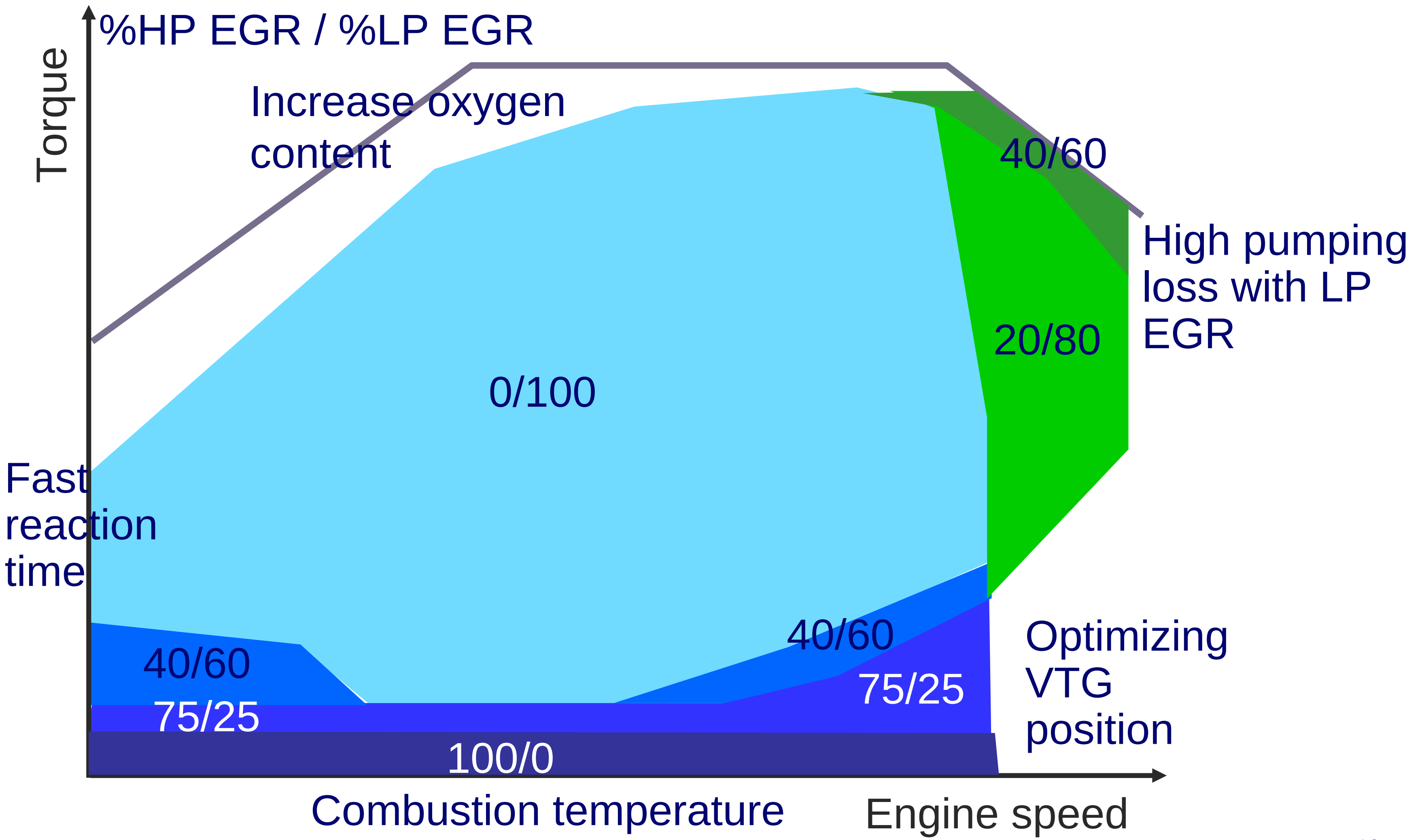
Coordinated Controller Results

- **Static EGR Estimation Improvement**
  - Better fuel economy achieved at same NOx level
- **EGR Boost Optimization Block**
  - Fuel economy improved by higher Turbo Efficiency and lower NOx achieved by increasing EGR
- **Dynamic feedback control of EGR mass flow, both EGR loops and VTG**
- **Improved Dynamic Control**
  - Decoupling of VTG and EGR allows control of each during transients
  - Less NOx and PM spikes
- **Easy to implement in production ECU**
  - Low memory and CPU usage
  - No extra I/O

