Model-based Controls for Low Carbon Commercial Vehicle Engines and Powertrains

IFAC Advances in Automotive Control Symposium

Wednesday, August 31st, 2022

Professor Greg Shaver

School of Mechanical Engineering

Collaborators & funders:

Commercial Vehicle Powertrains of the Future

- The IC Engine will continue to play a key role:
  - Lower/low/no-carbon fuels:
    - Very high efficiency diesel – lean-burn engines
    - Natural gas – stoichiometric engines
    - Hydrogen – stoichiometric and lean-burn engines
    - Bio-derived fuels
  - Use in hybrids electric drivetrains – coordinated control is critical
  - Electrification of some engine functions – EGR pumping, eBoosting, etc.

- Model-based controls is critical
  - Very high demand for this talent in commercial vehicle industry

Shaver Research Group

18 Graduate Students (9 Phd, 9 MSME)

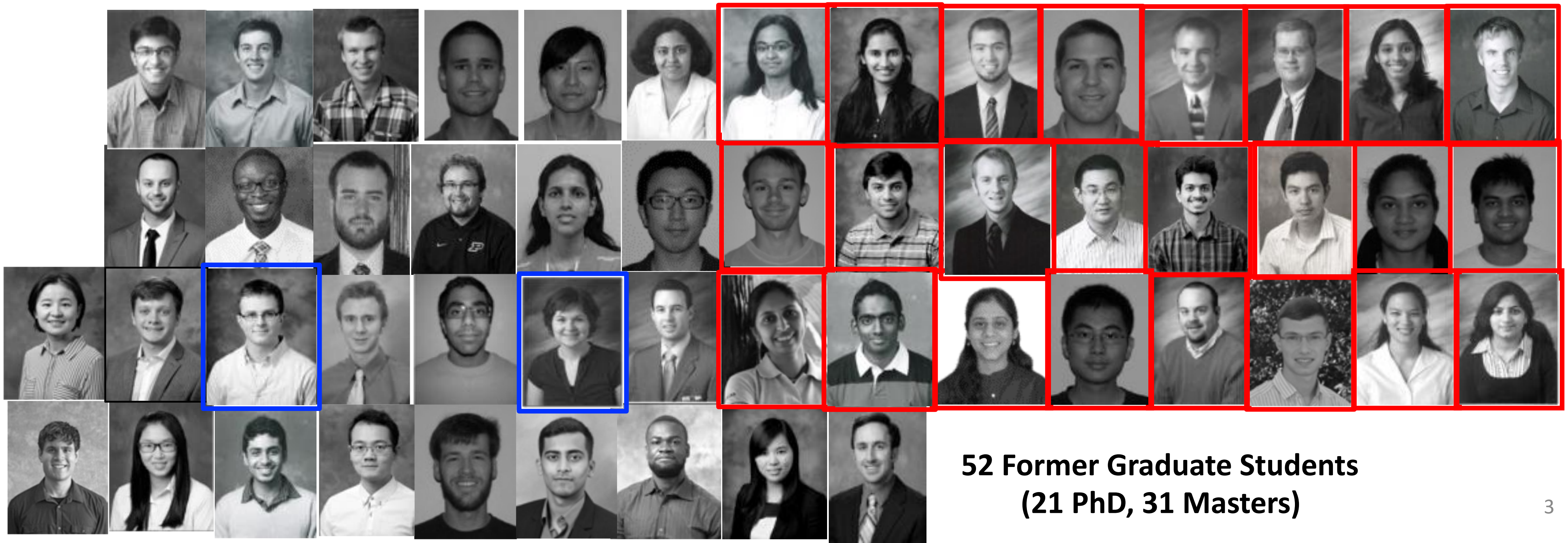
Greg Shaver, PhD
Faculty Lead

Eric Holloway, PhD
Project management for select projects

Ryan Thayer
Testcell & vehicle leadership

Employed at industry partner companies.

Tenure-track faculty.



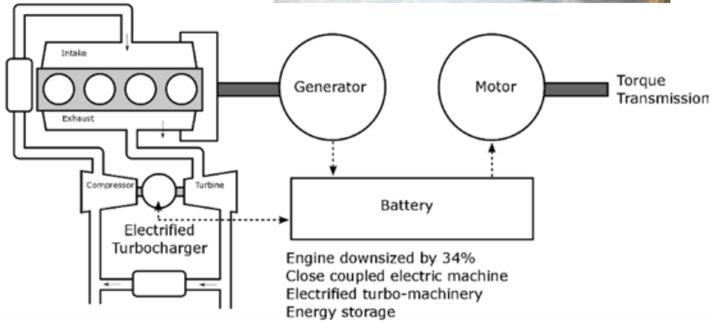
52 Former Graduate Students (21 PhD, 31 Masters)

Ongoing Projects

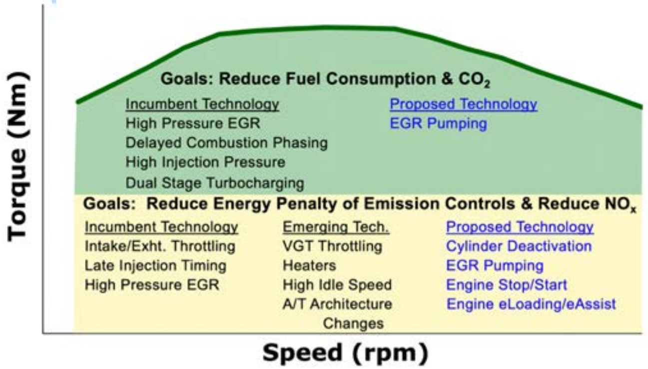
Heavy-duty Diesel Hybrid Electric Drivetrain

- Collaboration with U. of Wisconsin and Deere
- Engine testing at UW
- Vehicle testing at Deere

- Purdue is leading control algorithm development for engine & powertrain



High Efficiency Off-Road Engines



13.6L 273-510 (kW)	Power (kW)	Customer Usage	8 Mode	NRTC
Combines	>450	Harvesting: ≥5% 5% H-Load <1% L-Load	≥5% 4% H-Load 1% L-Load	≥5% 4% H-Load 1% L-Load
Tractors	<450	Tillage: ≥5% 5% H-Load <1% L-Load	≥5% 4% H-Load 1% L-Load	≥5% 4% H-Load 1% L-Load
Articulated Dump Truck	<360	Load-dump-load ≥ 6% >20% L-Load	≥3% 1% H-Load 2% L-Load	≥5% 1% H-Load 4% L-Load

Expected Fuel Savings

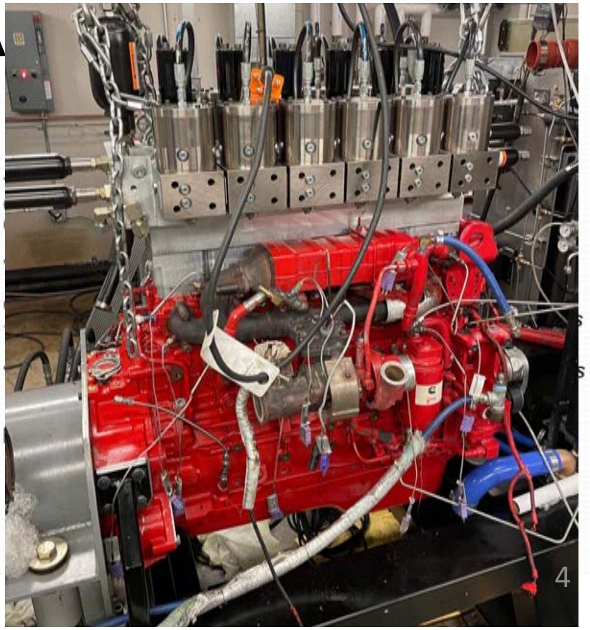
- Funders: Deere & Eaton
- Cylinder deactivation, EGR pumping & electrification
- 13.6L engine experiments at Purdue

Improving Transmission Resilience to Driveline Resonance Through Detection & Control (w/ J. Evans)

- Allison is funding
- Analyze Allison data
- Simulate resonant conditions
- Develop mitigation techniques

Natural Gas Engine VVA/CDA

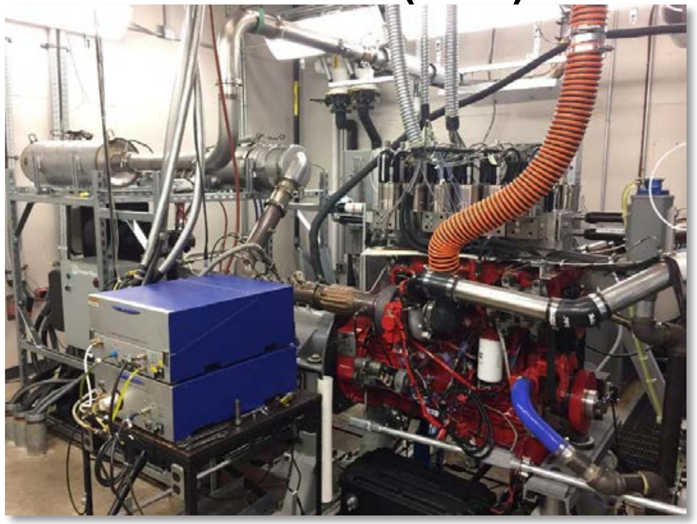
- Cummins is funding
- Knock and throttling reduce performance & efficiency
- Study merits of VVA/CDA for mitigation
- In-cyl mass & composition estimation
- Engine testing at Purdue



Examples of Recently Finished Projects

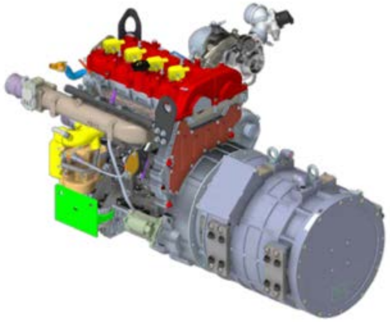
Improving Diesel Engine Efficiency & Thermal Management via Variable Valve Actuation (VVA)

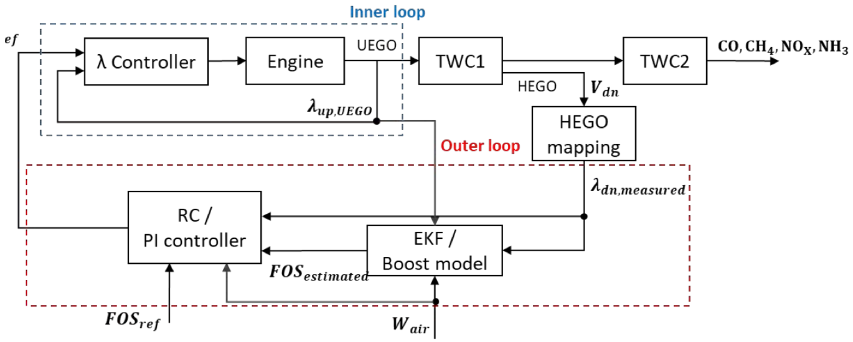
- Prior effort funded by Cummins, Eaton & DOE
- 7 papers cited by California Air Resources Board
- 3 papers citied by United States EPA
- New emissions regs.



Robust Control of Nat. Gas Engine Aftertreatment

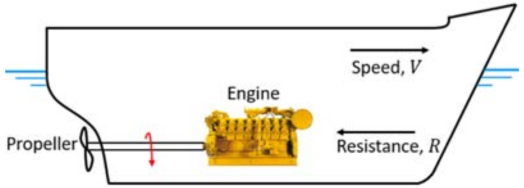
- DOE funded
- Collaboration with Cummins
- 2 journal papers with Cummins

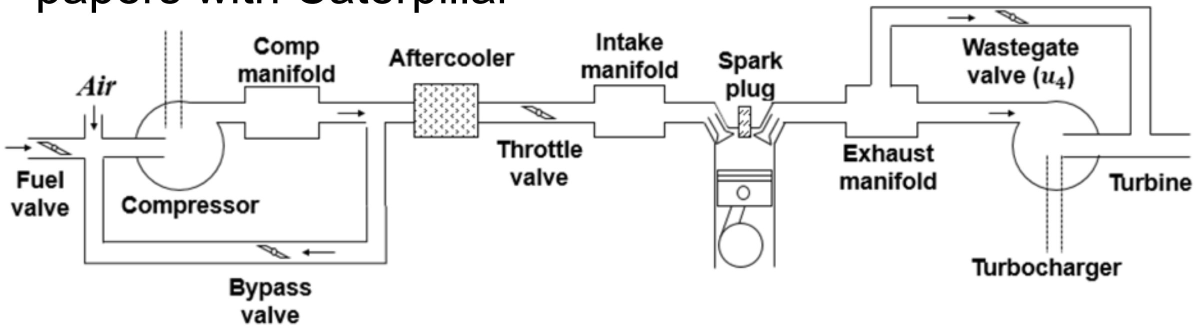




Robust Natural Gas Marine & Genset Engine Controls

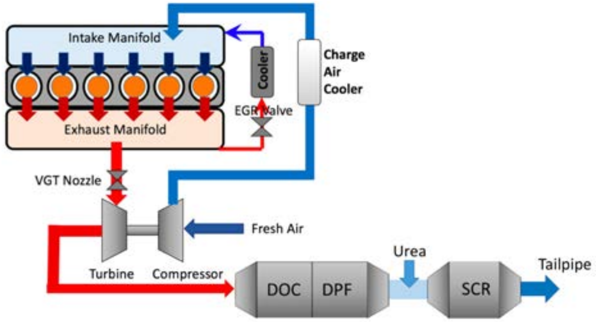
- New process for robust MIMO controls design
- 2 journal & conference papers with Caterpillar





Biodiesel Impact: Hvy-Duty Engine/Aftertreatment

- Demonstrated some issues w/ NOx and torque
- Can likely be mitigated via Purdue developed controls
- Sponsor: National Biodiesel Board



Examples of Recently Finished Projects

Auto-Unload of Grain while Harvesting is Occurring

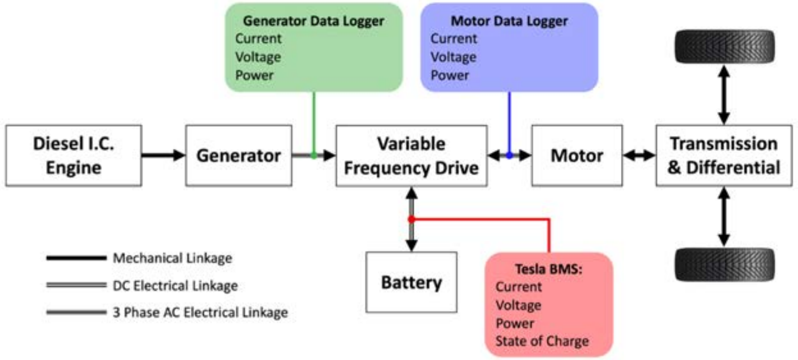
- Sponsor/Collaborator: Deere
- Co-PIs: Evans (ABE), Vyn (Agronomy)
- 4 journal papers with Deere
- 1 joint patent app. filed
- Experiments done at Purdue

Enabling Truck Platooning on Hilly Terrain

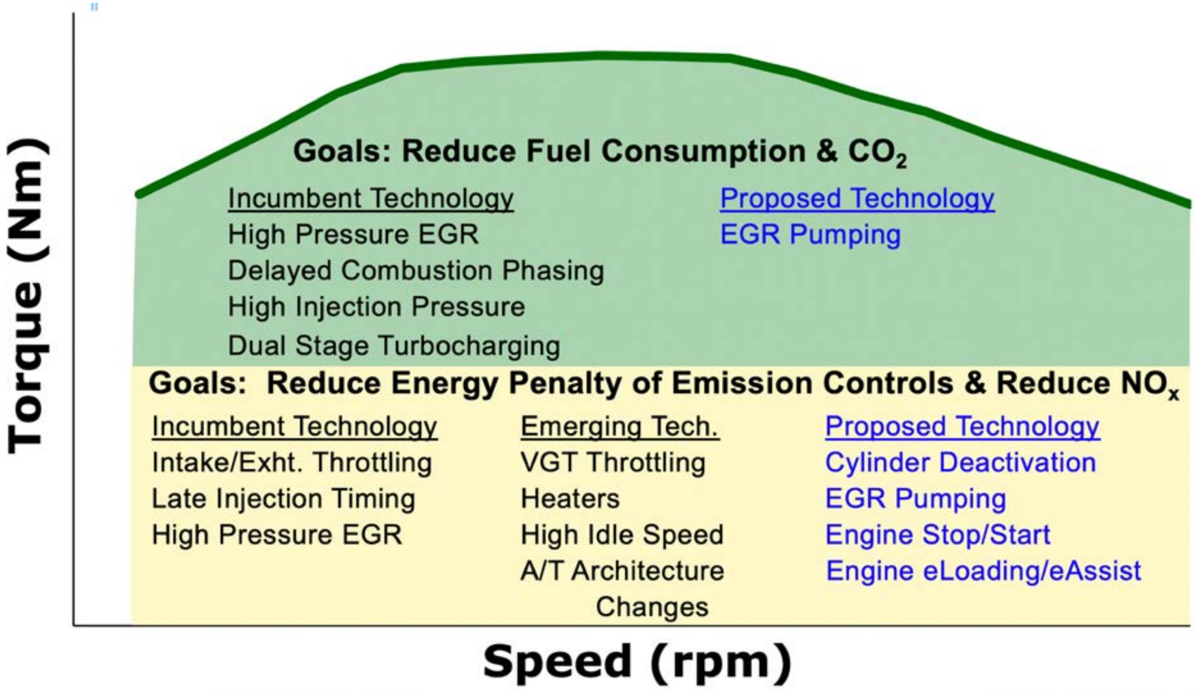
- 12.3% fuel savings + improved truck gap control
- collaborators: Peloton (start-up), Cummins, DOE & DOT
- COMVEC/etc. seminars + journal publications
- Co-PIs: Jain (ME), DeLaurentis (ABE), Bullock (CE)

Hybrid Electric Class 8 Truck Testing

- Sponsor/Collaborator: ePower (start-up)
- Report on fuel savings of their technology to VCs
- On-road testing



Farming & construction machine electrification & advanced engines



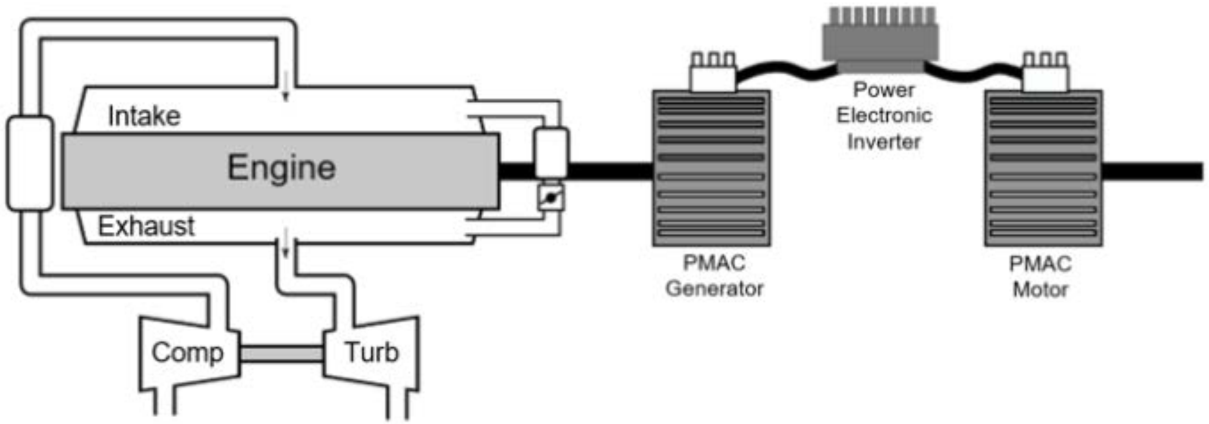
- Save fuel at high loads via electrically-driven exhaust gas recirculation (EGR) pumping
- Save fuel & improve aftertreatment function at low loads via powertrain electrification, cylinder deactivation and EGR pumping
- Deere/Eaton are funders & collaborators
  - Purdue is doing controls development & experiments

Construction machine electrification, controls & advanced engines

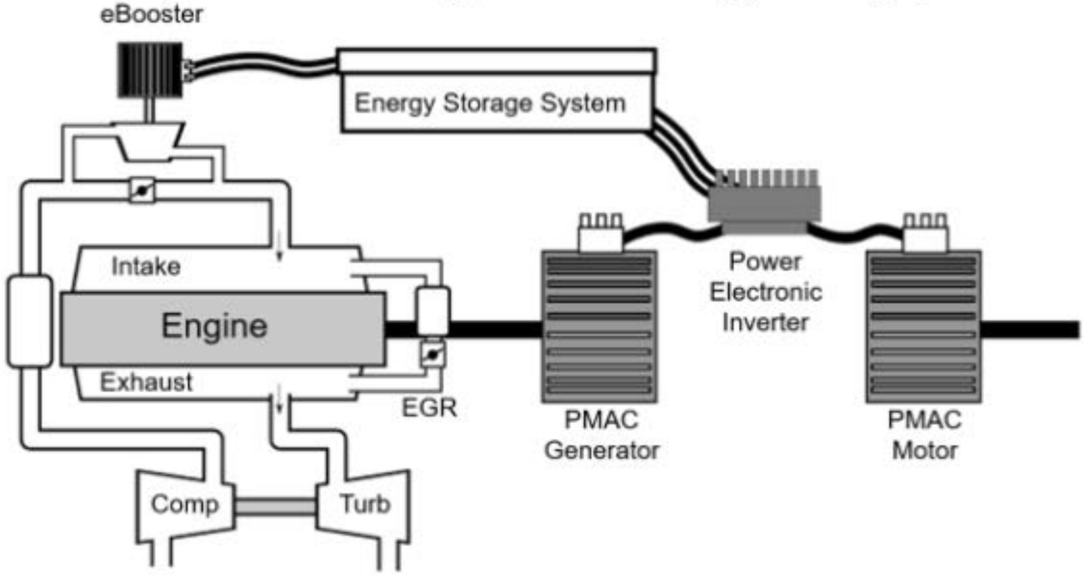
- John Deere 644K Hybrid Diesel Series Electric Three Speed Front End Loader
  - Converted from conventional to a series electric drivetrain in 2011 **without energy storage →** engine downsized from 9.0L to 6.8L providing a 30% gain in fuel efficiency
  - Current effort will further downsize to 4.5L by incorporating energy storage

- US DOE funded – Collaboration between U. Wisconsin (lead), Deere & Purdue
  - Purdue is leading model-based control systems for down-sized e-boosted engine & supporting powertrain controls