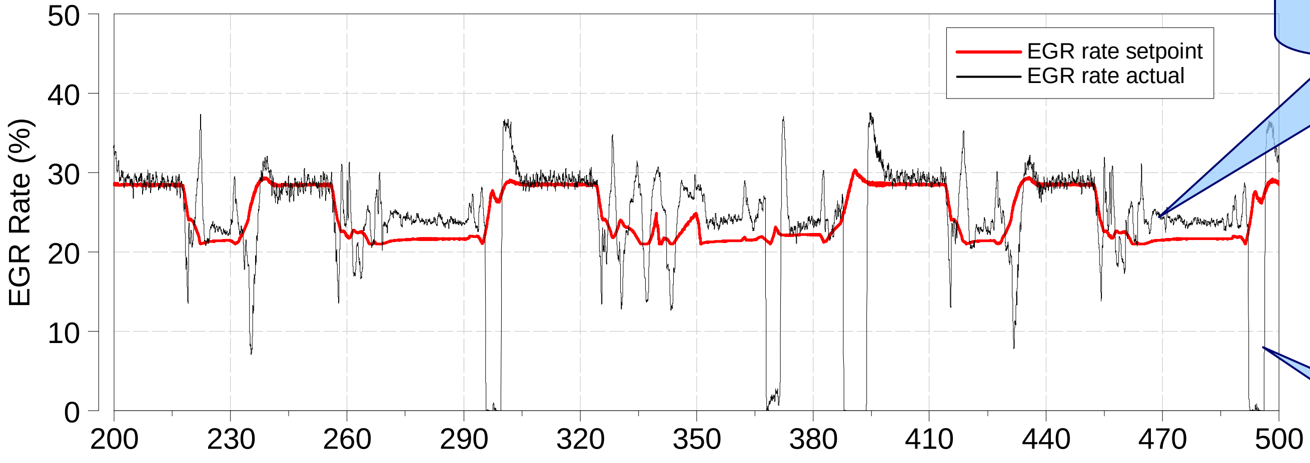
HPL/LPL Split Strategy

- Maximize Efficiency of Turbocharger
- Minimize pumping losses
- Improve dynamic Performance
- Control Charge air temperature
- Minimize Condensation in LPL

LP / HP EGR Split Strategy Steady State Map



Static and Dynamic Improvements – Relative to Baseline

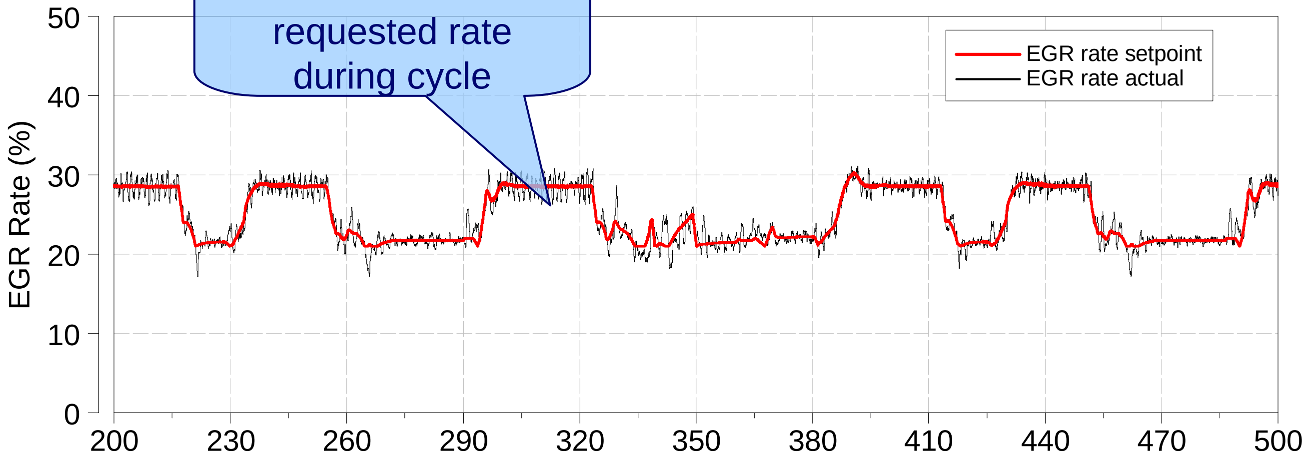


EGR Rate above requested rate