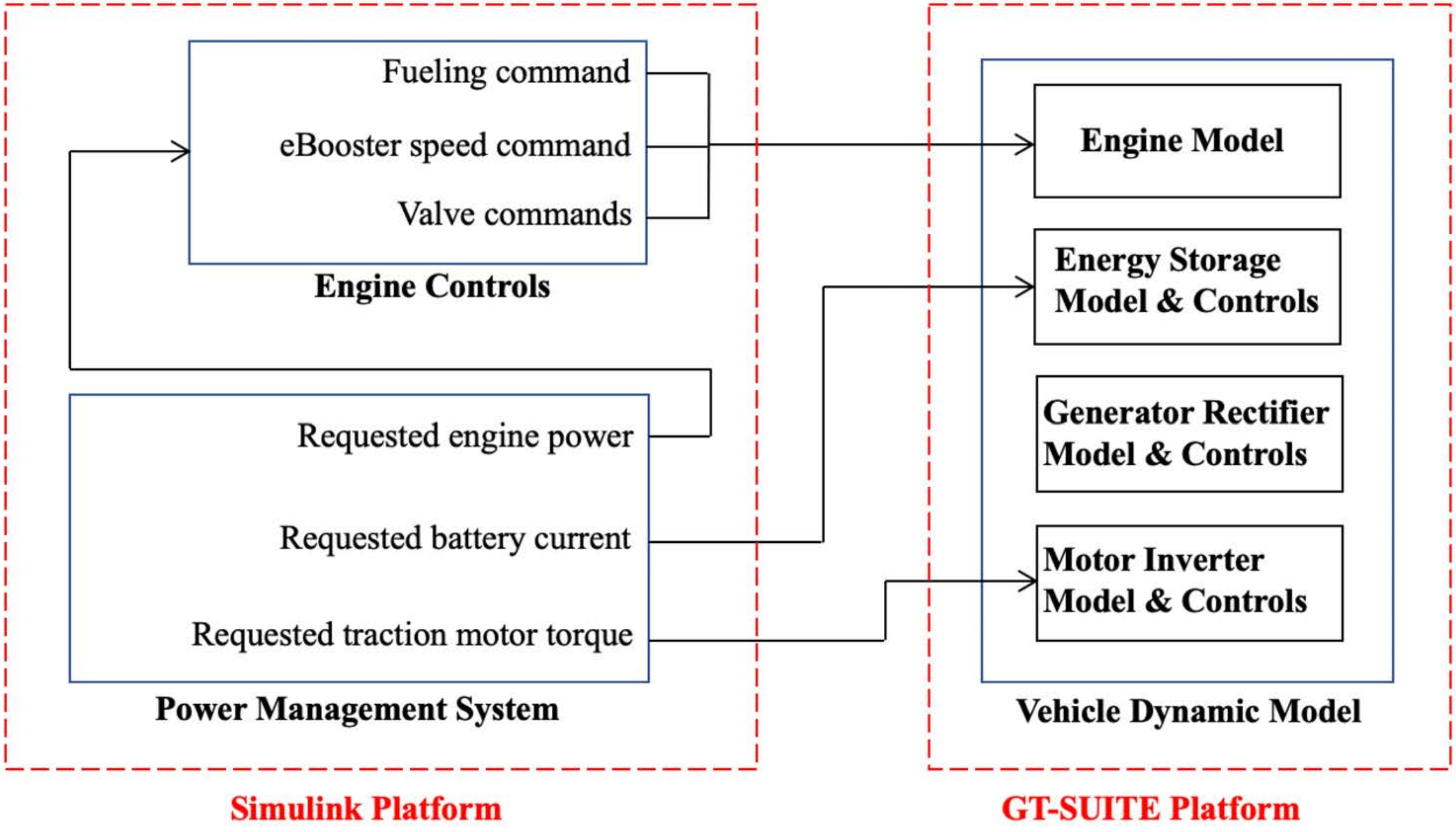
Baseline Powertrain
(6.8 L diesel engine without energy storage)



Proposed Powertrain
(4.5 L diesel engine with energy storage)



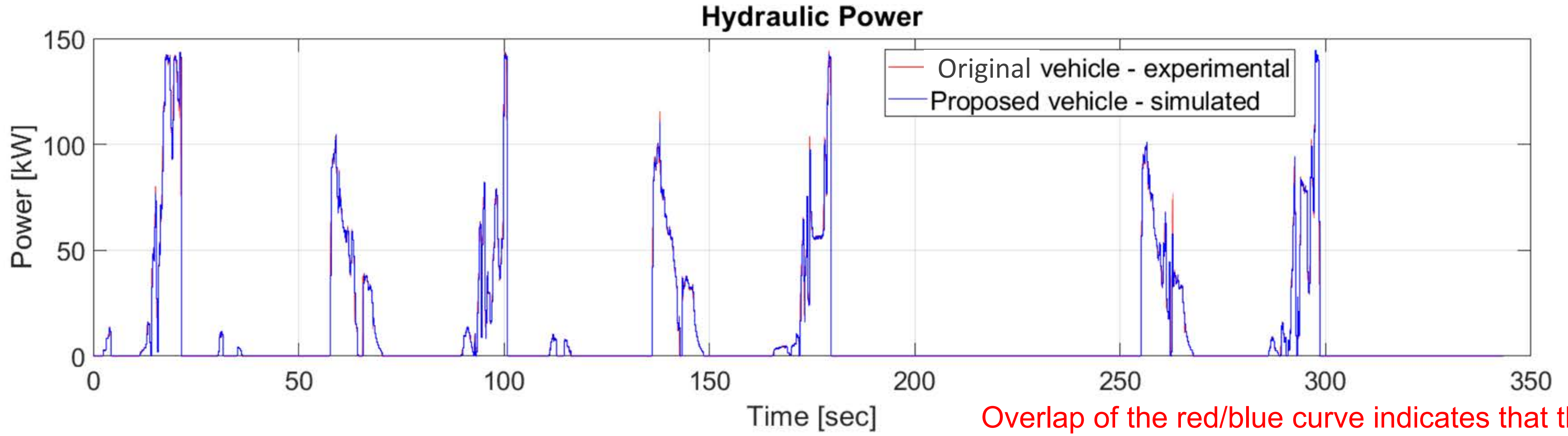
Construction machine electrification, controls & advanced engines



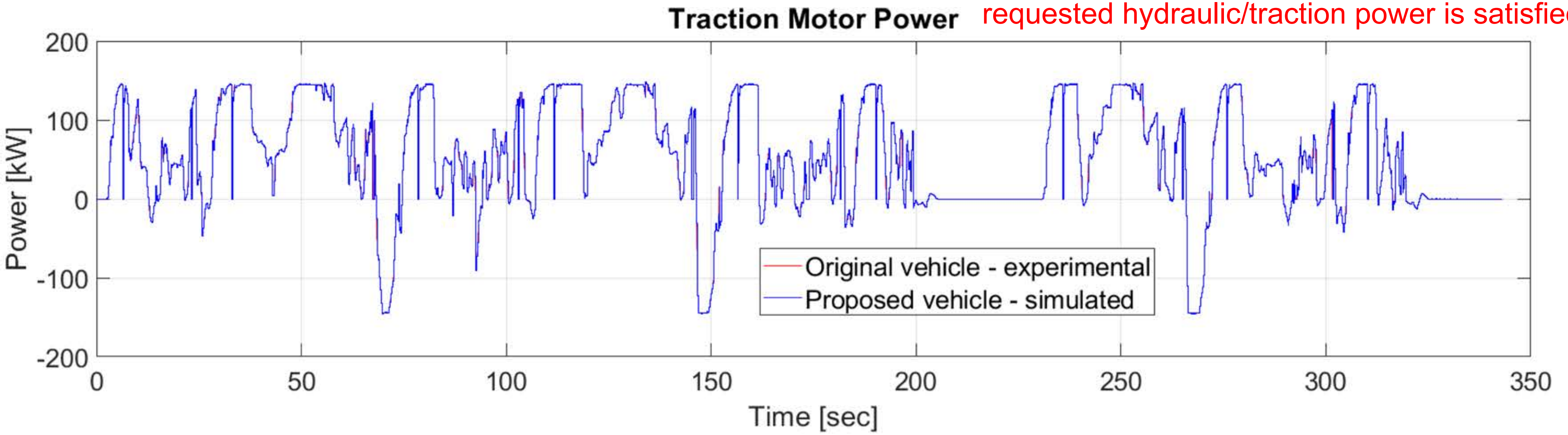
* Not all inputs/outputs/models are shown for simplicity

Construction machine electrification, controls & advanced engines

Simulation Results - Stockpile



Overlap of the red/blue curve indicates that the requested hydraulic/traction power is satisfied



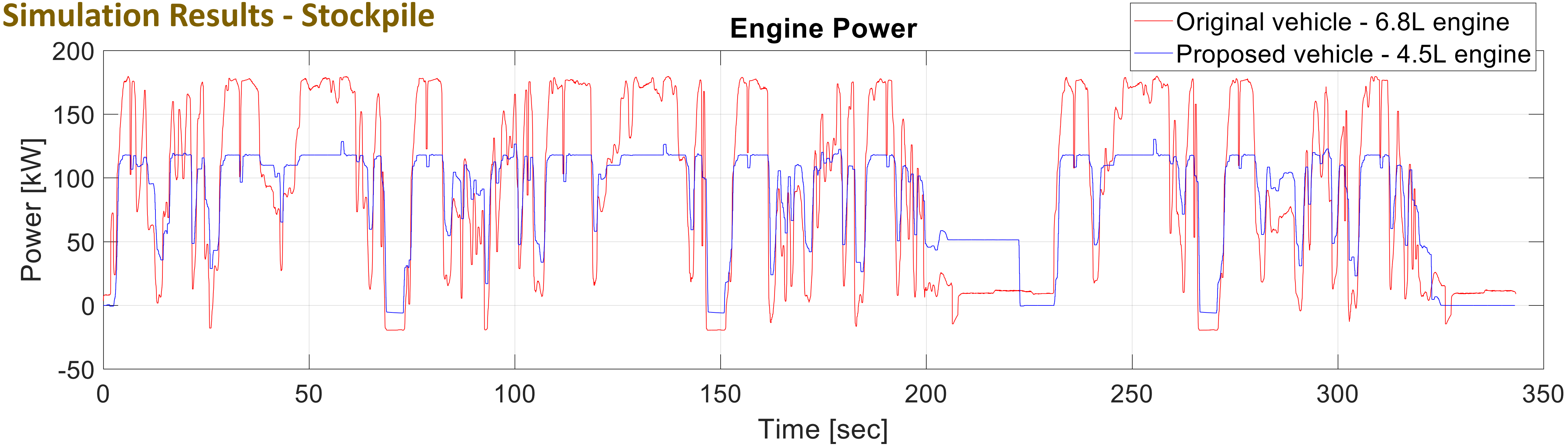
Construction machine electrification, controls & advanced engines

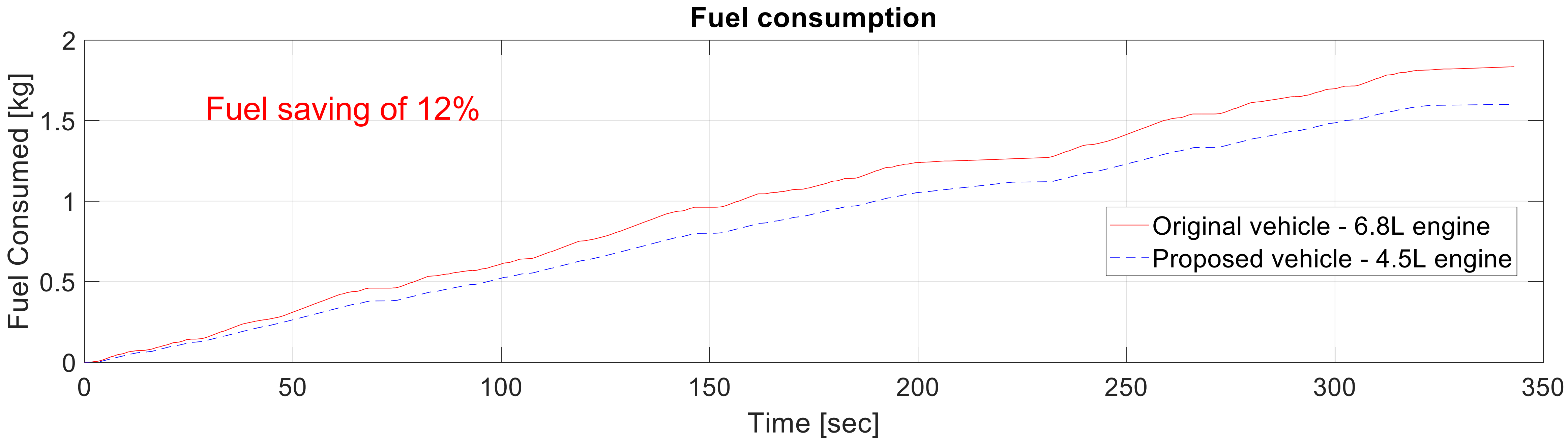
Simulation Results - Stockpile

Battery SOC is recovered back to initial value as regulated by the power management system, indicating the sustainability of the vehicle to continue working on this drive cycle (e.g., this is not a “plug-in hybrid”)

Construction machine electrification, controls & advanced engines

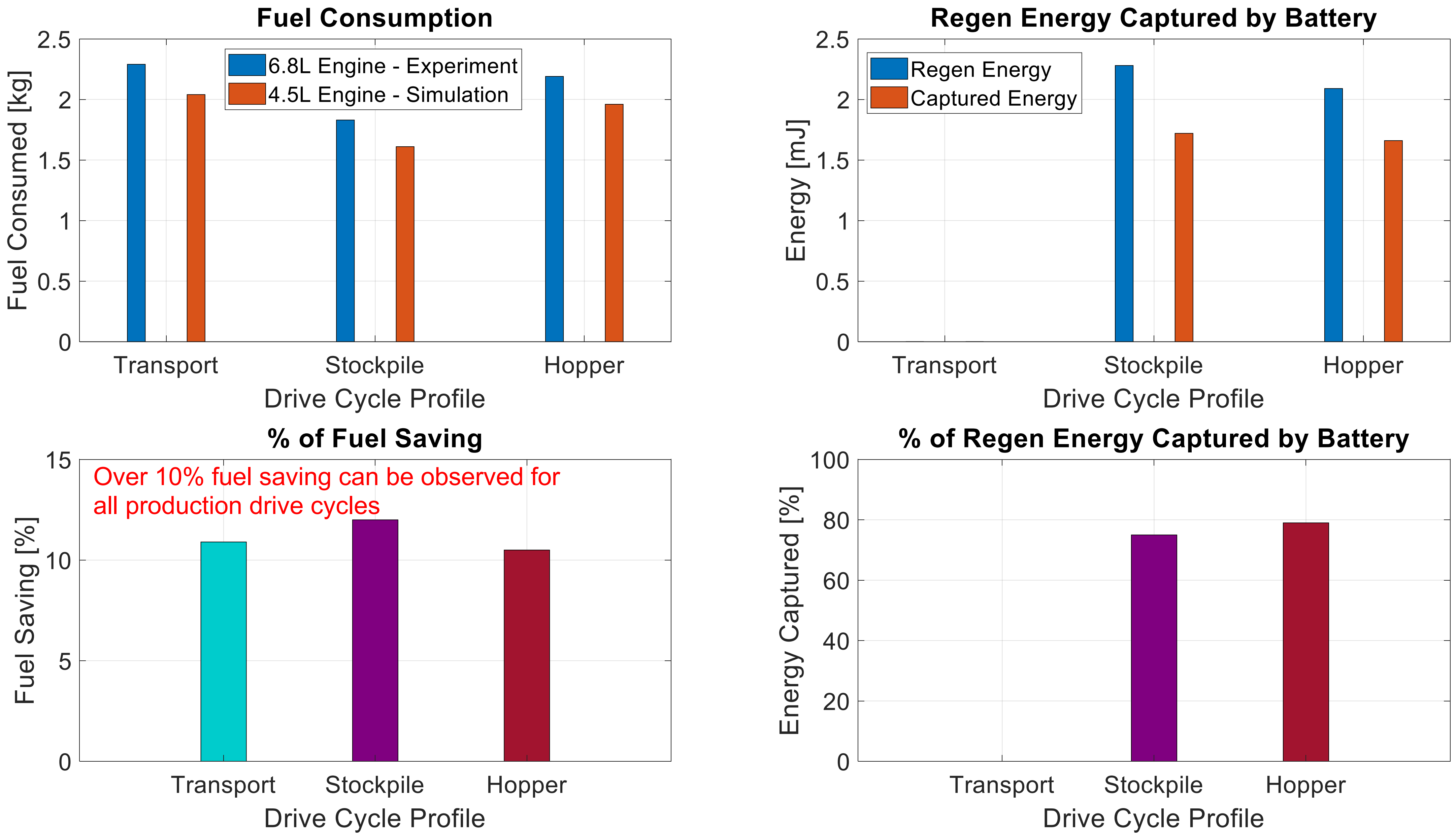
Simulation Results - Stockpile





Construction machine electrification, controls & advanced engines

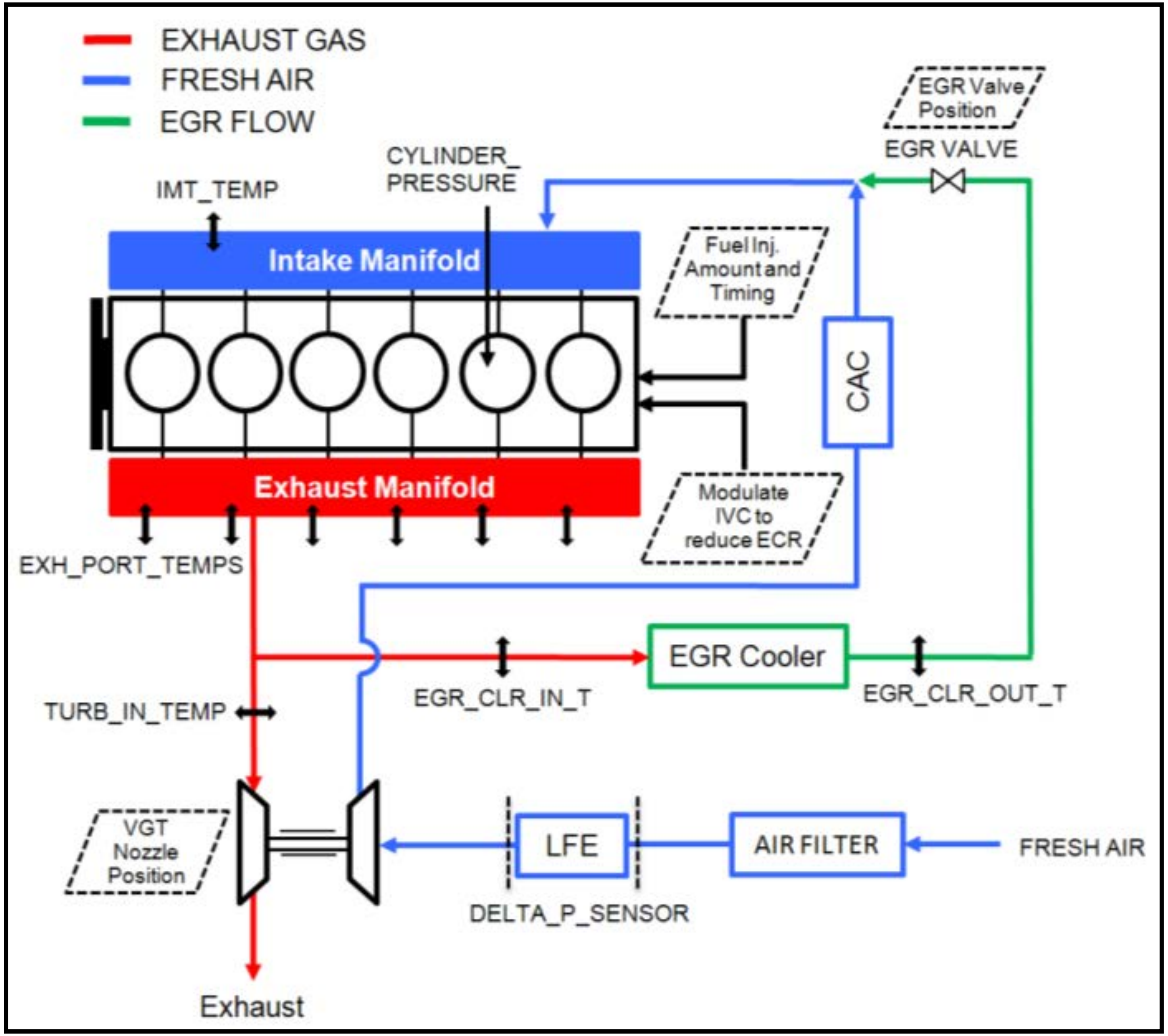
Simulation Results – Stockpile, Transport & Hopper Cycles



Controls for Lean Burn Engines Incorporating Valvetrain Flexibility

Controls for Lean Burn Engines Incorporating Valvetrain Flexibility

- Complex "gas exchange" process
- Opportunity with valve train flexibility
  - More flexible combustion "recipes"
  - Aftertreatment thermal management



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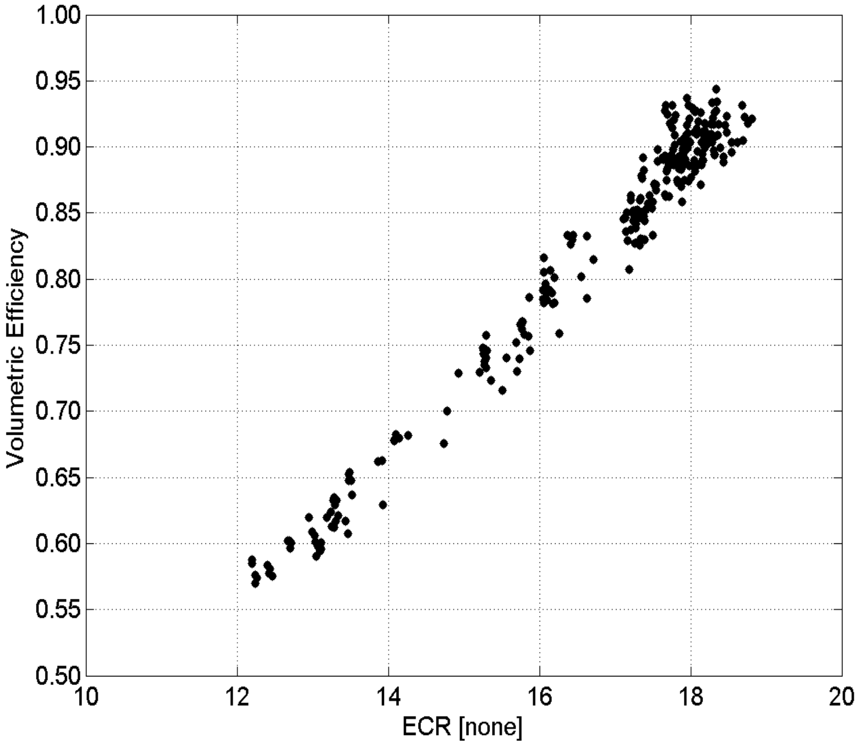
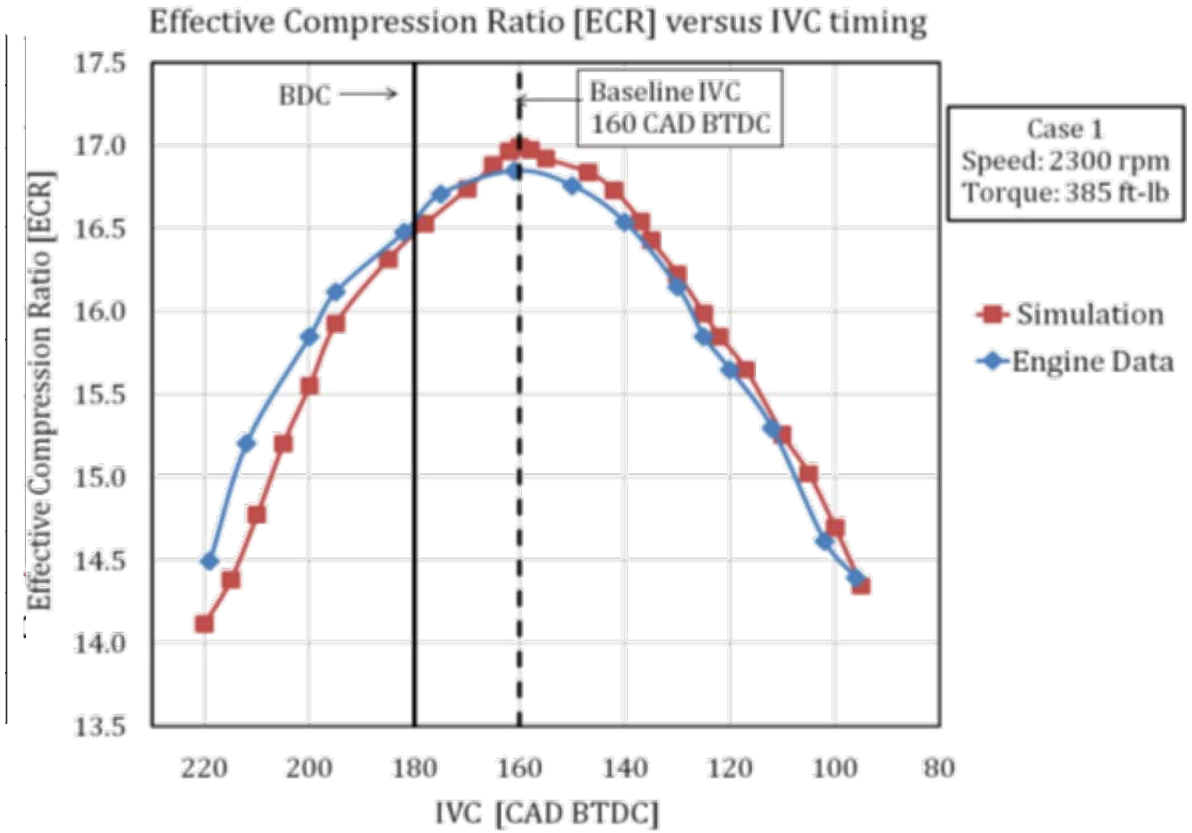




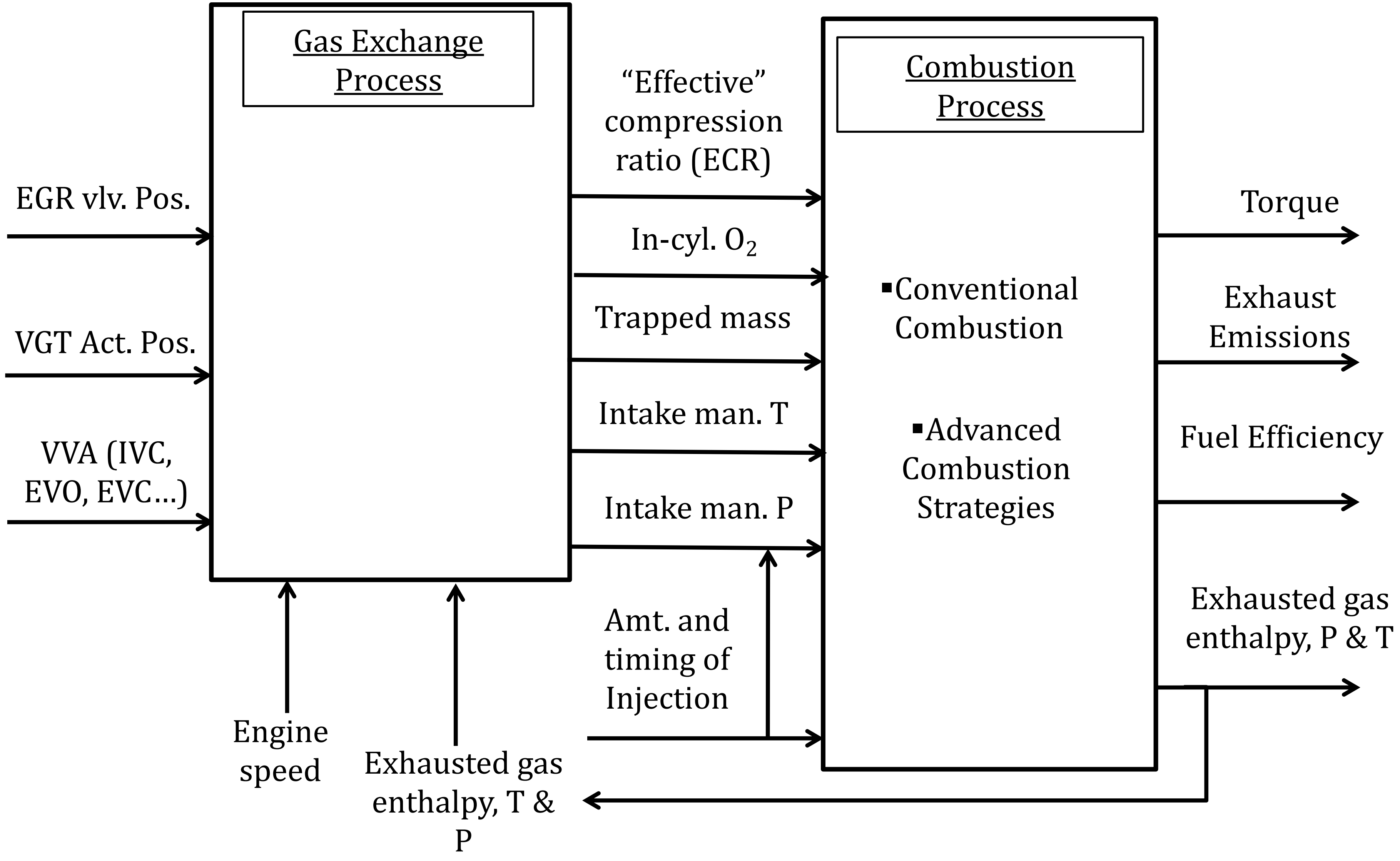
VVA provides additional control authority

…but complicates gas exchange dynamics

Effect of Intake Valve Closure Modulation on Effective Compression Ratio and Gas Exchange in Modern, Multi-Cylinder Diesel Engines. Intl. J. of Eng, Res., vol. 12 (6), 2011.

Controls for Lean Burn Engines Incorporating Valvetrain Flexibility

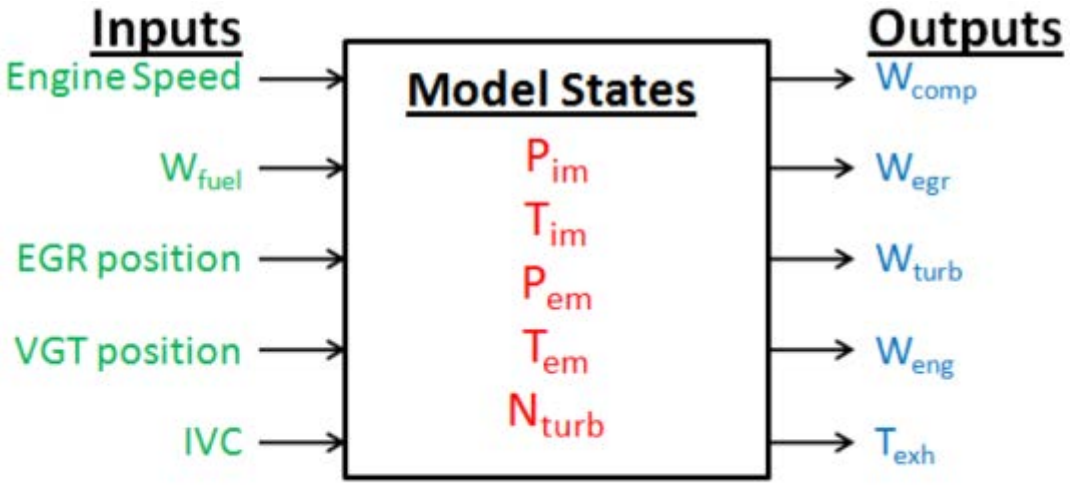
Combustion & Gas Exchange Process "Handshaking"

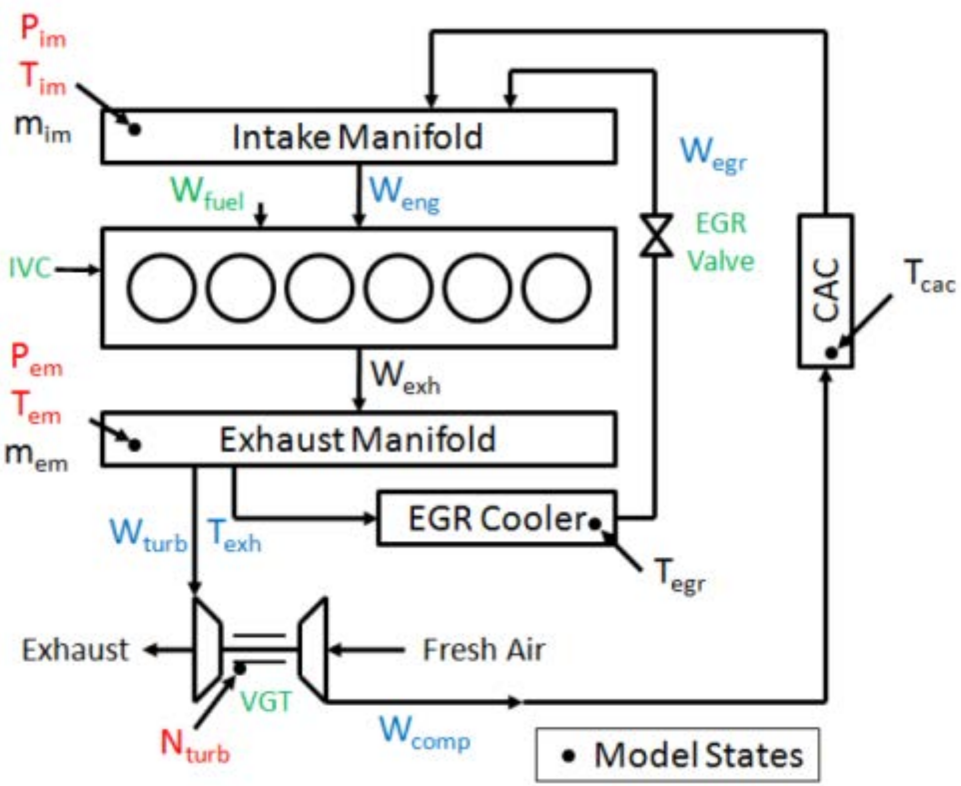


Controls for Lean Burn Engines Incorporating Valvetrain Flexibility

- ✧ Control/estimator design-oriented models
  - o Gas exchange modeling
    - ▪ Exhaust gas enthalpy
    - ▪ Volumetric efficiency
    - ▪ Analytical functions describing turbo
  - o PCCI combustion timing model
- ✧ Estimator designs for gas exchange process
  - o Effective comp. ratio estimator
  - o Oxygen fraction estimator
- ✧ Controller designs for advanced-mode combustion

Controls for Lean Burn Engines Incorporating Valvetrain Flexibility



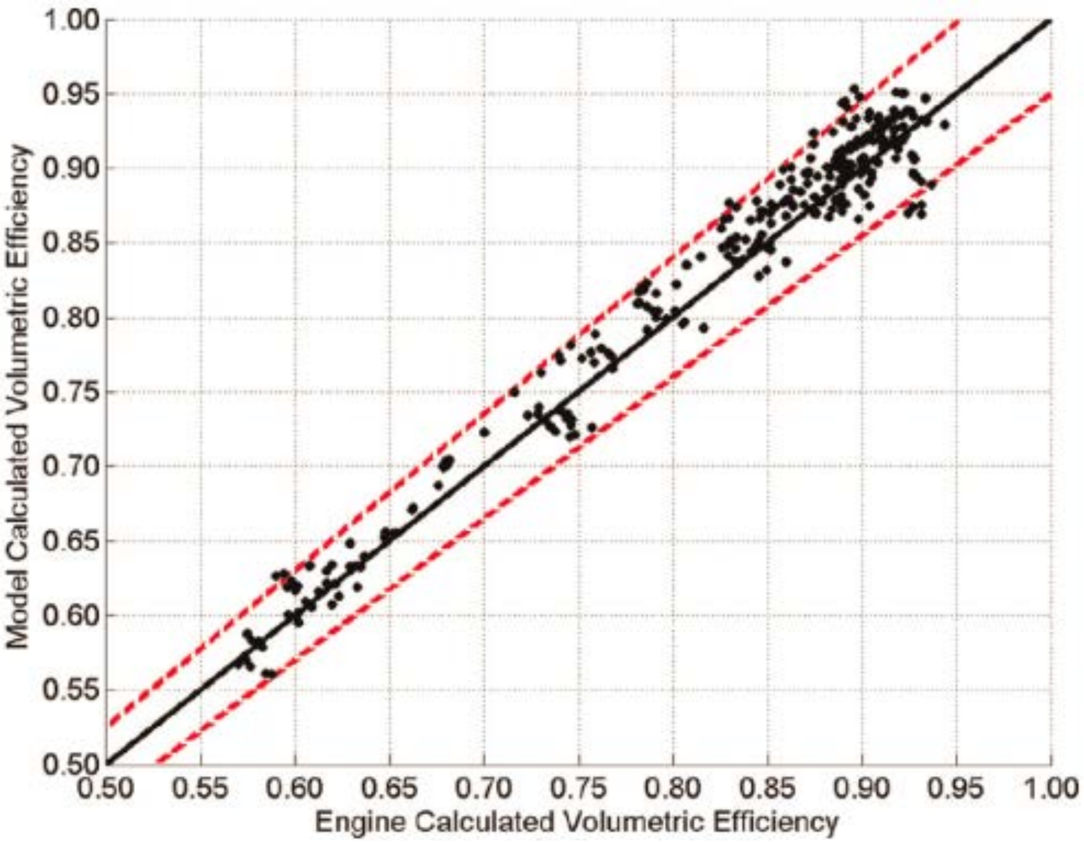


- "Algorithm design amenable", dynamic models
- Efforts include capturing impact of flexible IVC on:
  - ECR
  - Vol. efficiency
  - Exht. gas T & P
- Validated w. 286 steady state & 62 transient engine op. pts.
  - Worst case 15% error for charge/air flow, EGR fraction, turbo speed, & manifold temperatures
  - Worst case 10% error for manifold pressures

Control-Oriented Gas Exchange Model for Diesel Engine Utilizing Variable Intake Valve Actuation, ASME J. Dyn. Sys., Meas., and Control

Controls for Lean Burn Engines Incorporating Valvetrain Flexibility

- Traditional empirical/regression-based models cumbersome for flexible valve trains
- Model-based approach developed
  - Based on energy balance during intake process
  - Includes residual gas & exht. back flow models
- 286 points, within 5% for all, 2.5% mean square error

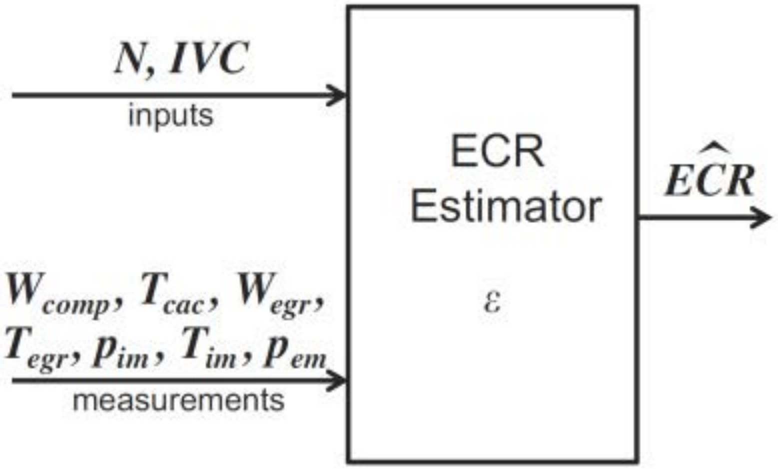


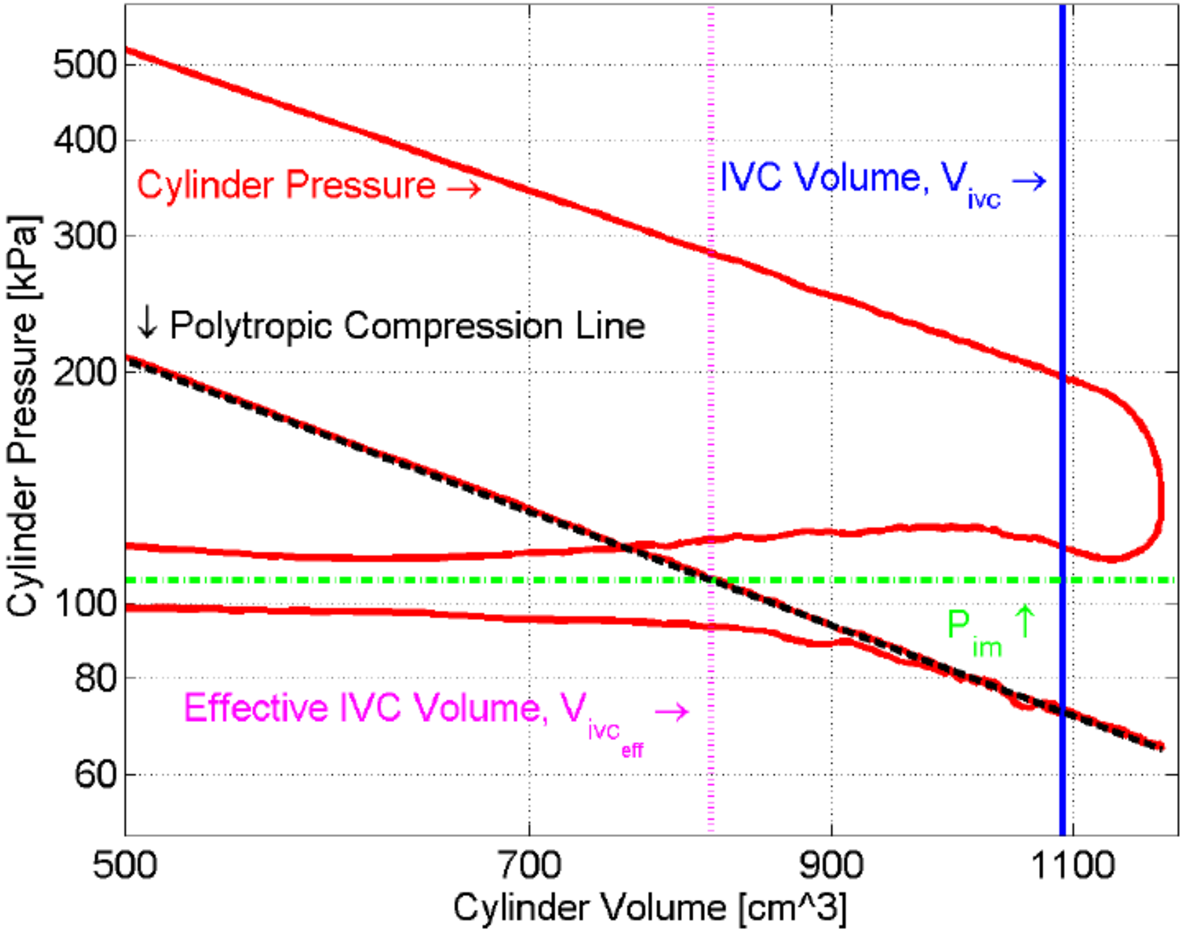
$$\eta_{vol} = \frac{P_{im}\left(\frac{V_{ivc_{eff}}}{V_{ivc}}\right)^{k} V_{ivc}c_v - P_{em}V_{ivo}c_v - P_{em}(V_{evc}-V_{ivo})c_p + P_{im}(V_{ivc_{eff}}-V_{ivo})R - (h_{ivo-ivc}(T_{wall}-T_{im})SA_{ivo-ivc})R}{P_{im}V_d c_p}$$

Physically Based Volumetric Efficiency Model for Diesel Engines Utilizing Variable Intake Valve Actuation, 13, 2012, Intl. J. of Engine Res.

Controls for Lean Burn Engines Incorporating Valvetrain Flexibility

- ECR calculable from cyl. pressure, but can be estimated using model-based approach w/o cyl. pressure
- Convergence within 4 engine cycles & steady-state error < 0.5 ECR, in the presence of 10% measurement error.
- Analytical **Lyapunov** guarantees for: (1) robustness to uncertainty, and (2) transient upper bound on estimator error





Estimation of Eff. Comp. Ratio for Engines Utilizing Flexible Intake Valve Actuation, 226(8), 2012, J. of Automobile Engr.

Input observer convergence and robustness: application to compression ratio estimation, IFAC Control Engr. Prac, 21, 2013

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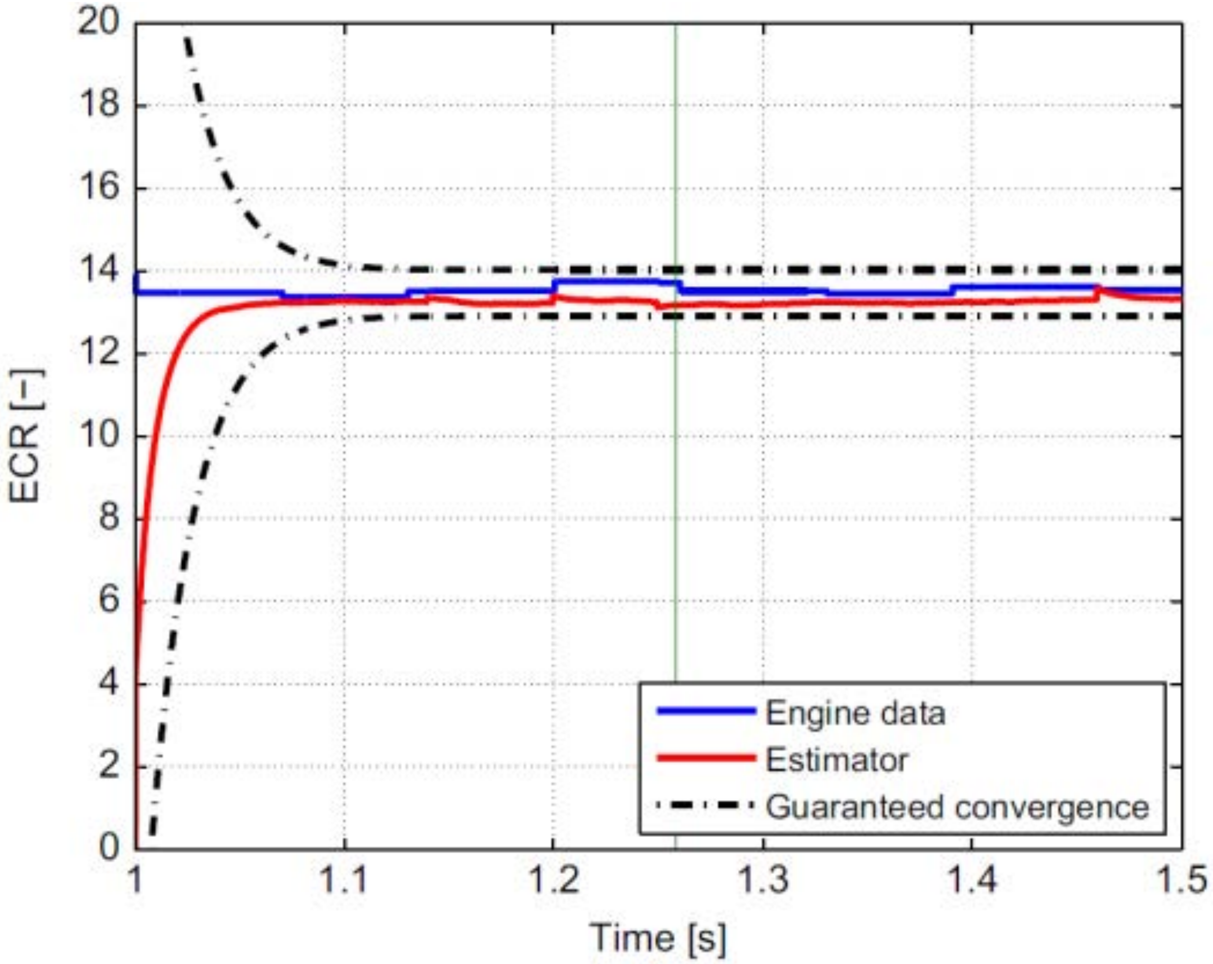

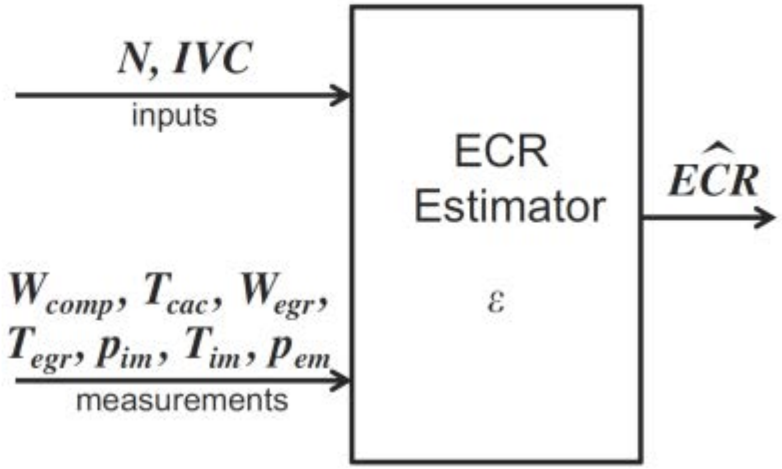

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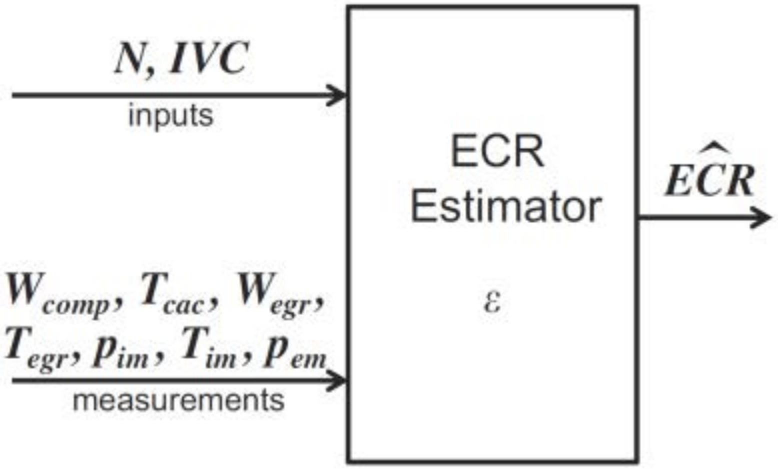