EGR valve shut-off to decouple

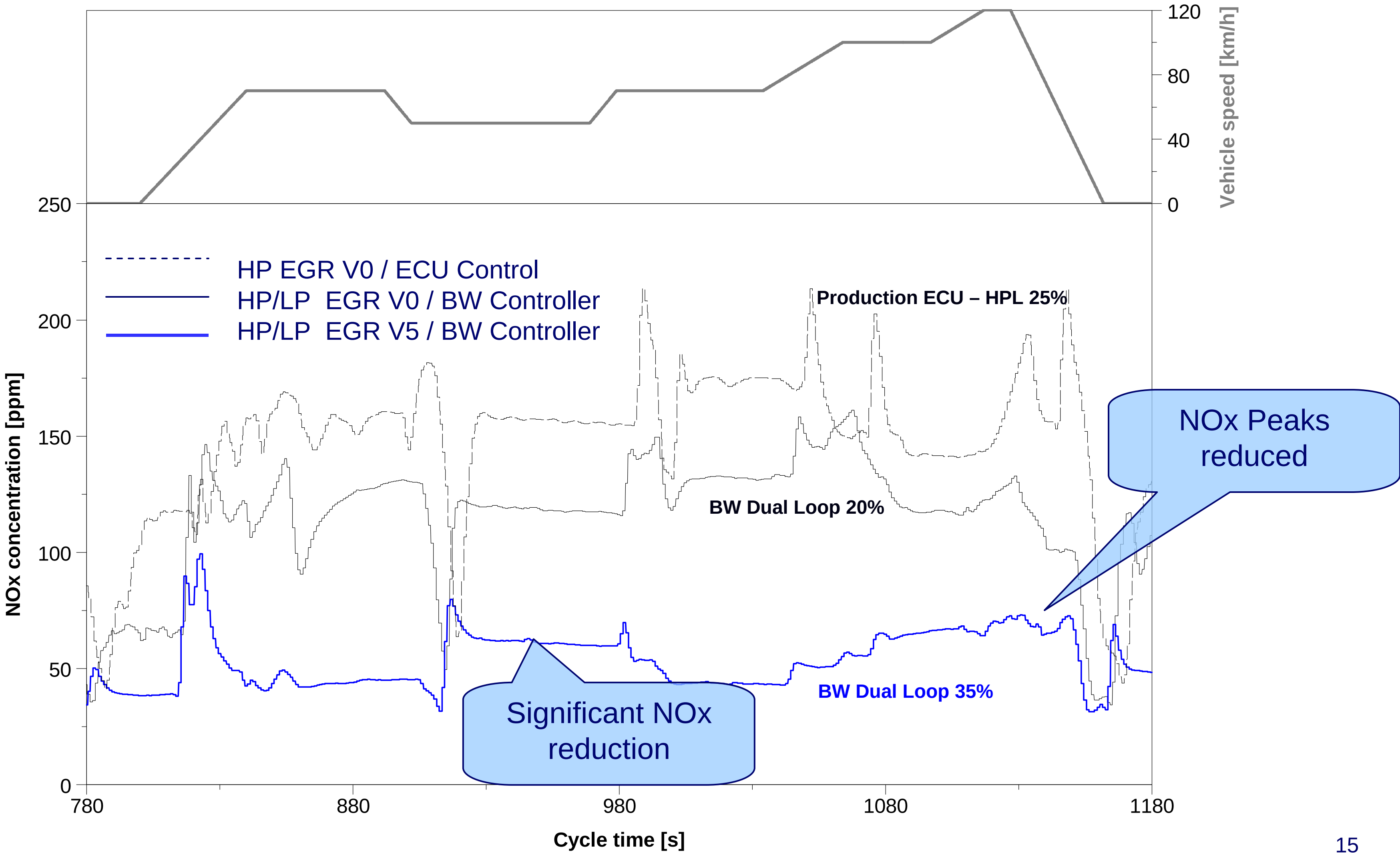
Production ECU Control

Maintains requested rate during cycle

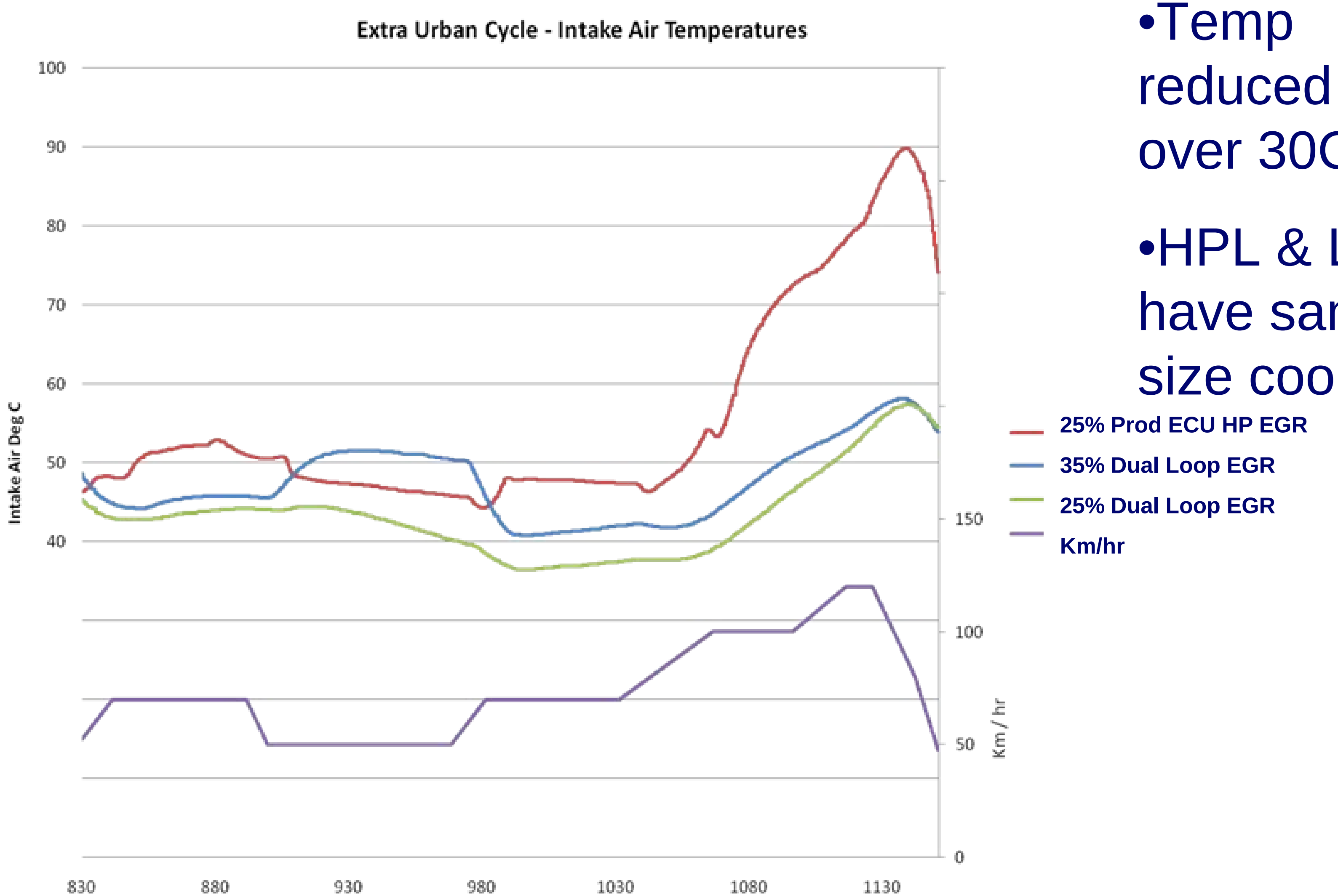


BorgWarner Control

EUD Cycle - On Engine NO_x Control



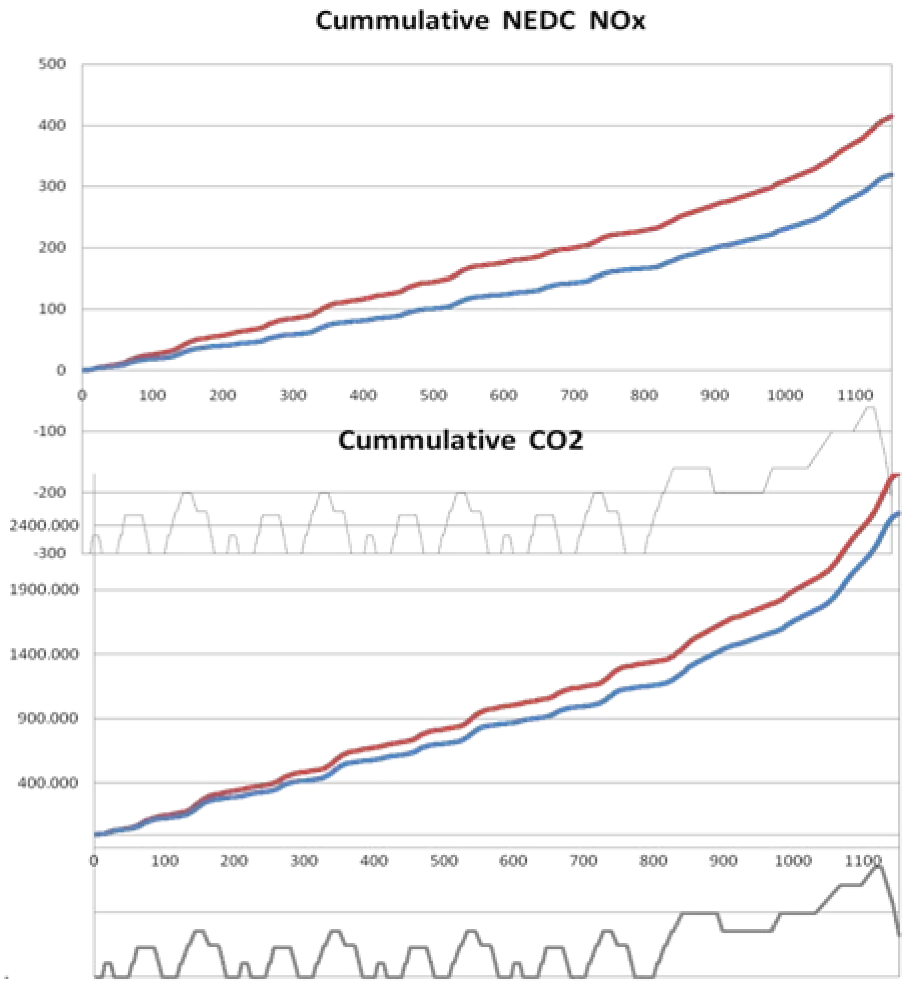
Charge temperatures reduced with dual Loop EGR