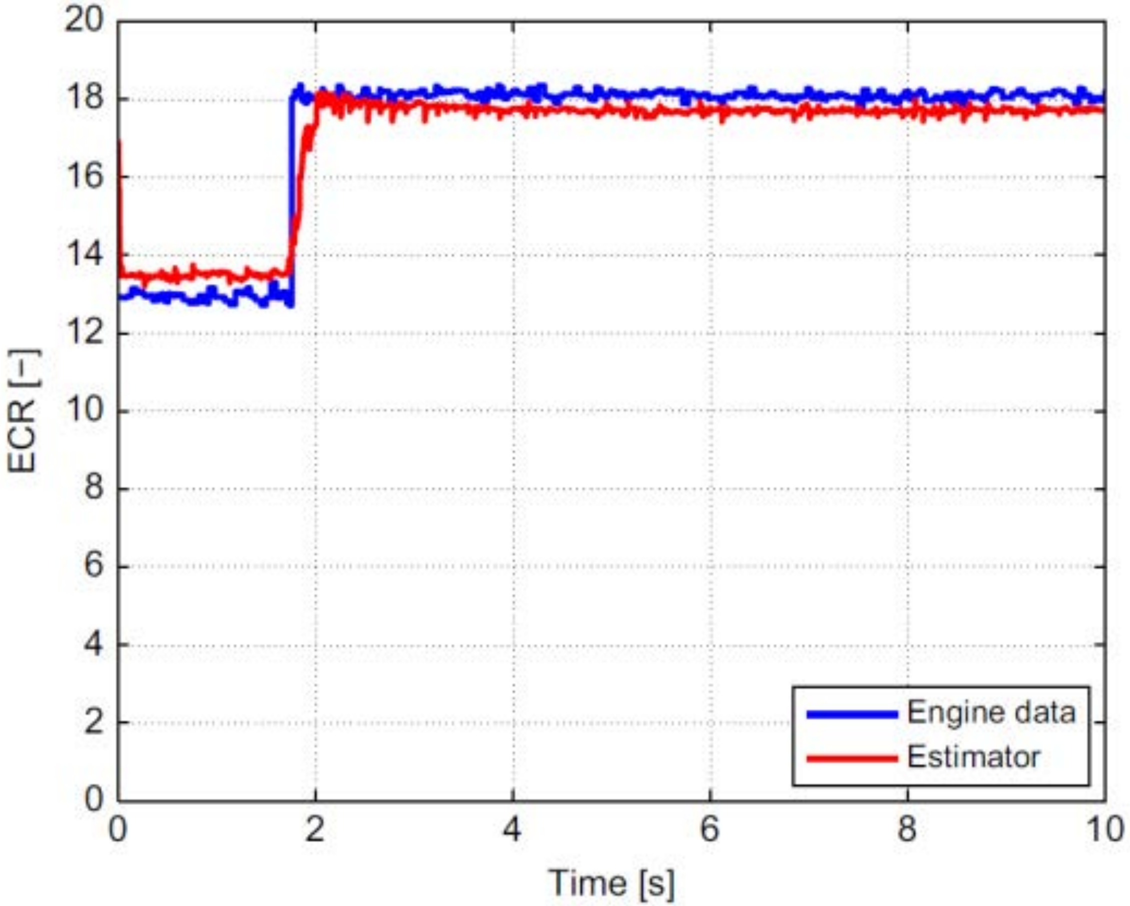

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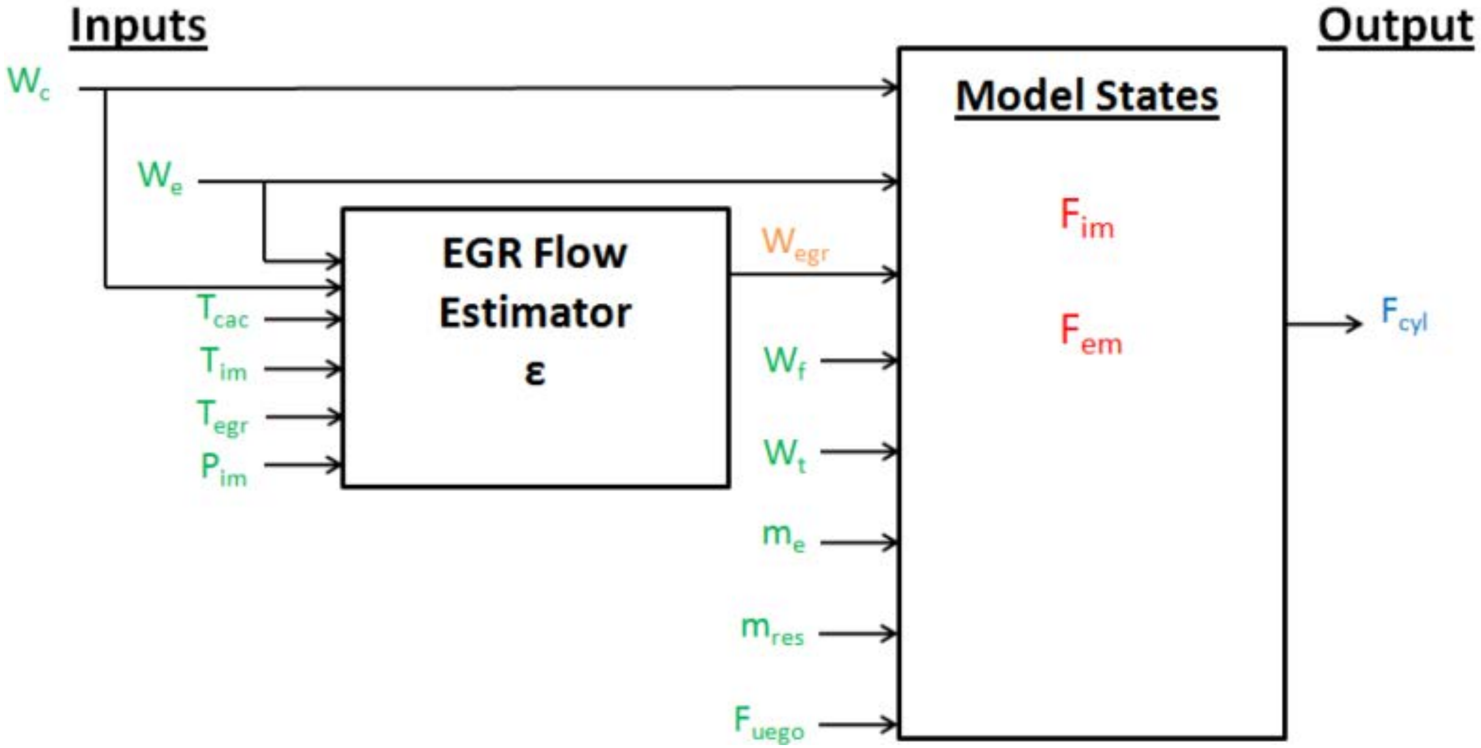
- In-cylinder O_2 mass fraction impacts combustion, but is not measureable
- Robust, model-based estimator developed (via Lyapunov-based strategies)
  - Errors < 0.5% O_2
  - Exponential estimator error convergence w/ time constant < 0.05 seconds

Robust O2 Fraction Estimation for Conv. and PCCI Engines with VVA, IFAC Cont. Engr. Practice



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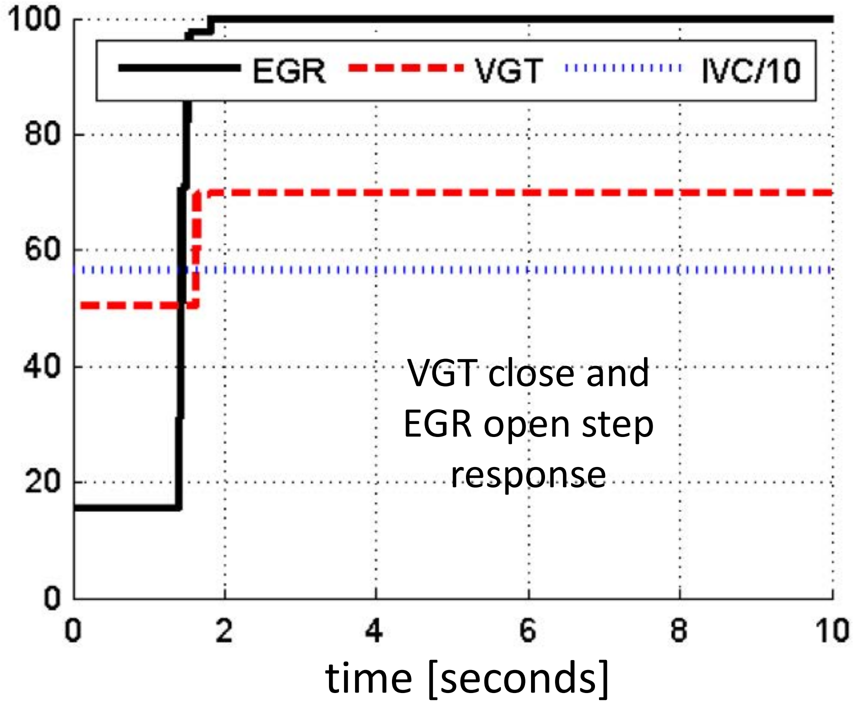

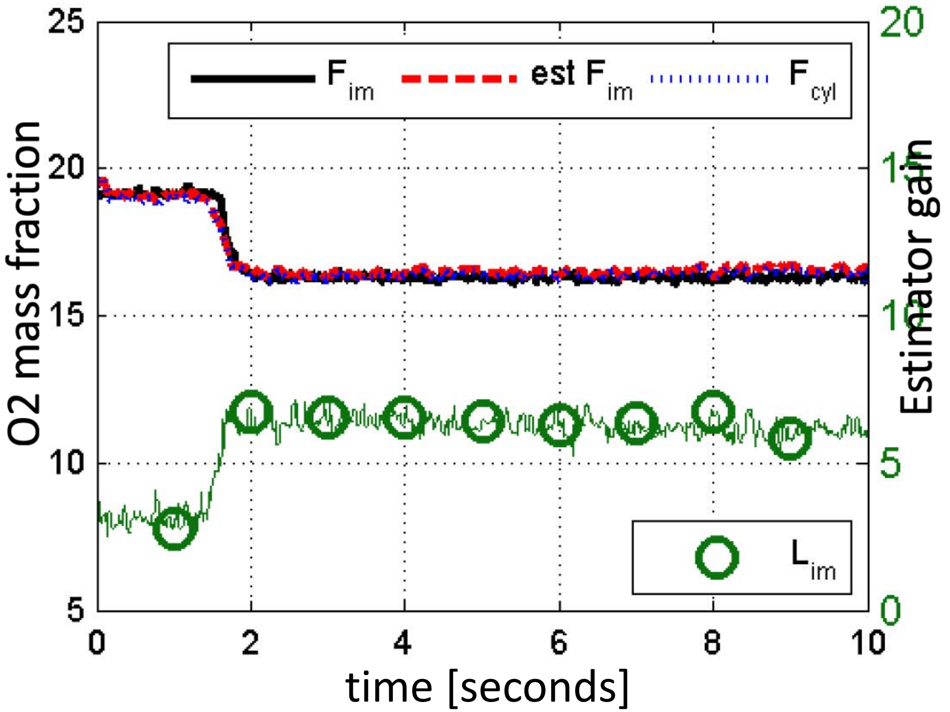

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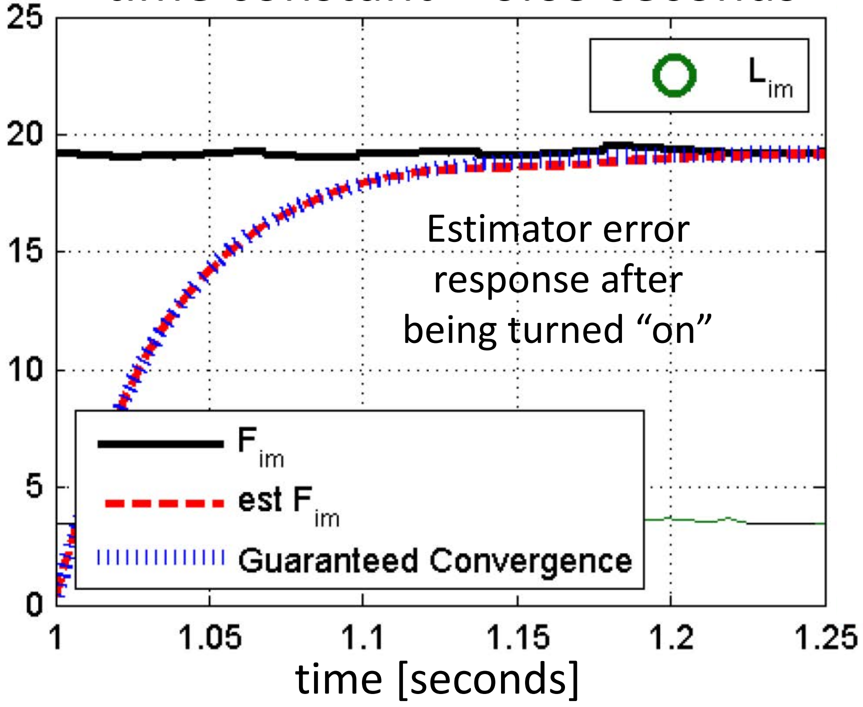
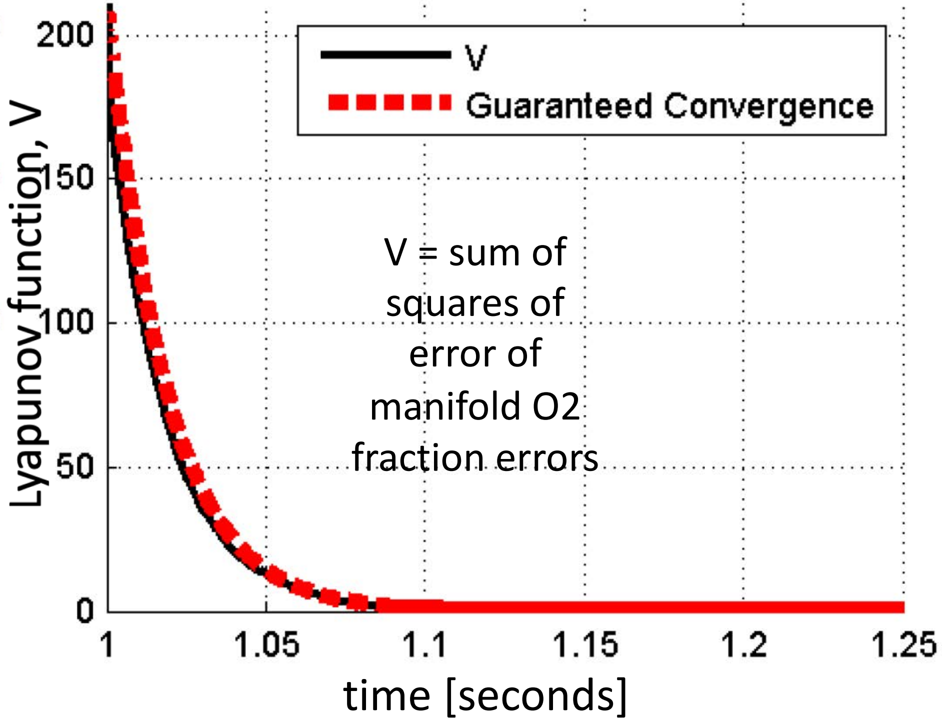
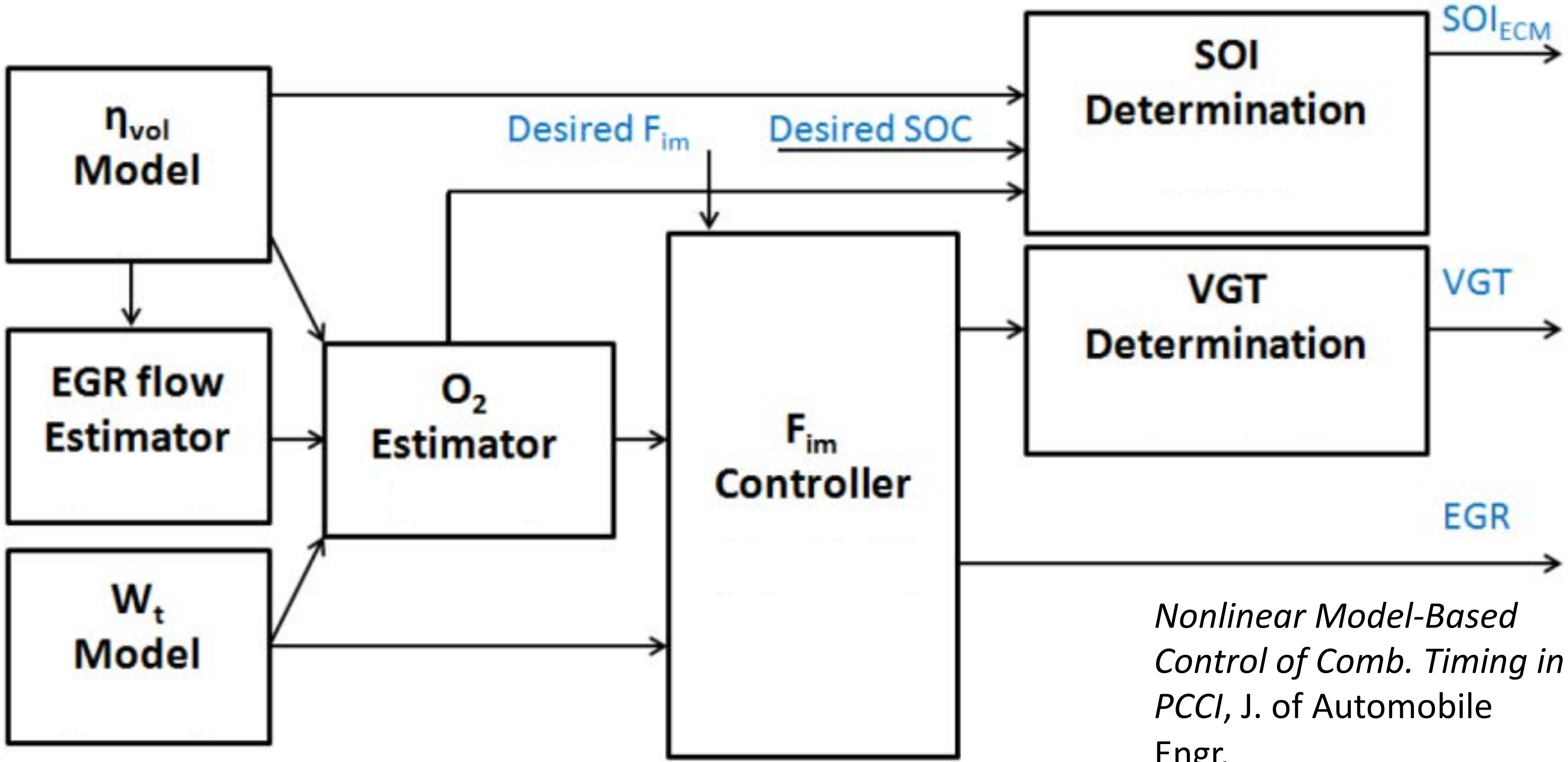




Controls for Lean Burn Engines Incorporating Valvetrain Flexibility

- Model-based (w/ stability and tracking error convergence rates guaranteed via **Lyapunov** method)
- Builds on all prior efforts



Nonlinear Model-Based Control of Comb. Timing in PCCI, J. of Automobile Engr.

Piezoelectric Fuel Injection Control

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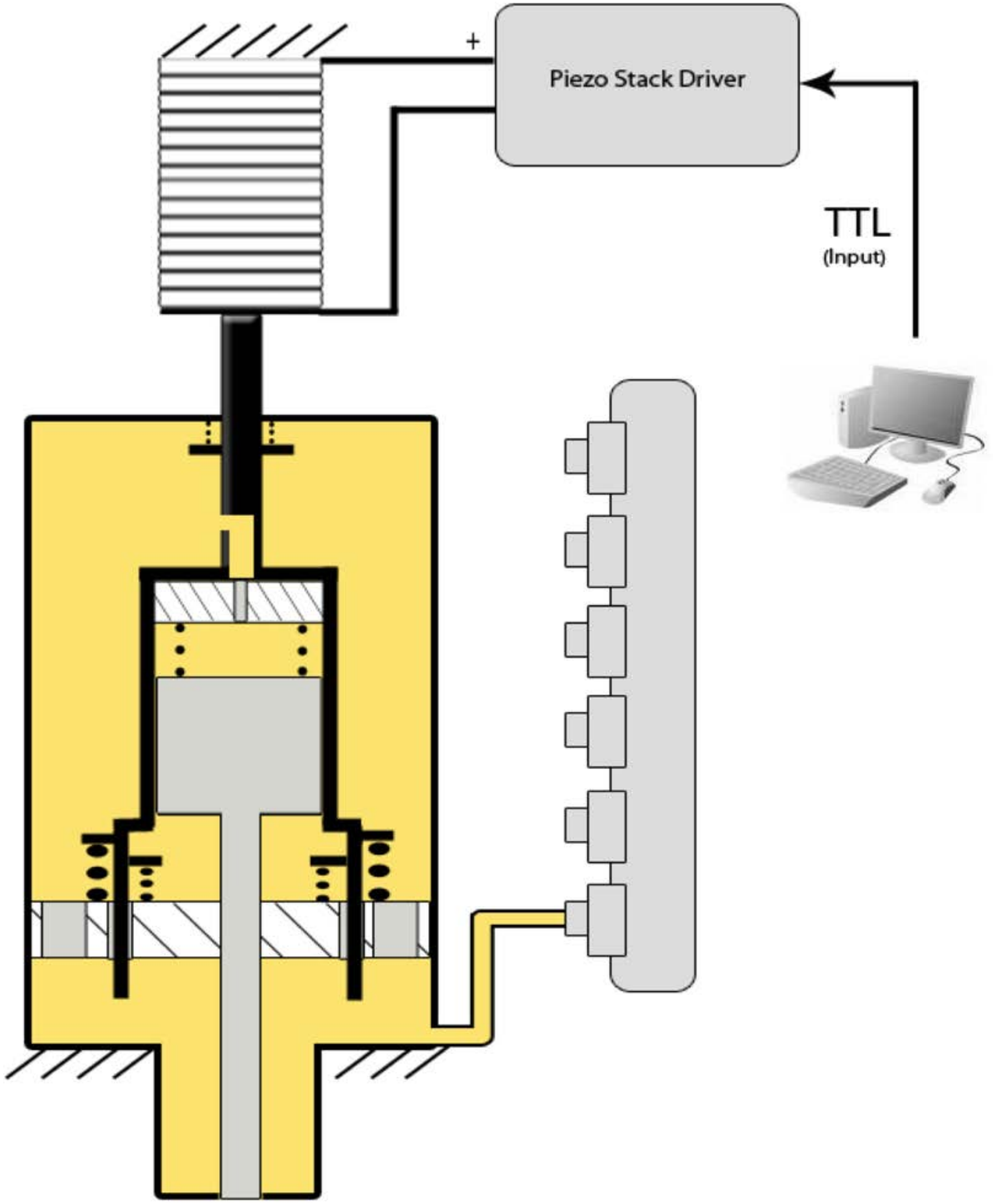


Dynamic Modeling of a Piezoelectric Actuated Fuel Injector, ASME J. of Dyn. Sys., Meas., and Control, 133(5), 2011.

Piezoelectric Fuel Injection: Pulse-to-Pulse Coupling and Flow Rate Estimation. IEEE/ASME Trans. on Mech., 16(4), 2011.

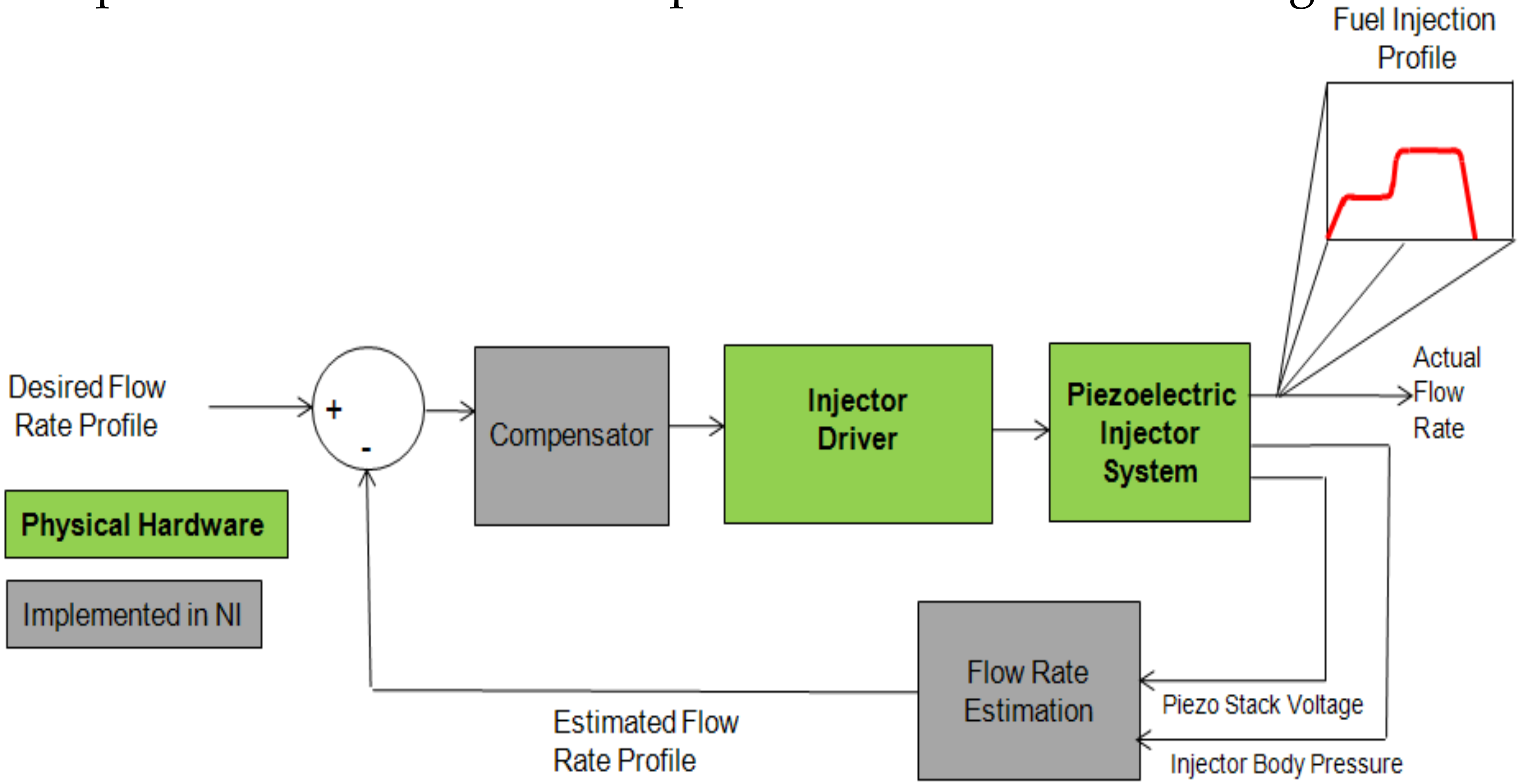
Piezo-electric Fuel Injection – Cycle-to-Cycle Control of Tightly Space Injections, IFAC Control Engr. Practice, vol. 20 (11), 2012

Dynamic Modeling of a Piezoelectric Fuel Injector During Rate Shaping, to appear in the Int. J. of Eng. Res.

Model-Based Within-a-Cycle Estimation of Rate Shaping…, submitted to IFAC Control Engr. Practice

Piezoelectric Fuel Injection Control

1. Developed physically-based 13 state dynamic simulation
2. Model reduction to obtain control amenable models
3. Implementation of closed loop control & estimation strategies



<u>Within-a-cycle</u> estimation & control of injected fuel rate shape

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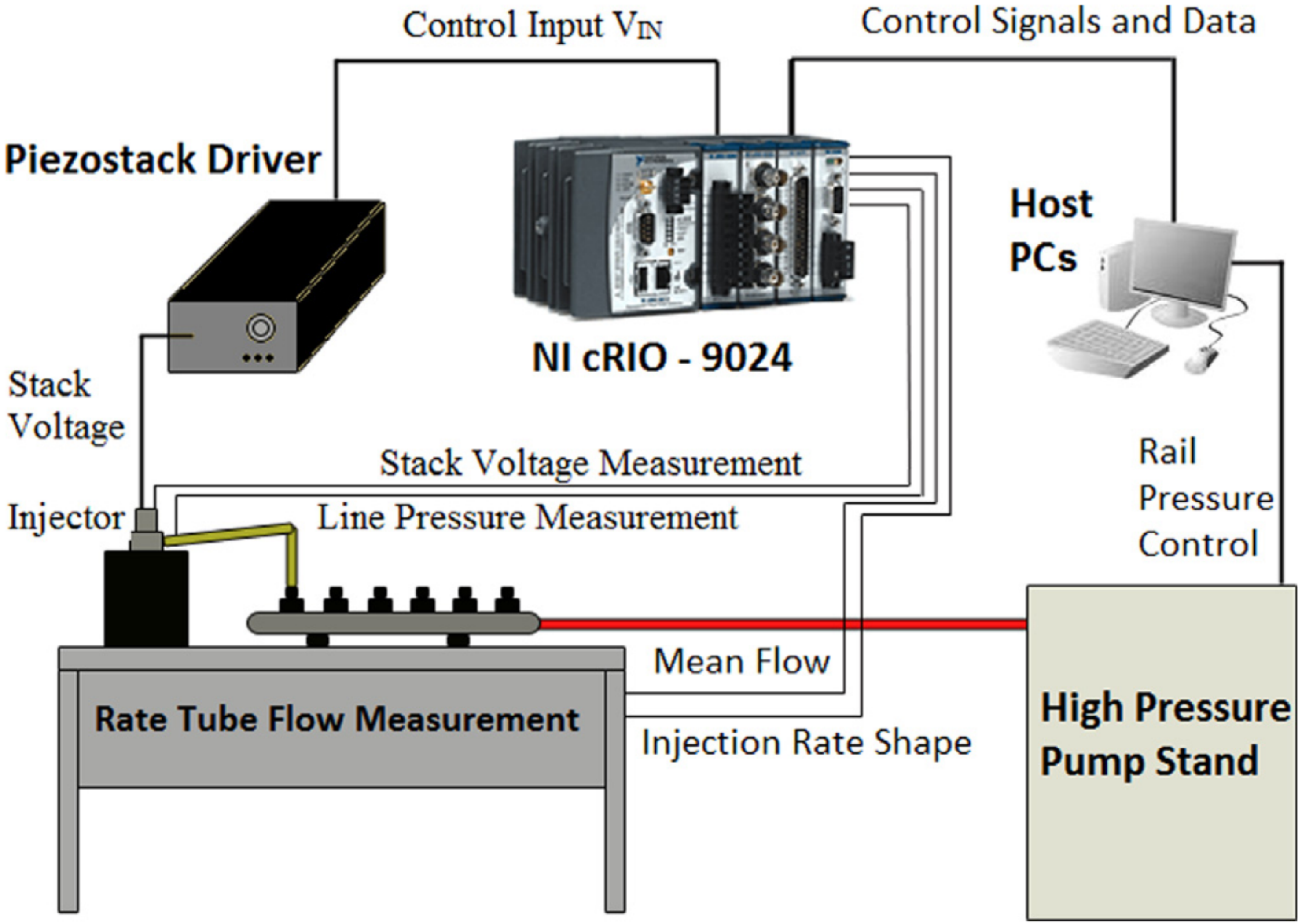

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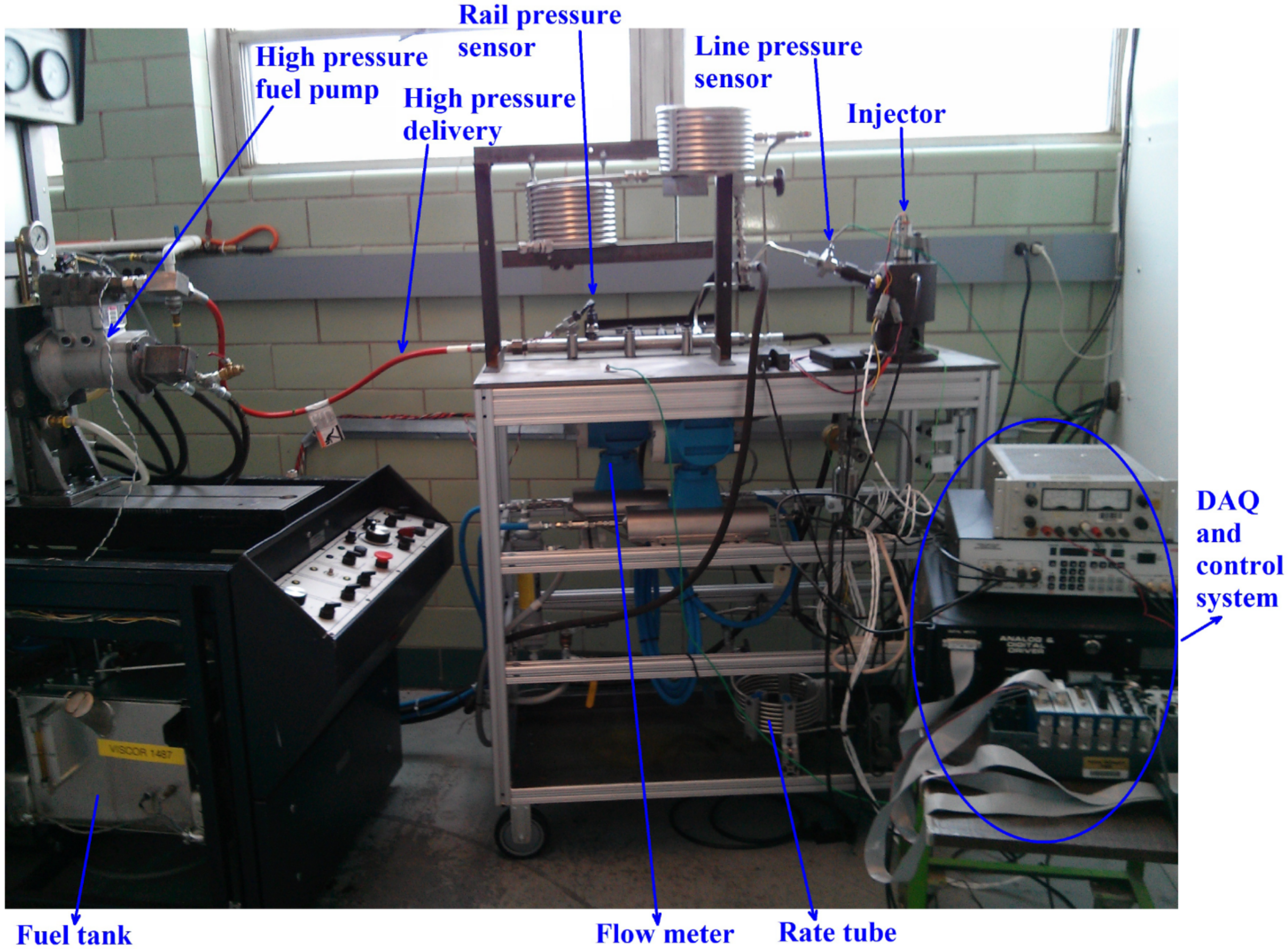
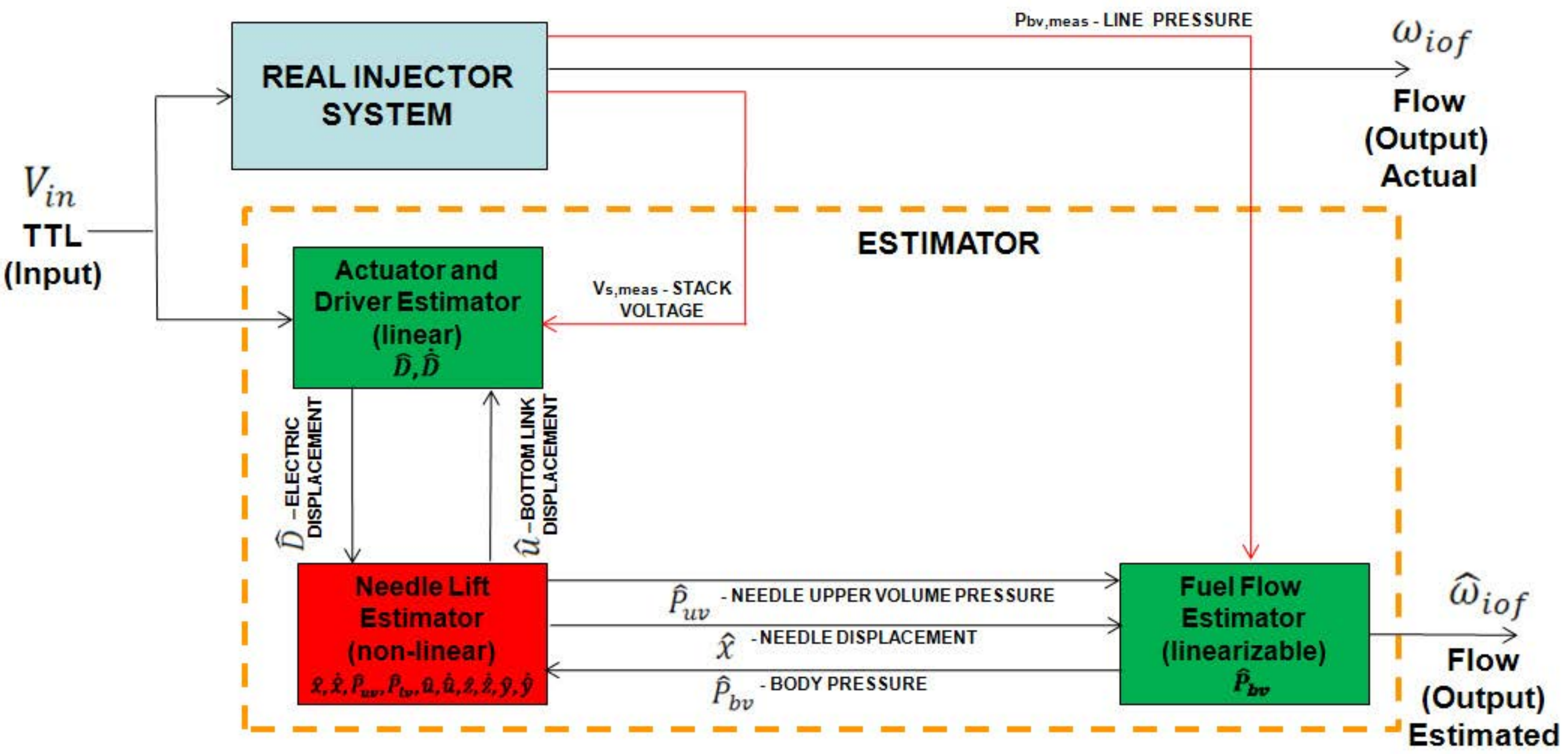


Piezoelectric Fuel Injection Control

Full-Order Estimation

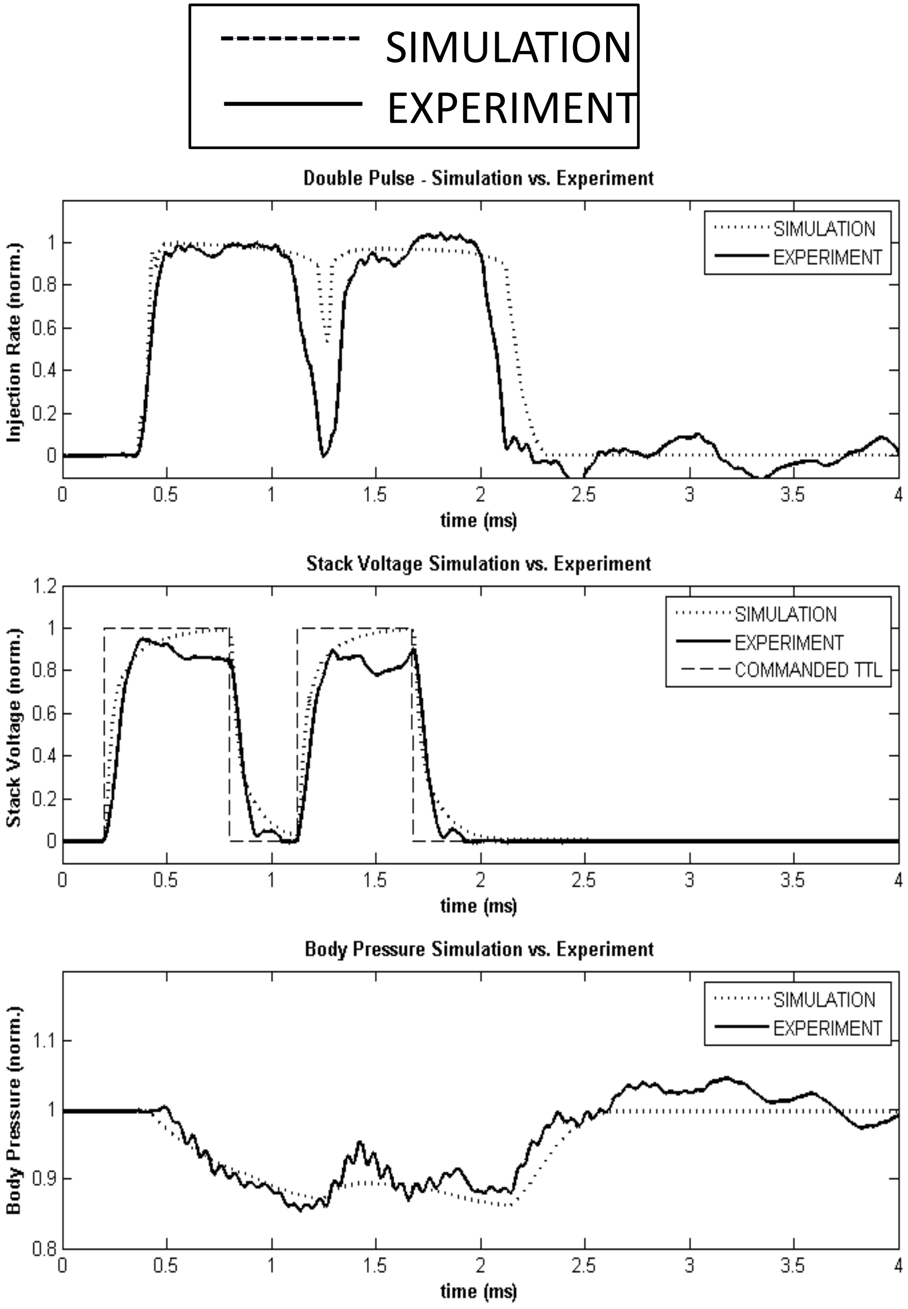


Estimator Model Structure

"Piezoelectric Fuel Injection: Pulse-to-Pulse Coupling and Flow Rate Estimation." Accepted to: IEEE/ASME Transactions on Mechatronics. 2010.