- Temp reduced over 30C
- HPL & LPL have same size coolers

Cumulative NOx and CO2 on NEDC Test

Production ECU Control HPL vs. BW Control Dual Loop EGR



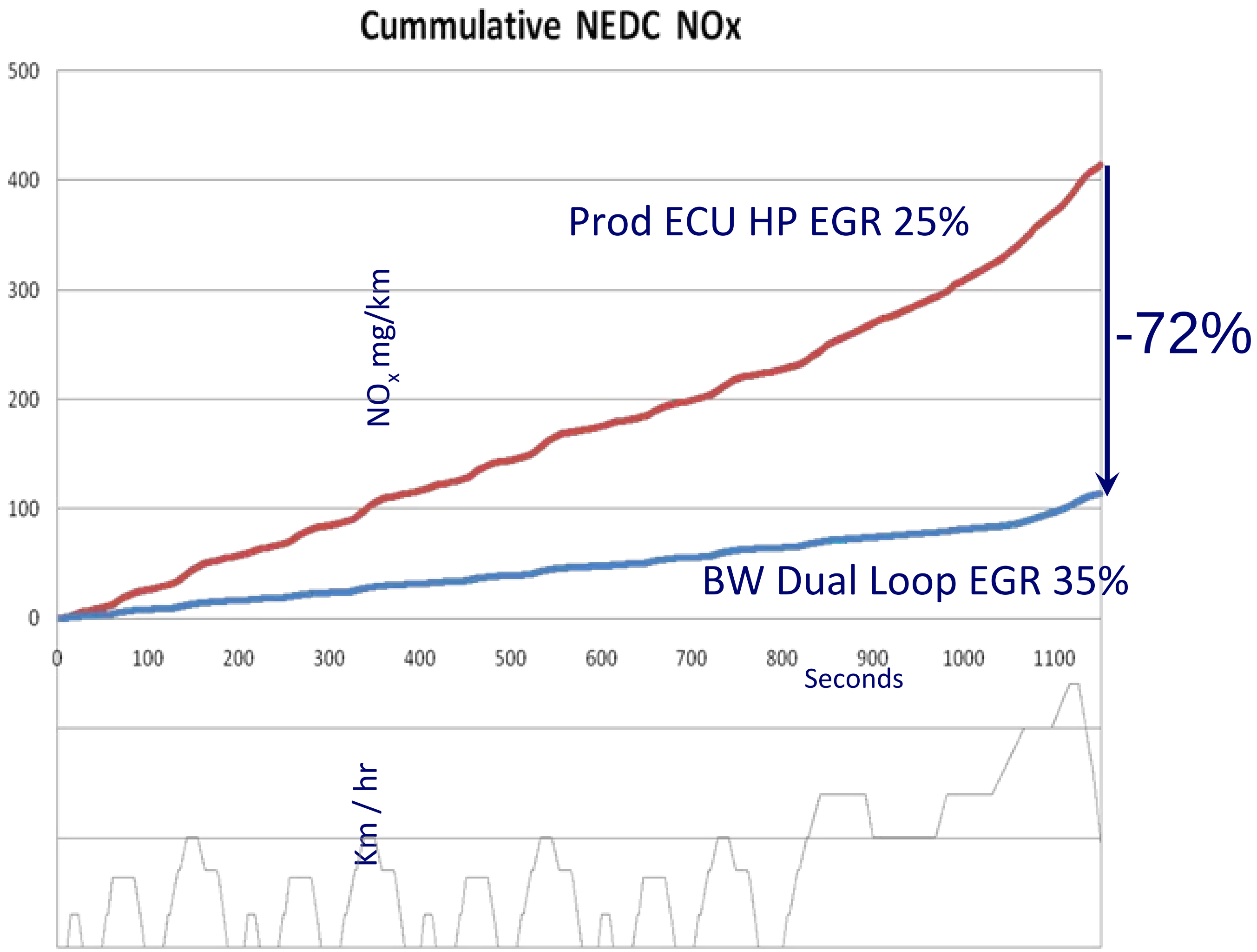
- **24% Reduction in NOx**
- **Constant PM**
- **6% less fuel consumption**