Results

Two Pulses



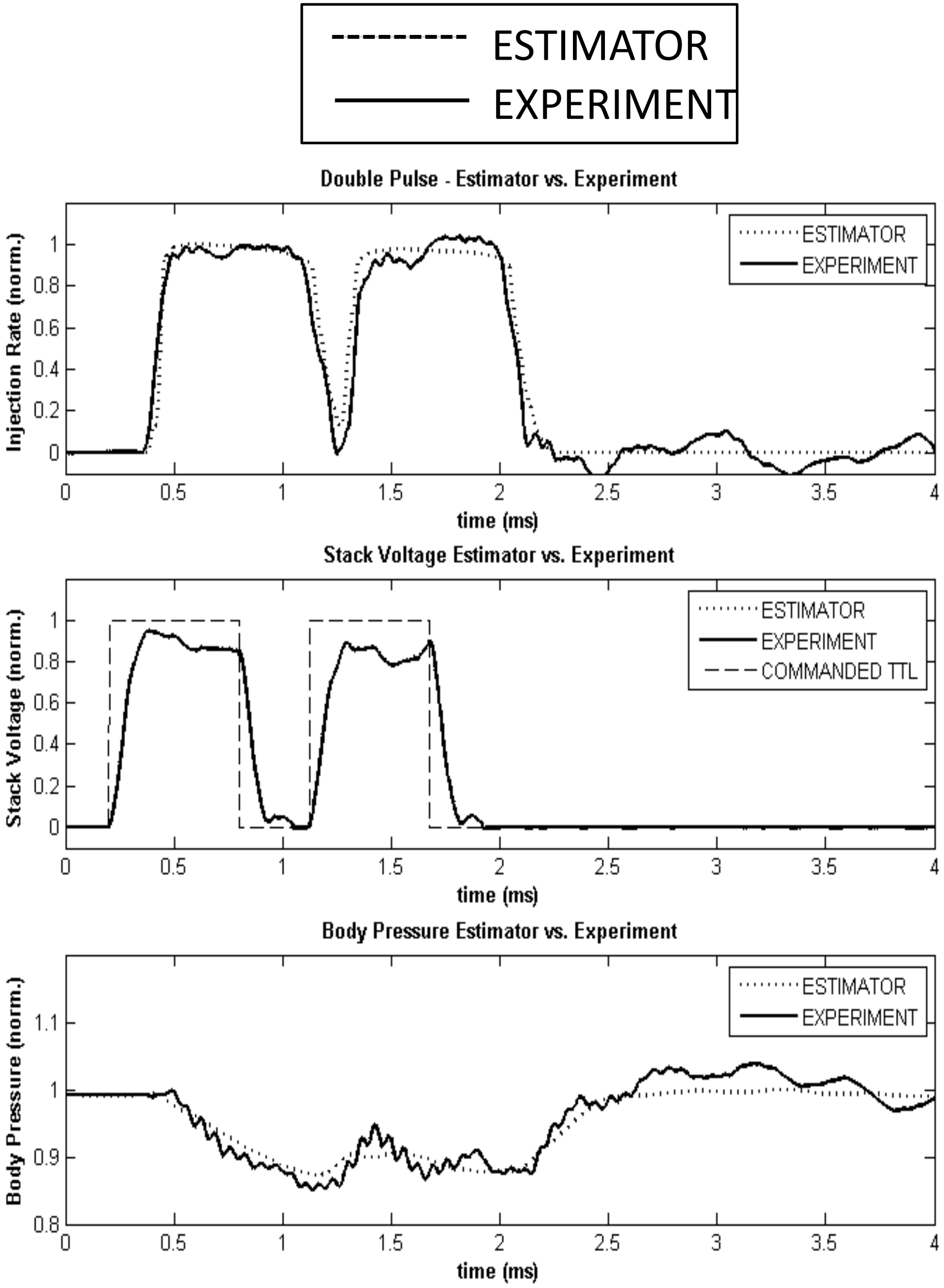
Simulation

Flow

Stack Voltage

Body Volume Pressure

Model Based Estimator



Estimator

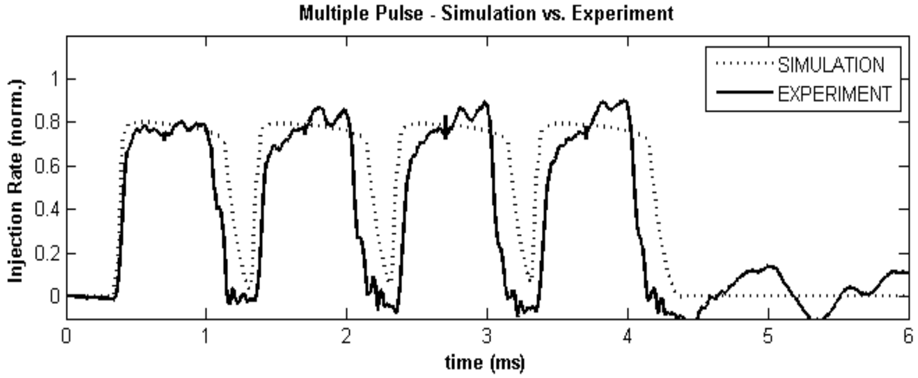
Results

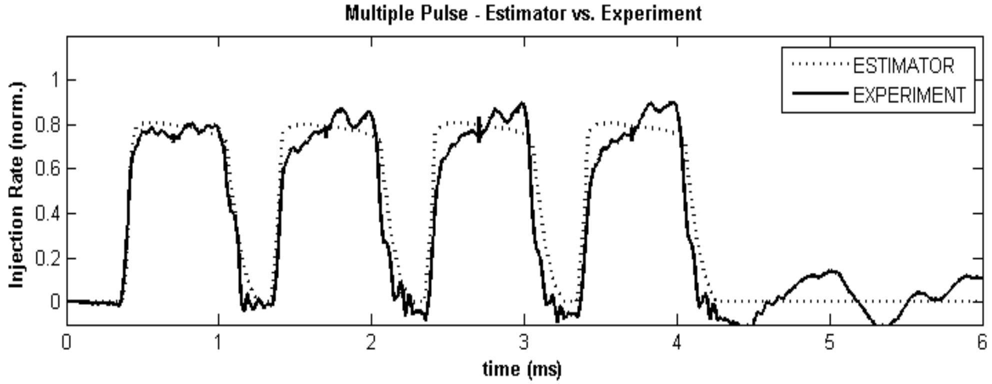
--------- SIMULATION
——— EXPERIMENT

--------- ESTIMATOR
——— EXPERIMENT

Multiple Pulses

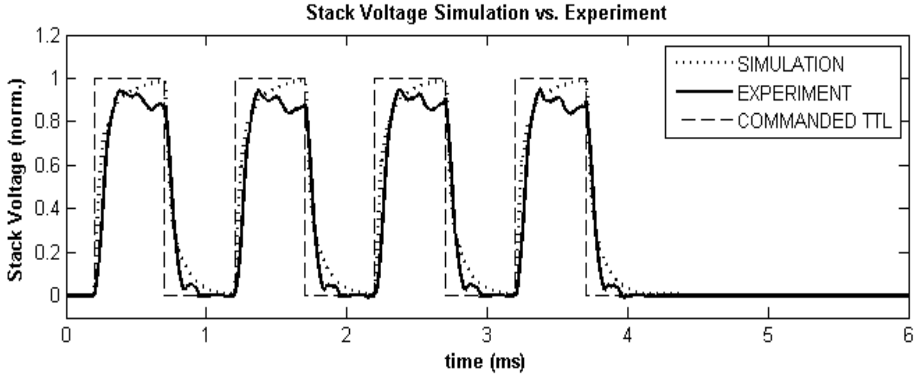
Flow

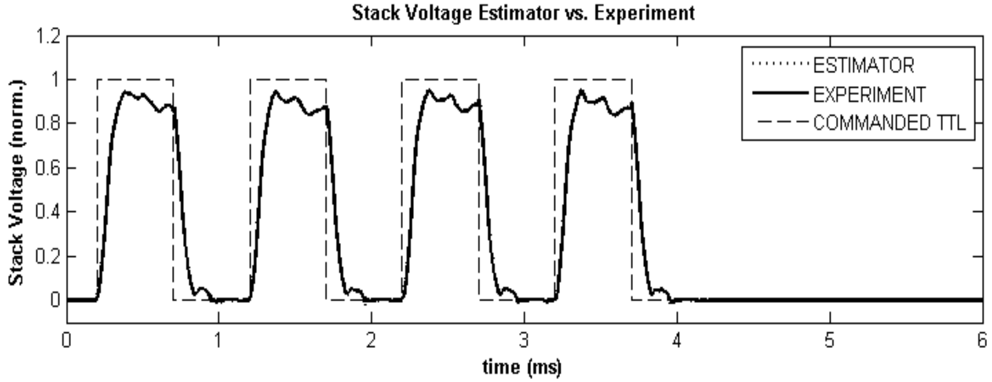




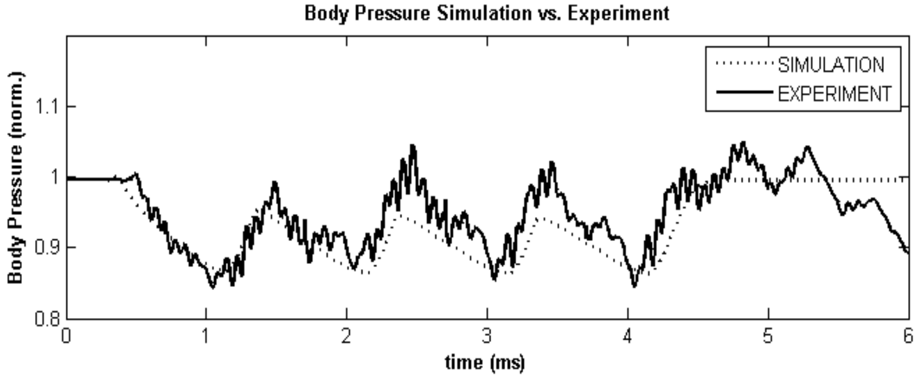
Model Based Estimator

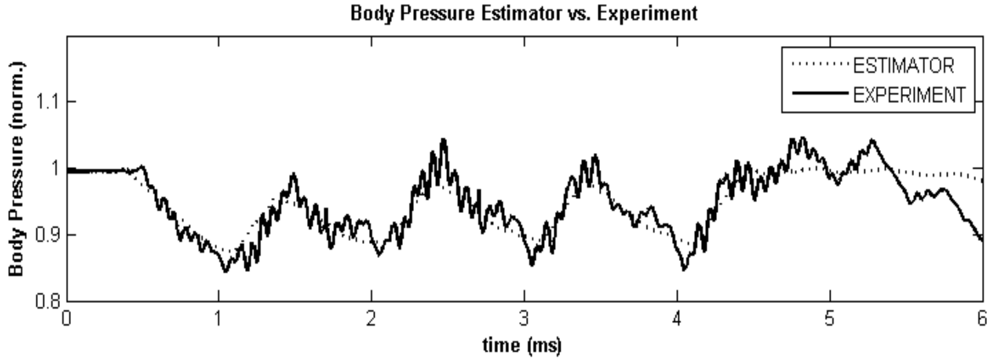
Stack Voltage





Body Volume Pressure



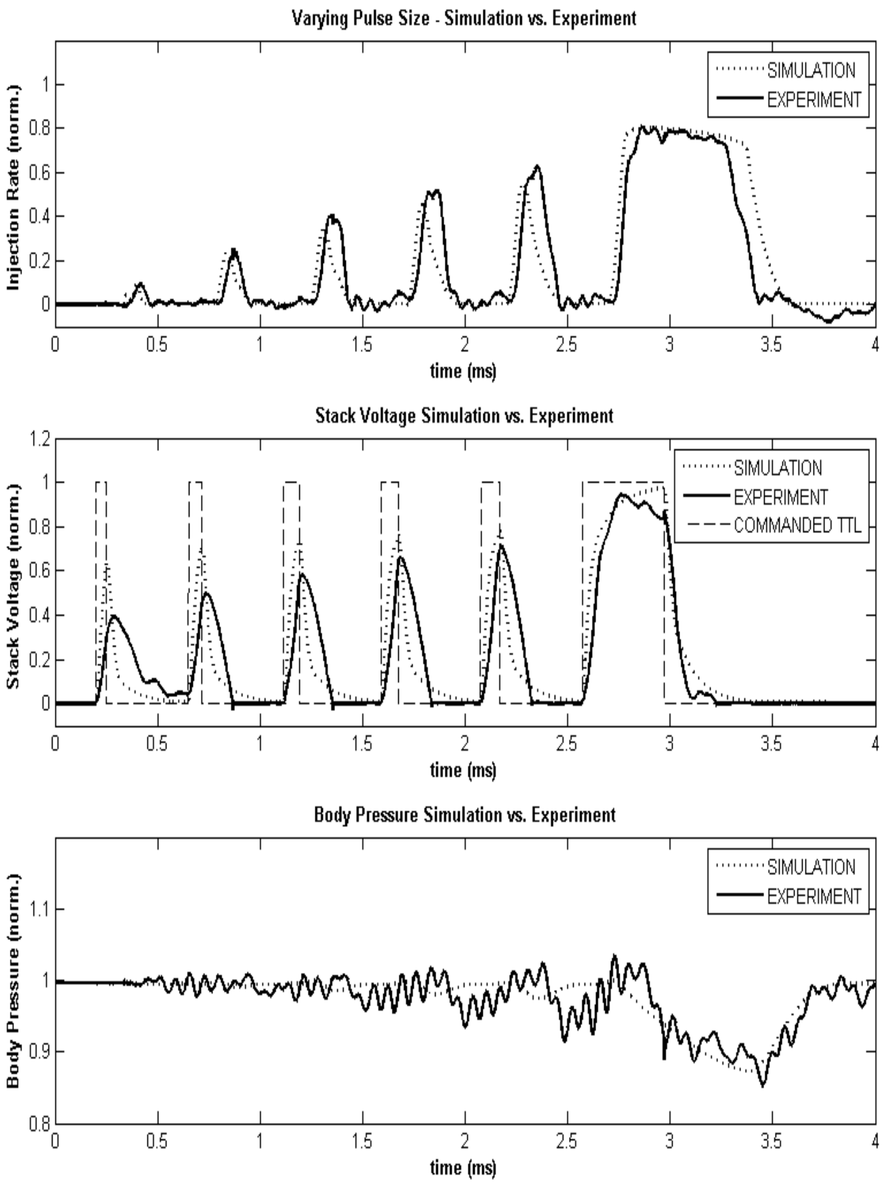


Results

--------- SIMULATION
——— EXPERIMENT

--------- ESTIMATOR
——— EXPERIMENT

Complex Profiles

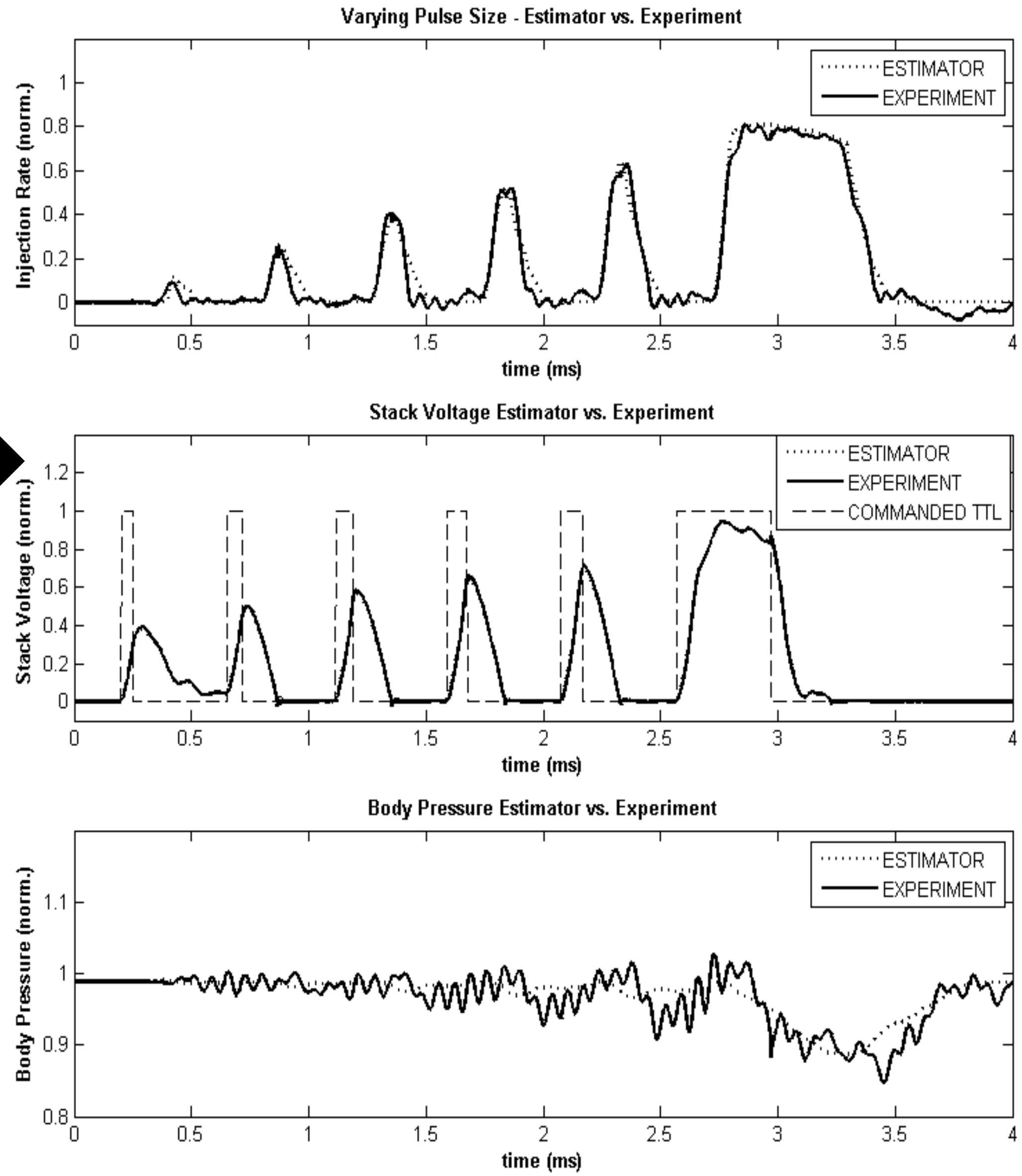


Flow

Model Based Estimator

Stack Voltage

Body Volume Pressure

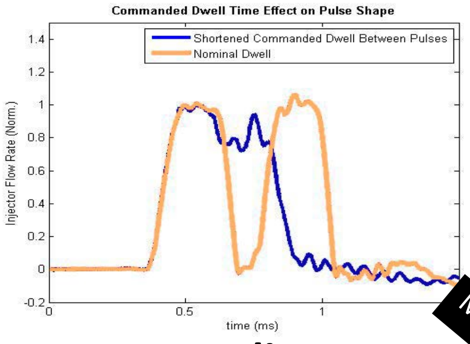


Piezoelectric Fuel Injection Control

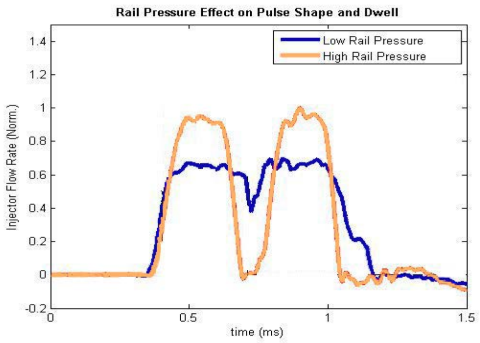
Results

Experimental Effect

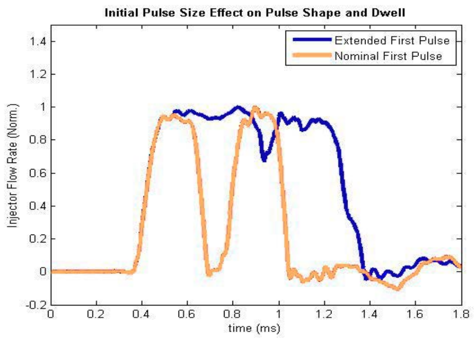
Pulse-to-Pulse Interactions



Commanding Pulses Too Closely



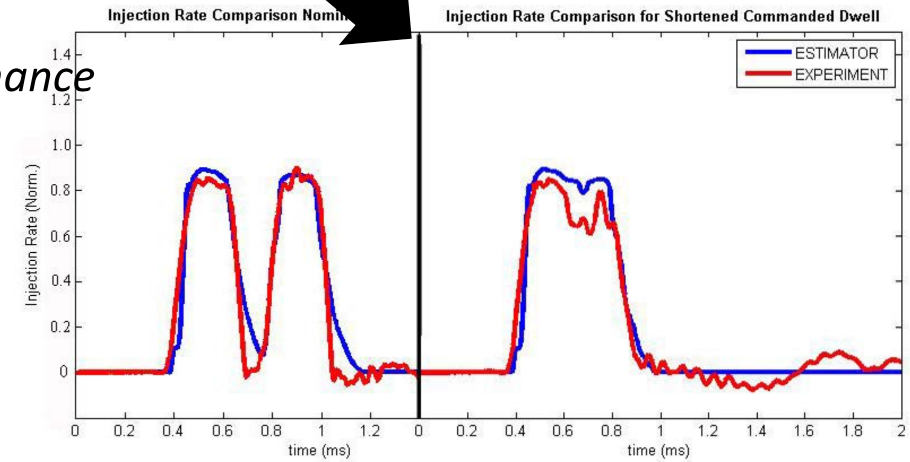
Dropping Rail Pressure



Extending the First Pulse

Model Based Estimator

Estimator Performance



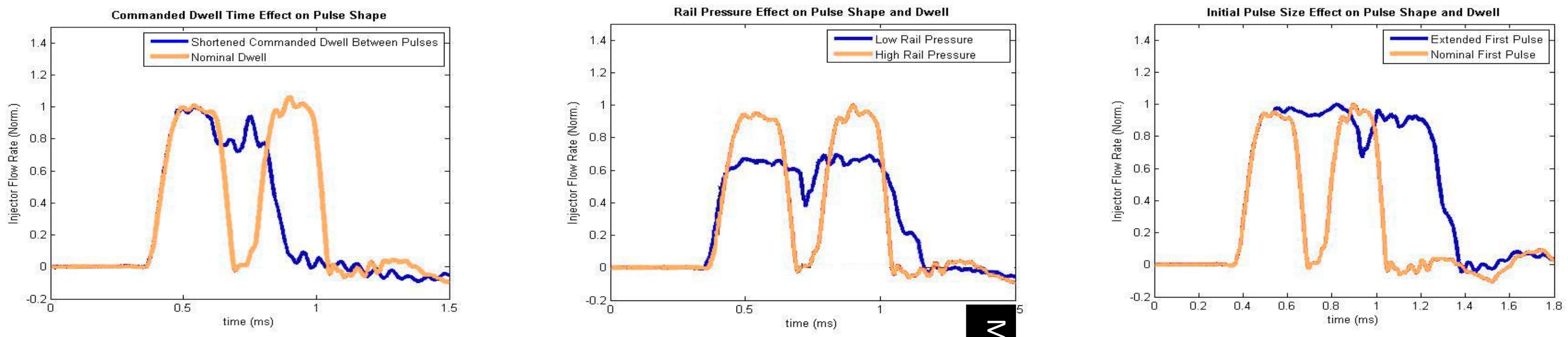
ESTIMATOR
EXPERIMENT

Piezoelectric Fuel Injection Control

Results

Experimental Effect

Pulse-to-Pulse Interactions



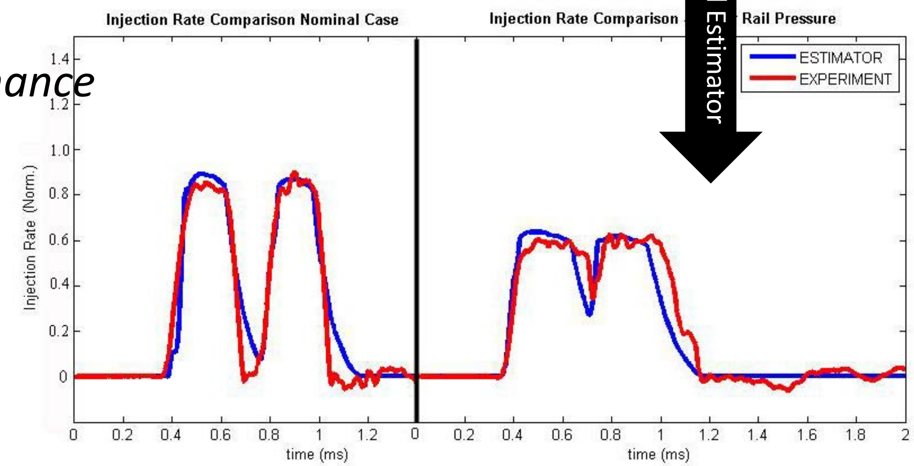
Commanding Pulses Too Closely

Dropping Rail Pressure

Extending the First Pulse

Model Based Estimator

Estimator Performance



ESTIMATOR
EXPERIMENT

Piezoelectric Fuel Injection Control

Results

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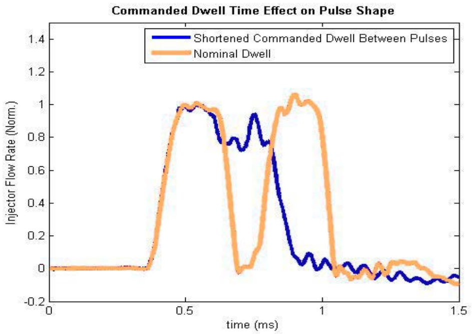
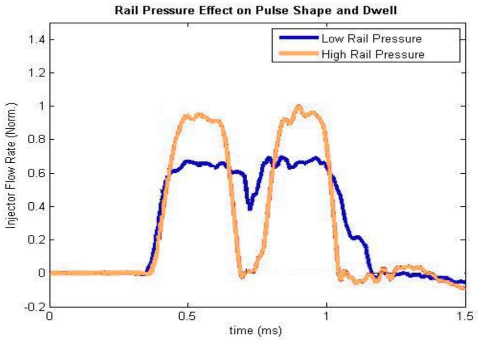
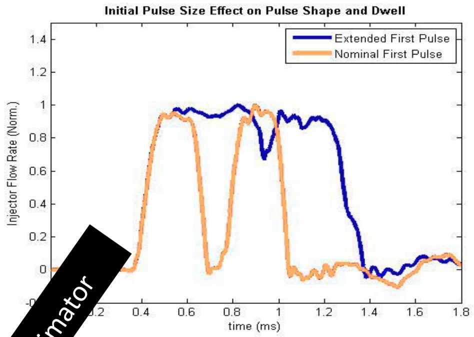