BW Dual Loop EGR 20%

Prod ECU HP EGR 25%

Increased EGR rate to Maximize NOx Reduction

Production ECU vs BorgWarner Coordinated Controls

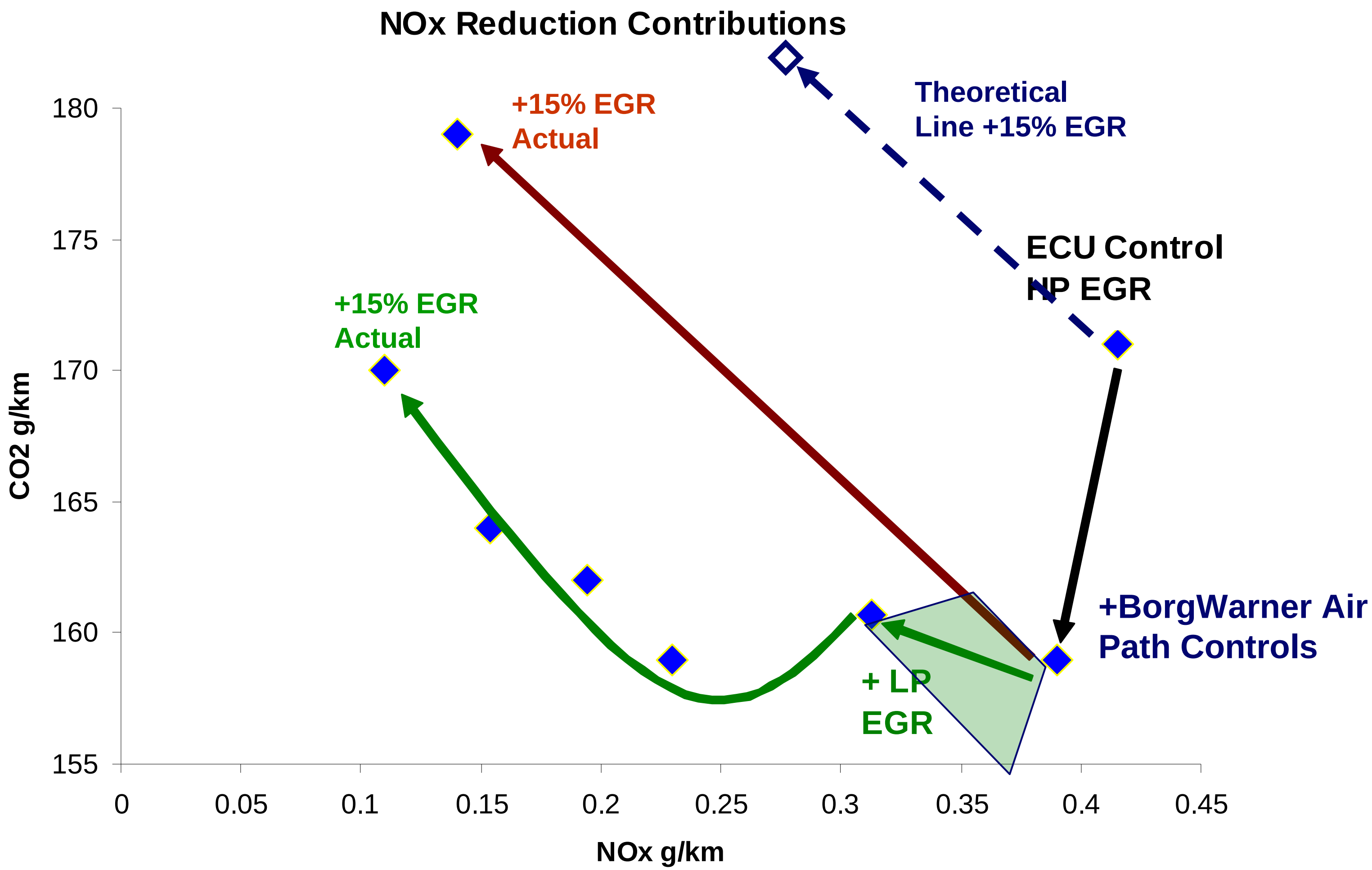


- 72% Reduction in NOx
- Increased EGR to Obtain Equivalent Fuel Consumption & PM

System Summary

System	EGR System	Fuel Consumption reduction (%)	NOx Reduction (%)
Baseline	High Pressure loop w/ cooler 25%	NA	NA
BorgWarner coordinated controls	High Pressure loop w/ cooler 20%	8	0
BorgWarner coordinated controls	Dual Loop EGR w/ coolers 20%	6	24
BorgWarner coordinated controls w/ increased EGR	Dual Loop EGR w/ coolers 35%	0	72

Summary Map: CO_2 vs NOx
Relative Contributions to Emissions Reduction



Conclusions

- **Dual Loop EGR offers significant advantages to reduce emissions and fuel consumption to meet future emission requirements**
- **A coordinated control system has been developed to optimize the EGR and air boost system**
  - **Significantly reduces fuel consumption and / or NOx**
  - **Improves dynamic performance of turbocharger**
- **Potential for NOx aftertreatment system cost reduction**
- **Future work includes two stage boosting systems together with dual loop EGR allows further enhanced performance while utilizing down speeding to achieve CO2 targets.**

Thank You For Your Attention

OUR BELIEFS

- Respect
- Collaboration
- Excellence
- Integrity
- Community

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