Commanding Pulses Too Closely



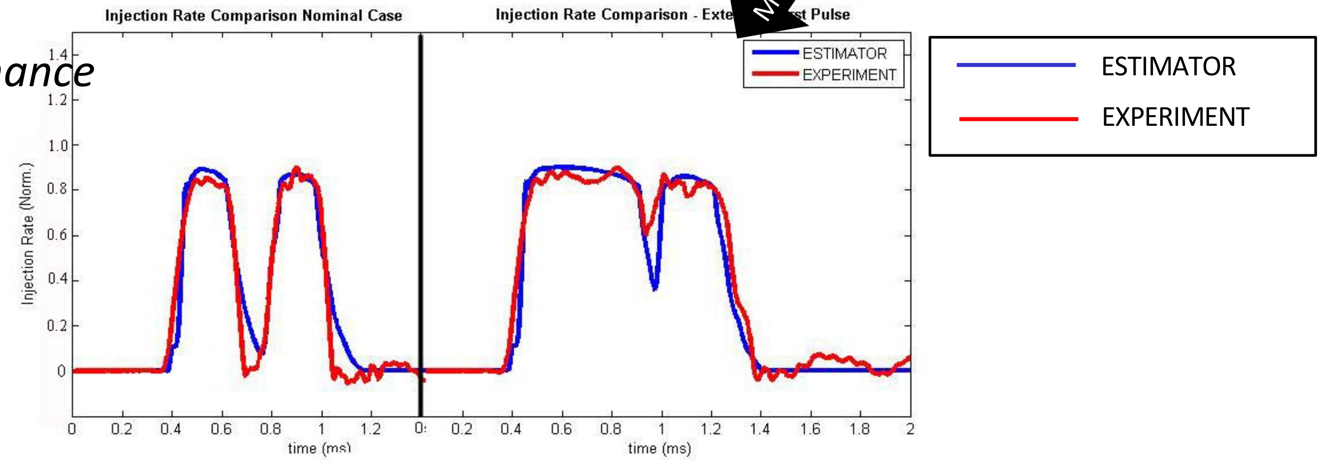
Dropping Rail Pressure



Extending the First Pulse

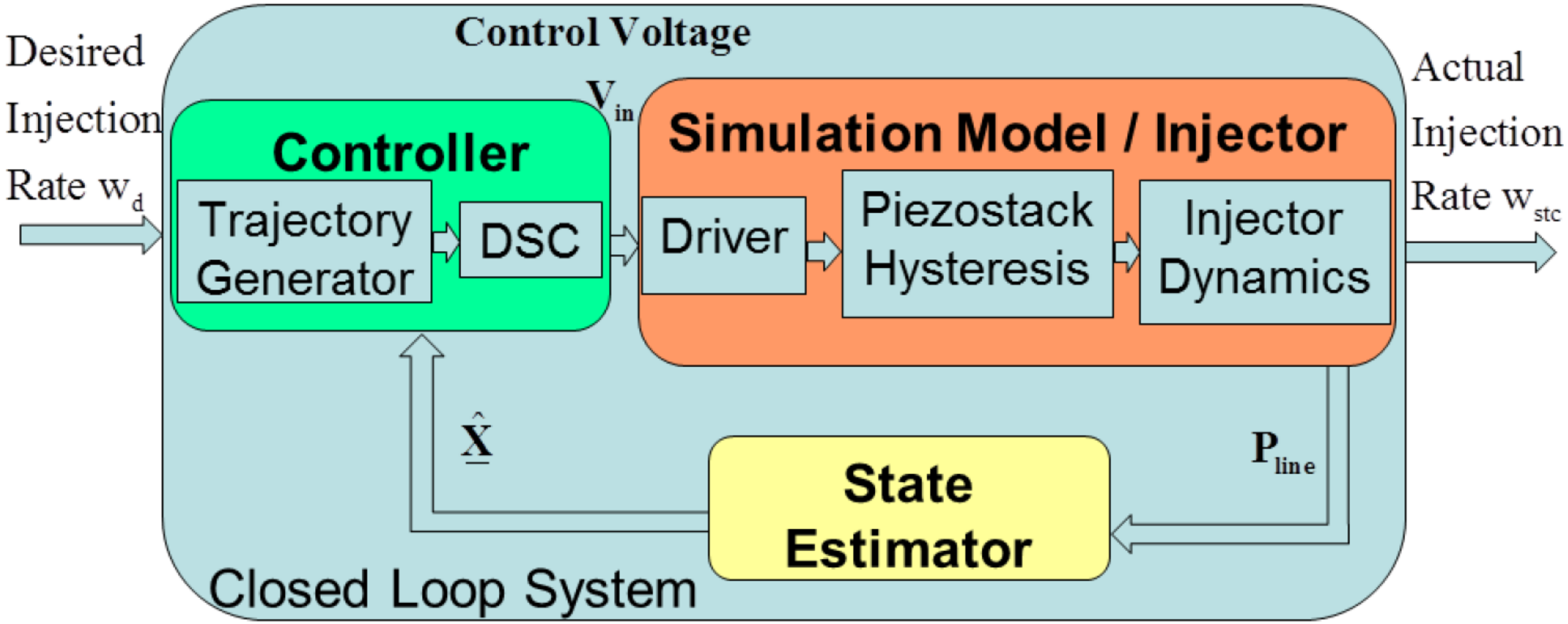
Model Based Estimator

Estimator Performance



Piezoelectric Fuel Injection Control

1. Developed physically-based 13 state dynamic simulation
2. Model reduction to obtain control amenable models
3. Implementation of closed loop control & estimation strategies



<u>Within-a-cycle</u> estimation & control of injected fuel rate shape

Piezoelectric Fuel Injection Control

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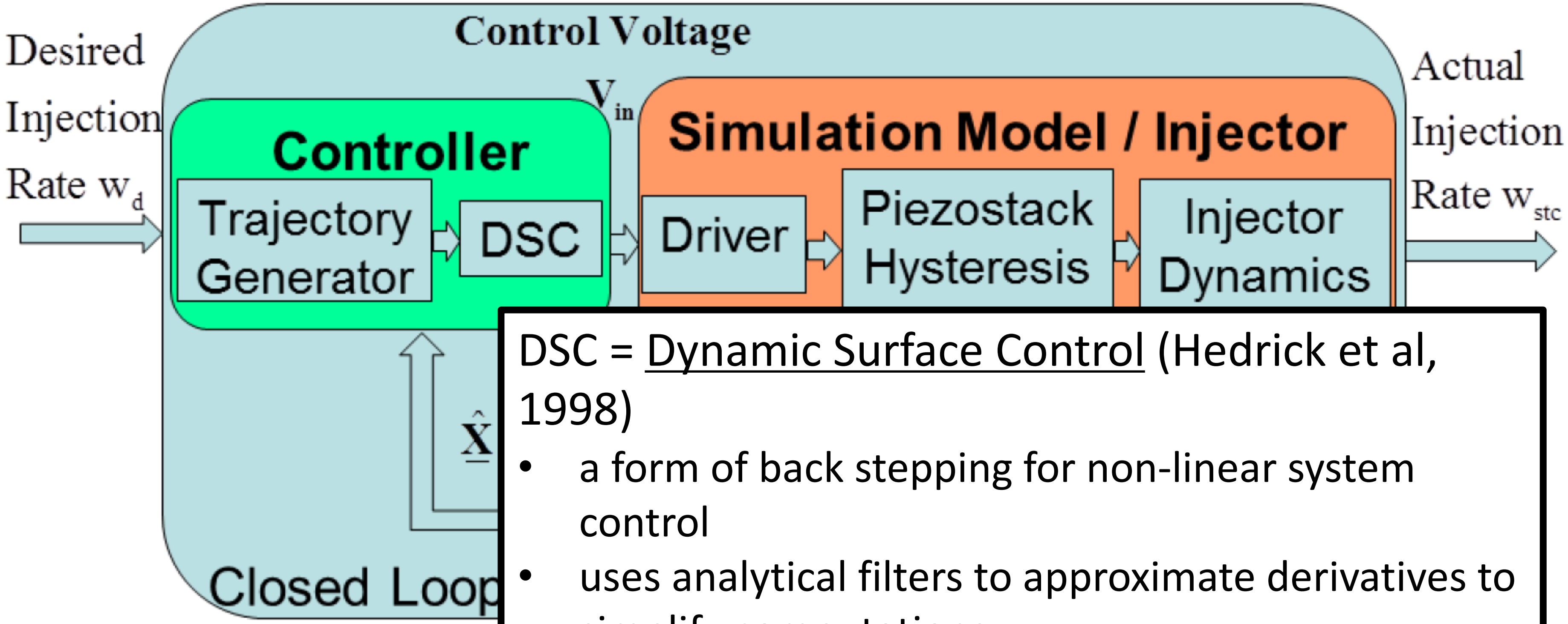

DSC = <u>Dynamic Surface Control</u> (Hedrick et al, 1998)

- a form of back stepping for non-linear system control
- uses analytical filters to approximate derivatives to simplify computations

Effort also includes stability & robustness guarantees

Wit

injected fuel rate shape

Piezoelectric Fuel Injection Control

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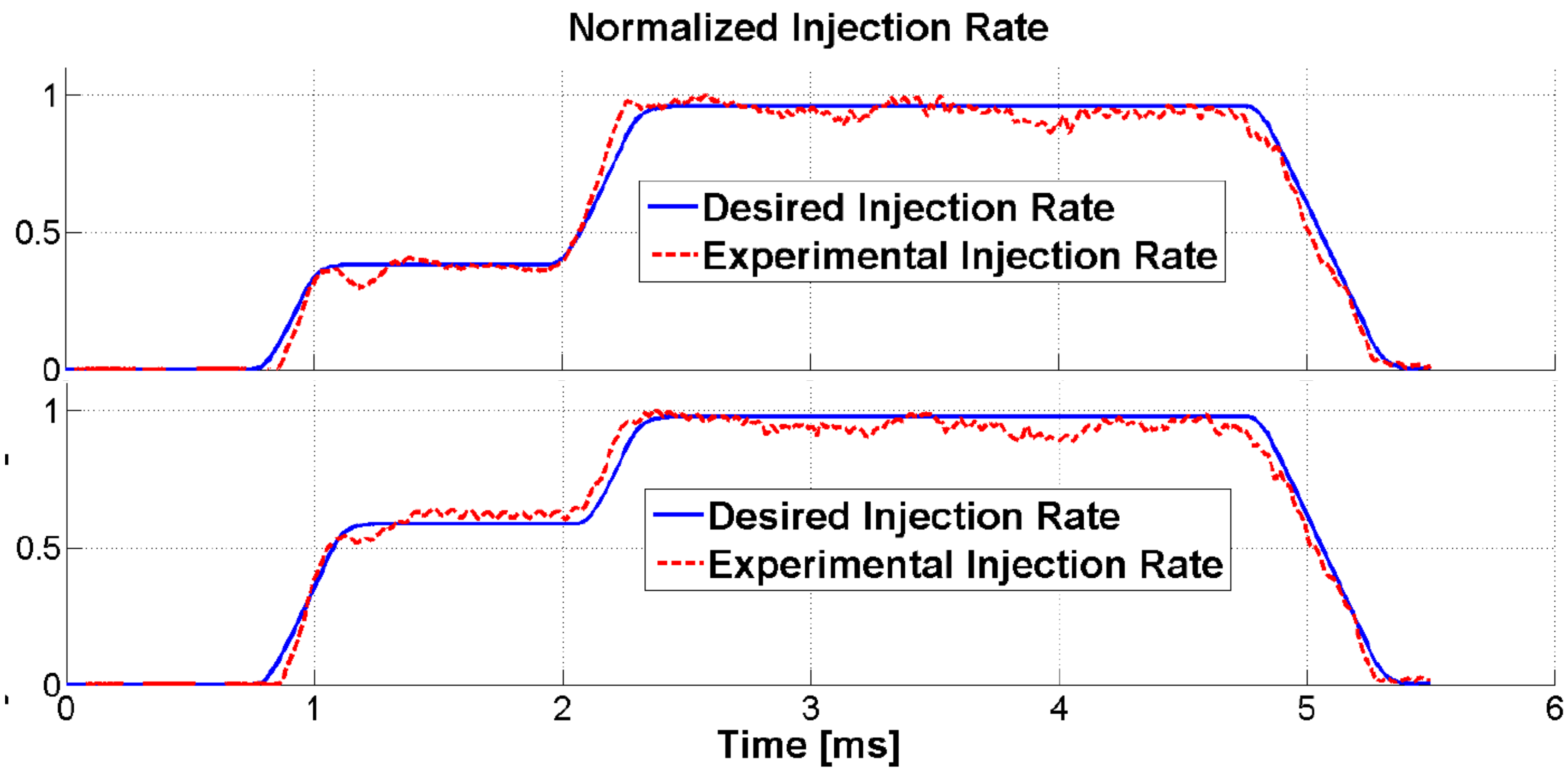


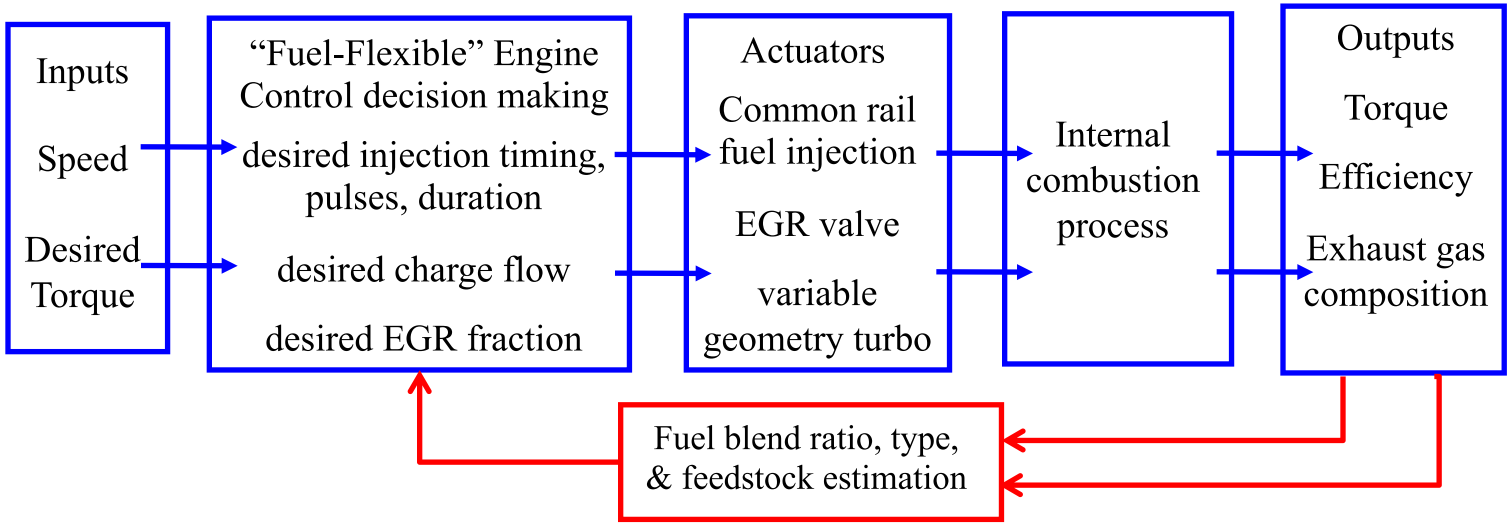
<u>Within-a-cycle</u> estimation & control of injected fuel rate shape

Fuel Adaptive CI Engine Control

Fuel Adaptive CI Engine Control

- Alternative fuels can provide significant benefits:
  - Increased domestic energy security
  - Reduced emissions
  - Lower costs (more choices, better price)

- Requirement: estimate & accommodate different combustion behavior for variable:
  - Blend ratios
  - Types
  - Feedstocks

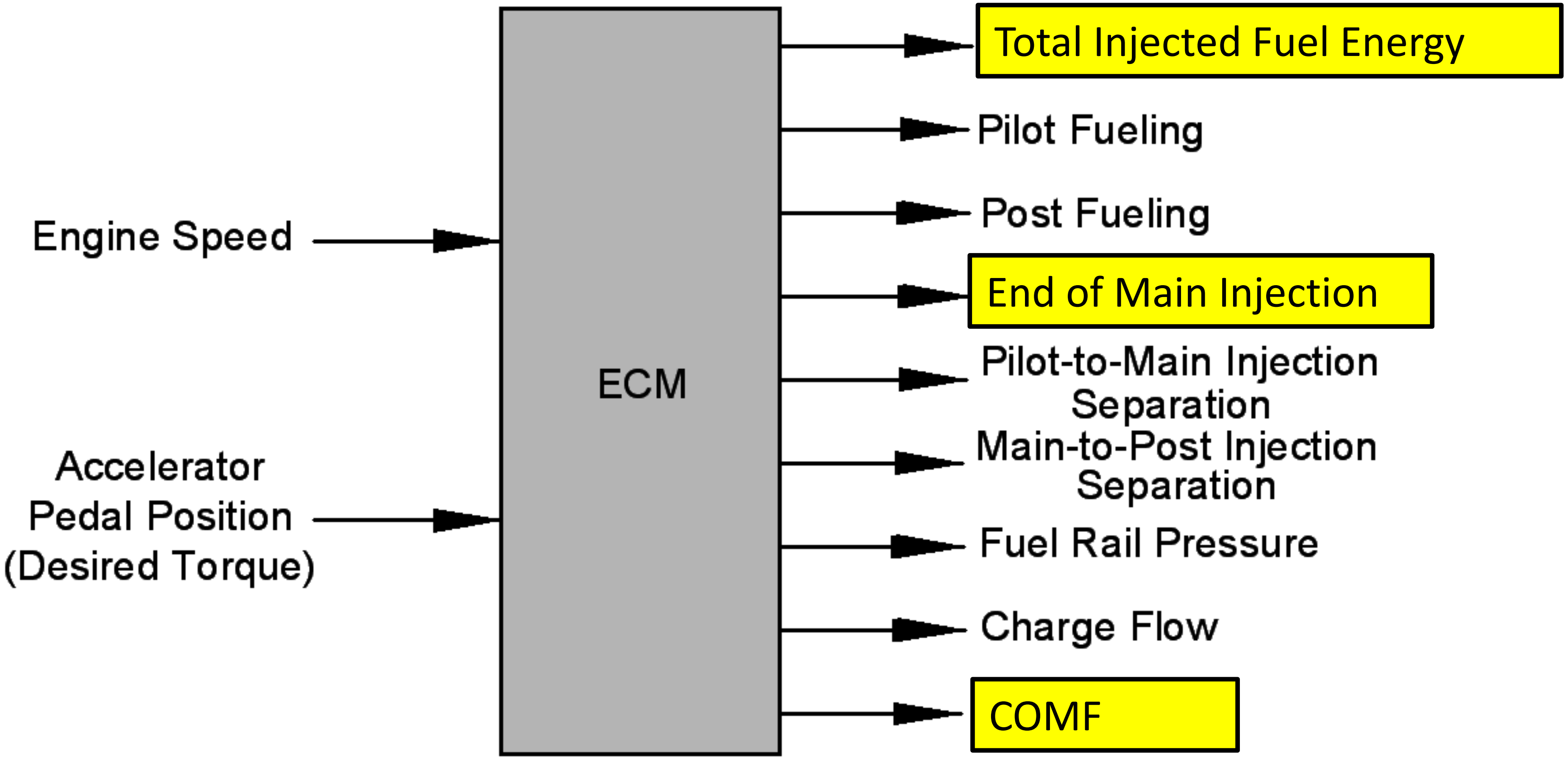


Fuel Adaptive CI Engine Control

Soy-Biodiesel Impact on NOx Emissions and Fuel Economy for Diffusion-Dominated Combustion…, Energy and Fuels, 23, 2009.

Proposed Approach

~Three control variable should be replaced:

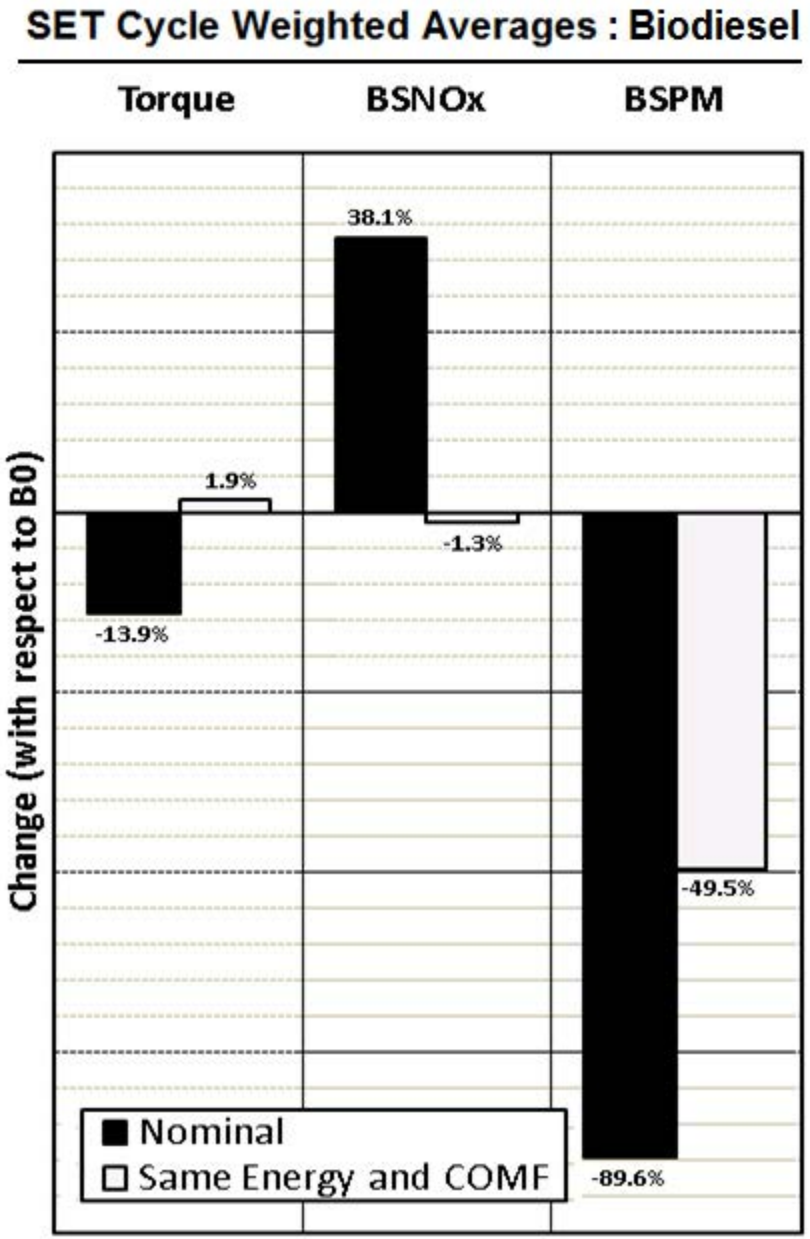


Fuel Adaptive CI Engine Control

Also works well for biodiesel made from other feedstocks! Since energy and oxygen content does not change very much

Biodiesel feedstock	$Y_{O,\,fuel}$
Canola	0.107
Sunflower	0.109
Corn	0.108
Peanut	0.111
Palm	0.115
Lard	0.111
Beef tallow	0.112
Soybean	0.109
Cold-flow soybean based	0.1086
Hot-flow soybean based	0.1101

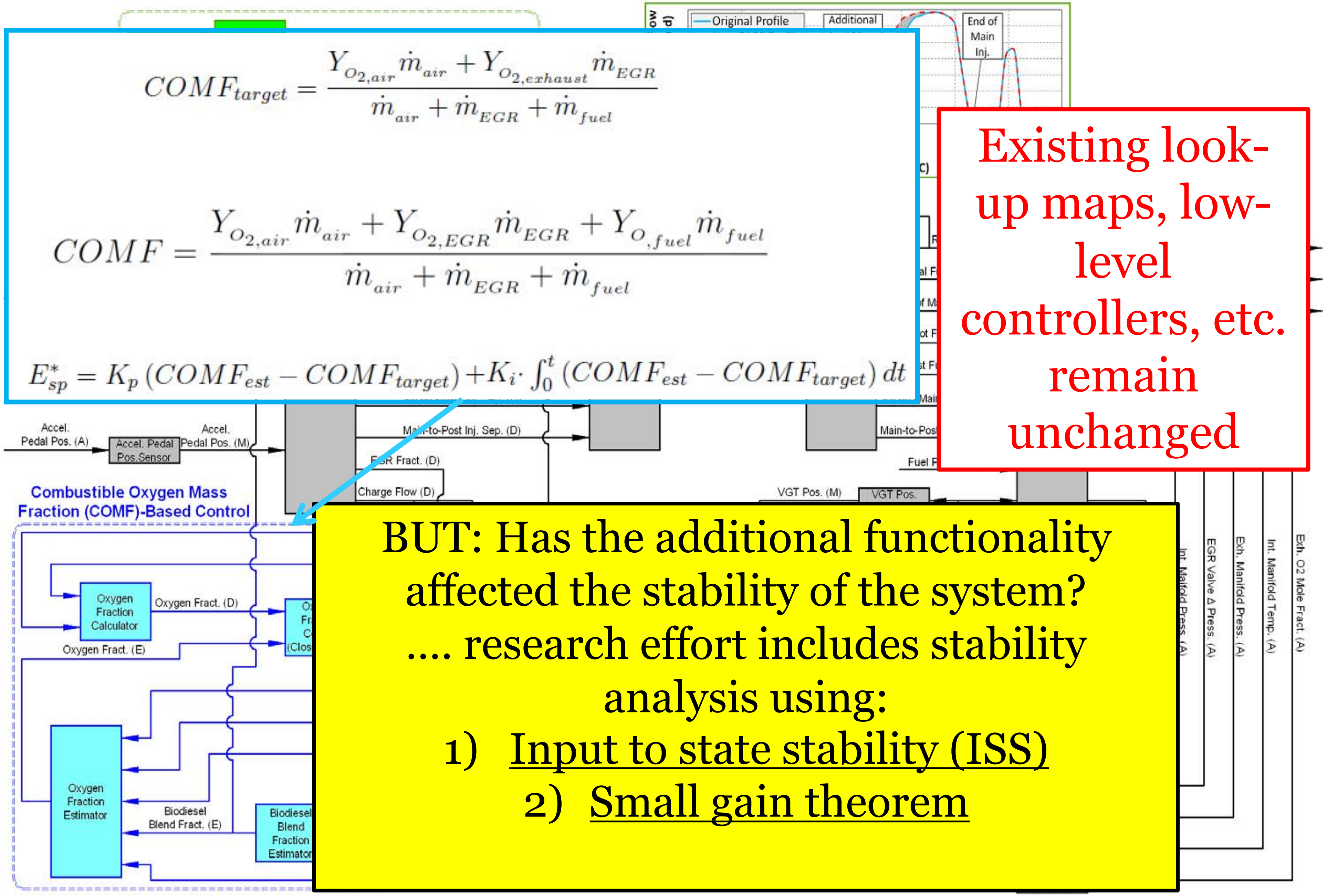
[a]Values taken from available literature.



Control Variable Based Accommodation of Biodiesel Blends, Intl. J. of Engine Res., 12(6) 2011.

A Robust Fuel Flexible Combustion Control Strategy for Biodiesel with Variable Fatty Acid Composition…, Intl. J. of Engine Res.

Fuel Adaptive CI Engine Control



$$COMF_{target} = \frac{Y_{O_2,air}\,\dot{m}_{air} + Y_{O_2,exhaust}\,\dot{m}_{EGR}}{\dot{m}_{air} + \dot{m}_{EGR} + \dot{m}_{fuel}}$$

$$COMF = \frac{Y_{O_2,air}\,\dot{m}_{air} + Y_{O_2,EGR}\,\dot{m}_{EGR} + Y_{O,fuel}\,\dot{m}_{fuel}}{\dot{m}_{air} + \dot{m}_{EGR} + \dot{m}_{fuel}}$$

$$E_{sp}^{*} = K_p\left(COMF_{est} - COMF_{target}\right) + K_i \cdot \int_0^t \left(COMF_{est} - COMF_{target}\right) dt$$

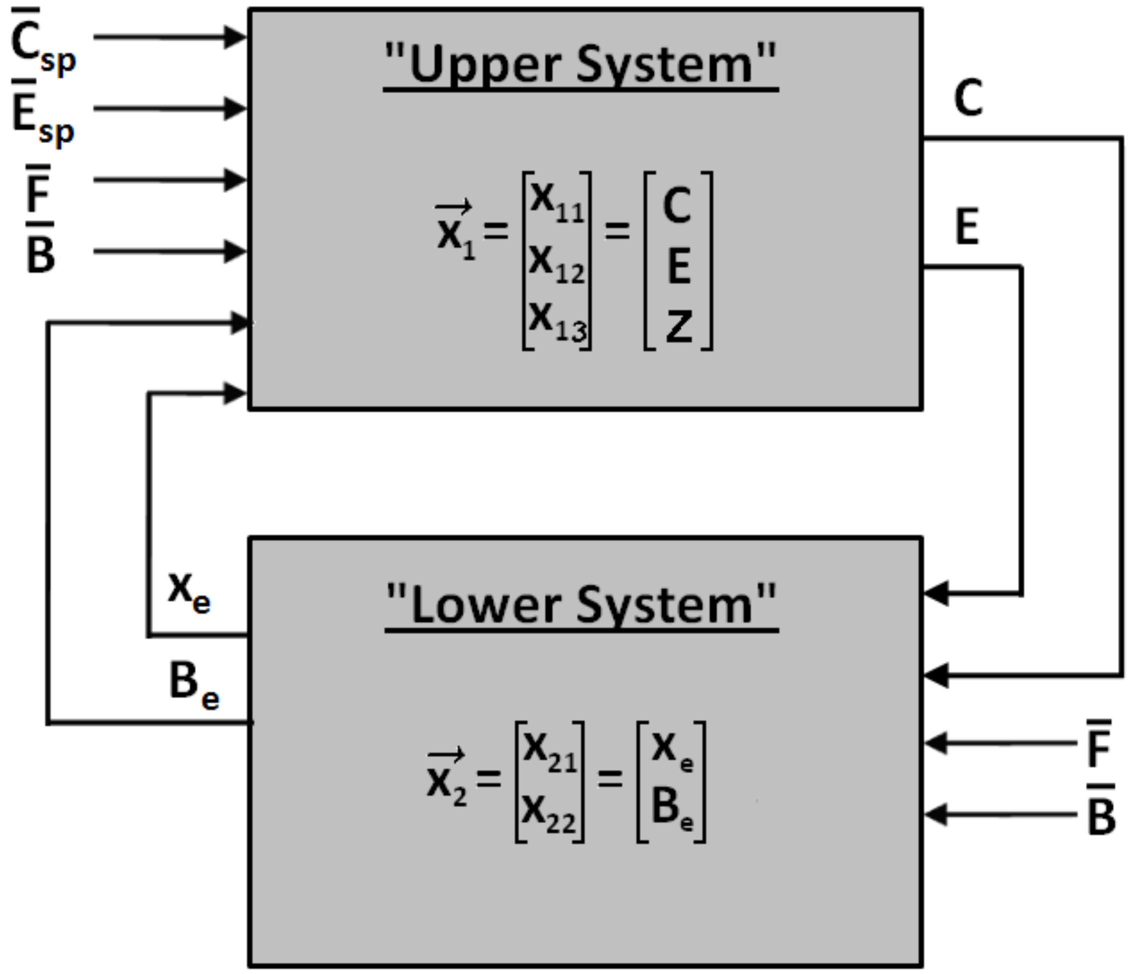
Existing look-up maps, low-level controllers, etc. remain unchanged

BUT: Has the additional functionality affected the stability of the system?
.... research effort includes stability analysis using:

1) Input to state stability (ISS)
2) Small gain theorem

Fuel Adaptive CI Engine Control

System Stability Analysis



C = charge flow

E = EGR fraction

Z = integrated COMF error

x_e = estimated exhaust O_2 mole fraction

B_e = estimated biodiesel blend fraction

$\bar{C}_{sp}$ = charge flow set point

$\bar{E}_{sp}$ = EGR fraction set point

$\bar{F}$ = total fueling set point

$\bar{B}$ = actual biodiesel blend fraction

Fuel Adaptive CI Engine Control

Small Gain Theorem

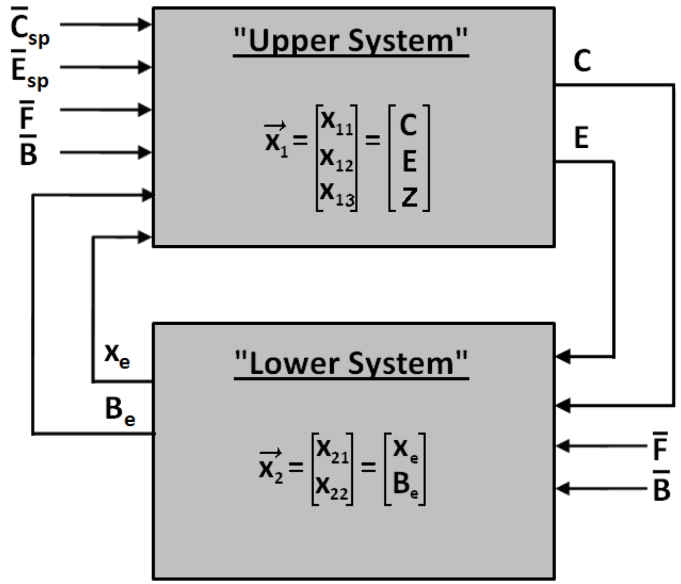
For the interconnected system

$$\dot{x}_1 = f_1(x_1, x_2)$$
$$\dot{x}_2 = f_2(x_2, x_1)$$

If gains of **“input to state stable” (ISS)**

subsystems are γ_1 and γ_2 with

$$\gamma_1 \gamma_2 < 1$$

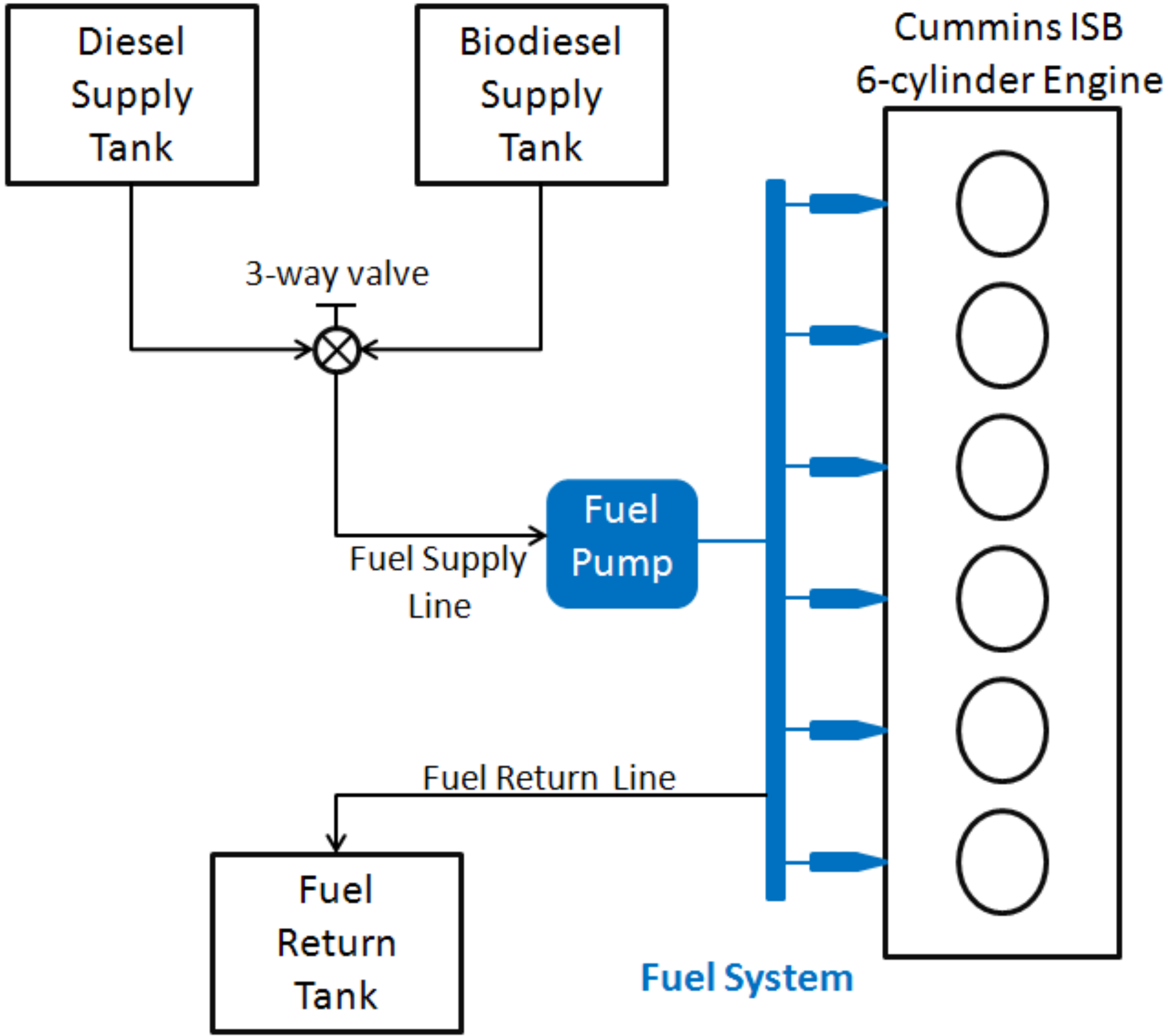


Then the interconnected system is globally asymptotically stable. (versions for both linear and non-linear systems)

Fuel Adaptive CI Engine Control

Experimental Validation

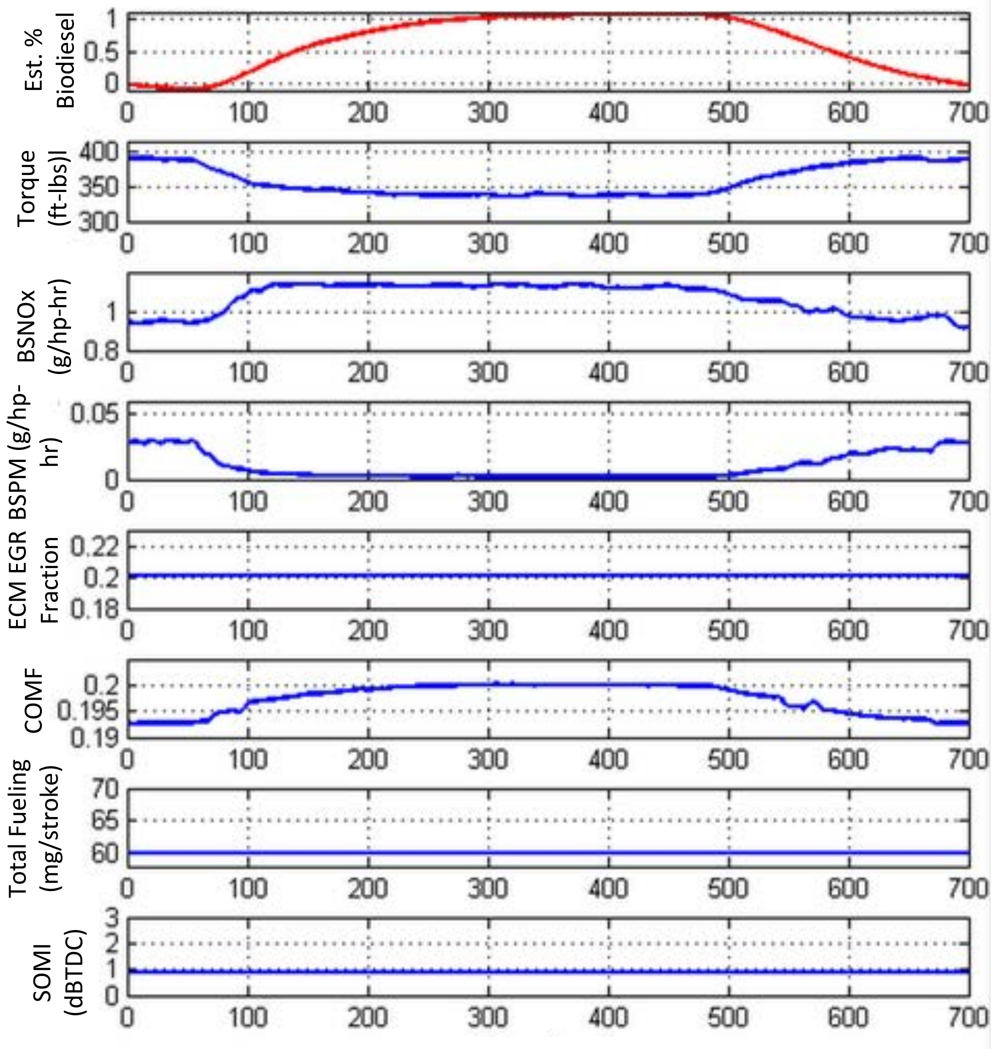
The closed loop control technique was tested on the Cummins ISB test cell in both steady state and transient tests.



Fuel Adaptive CI Engine Control

Real-Time Soy Biodiesel Estimation & Accommodation

Without Accommodation

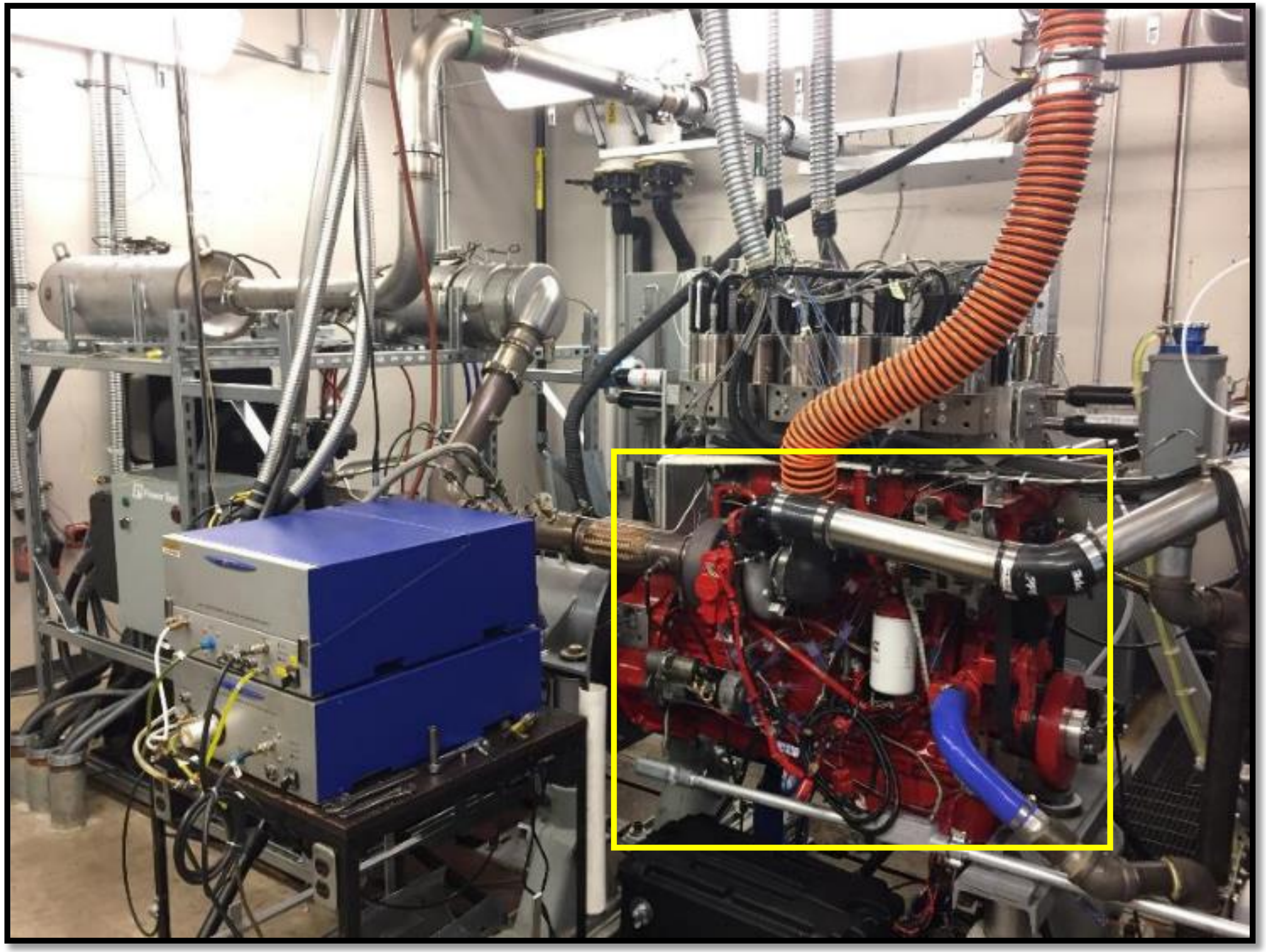


Fuel Flexible Combustion Control of Biodiesel Blends, ASME J. of Dyn. Sys., Meas., and Control.

More Valvetrain Flexibility for Lean Burn Engines

Experimental Setup

Cummins Power Lab – Test Cell 1



Cummins 6-cylinder camless diesel engine

Fully flexible VVA system

Cylinder-to-cylinder,
cycle-by-cycle control

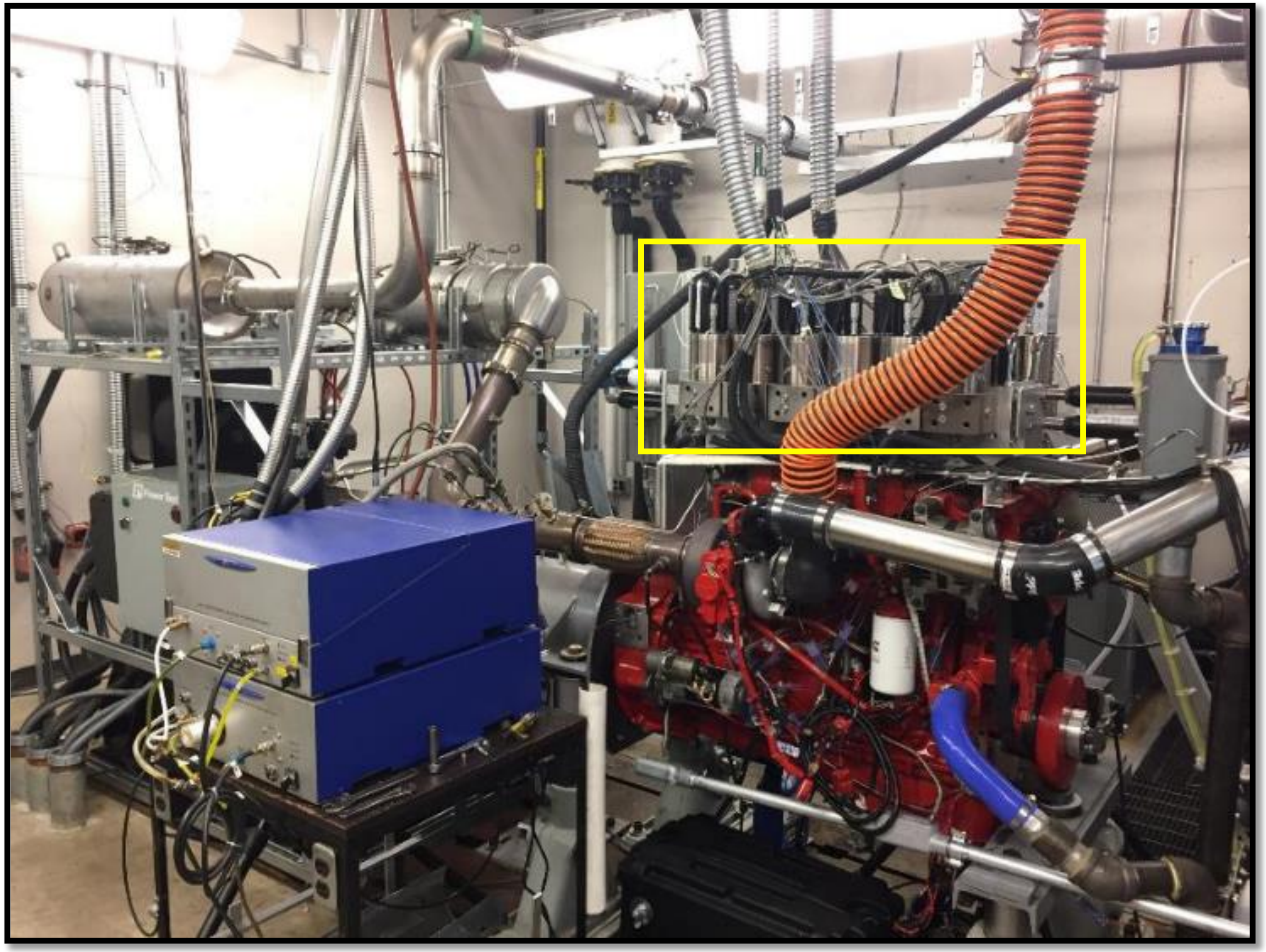
Aftertreatment system

DOC-DPF-SCR

Measurements

Emissions, temperatures, pressures, flow rates etc.

Experimental Setup
Cummins Power Lab – Test Cell 1



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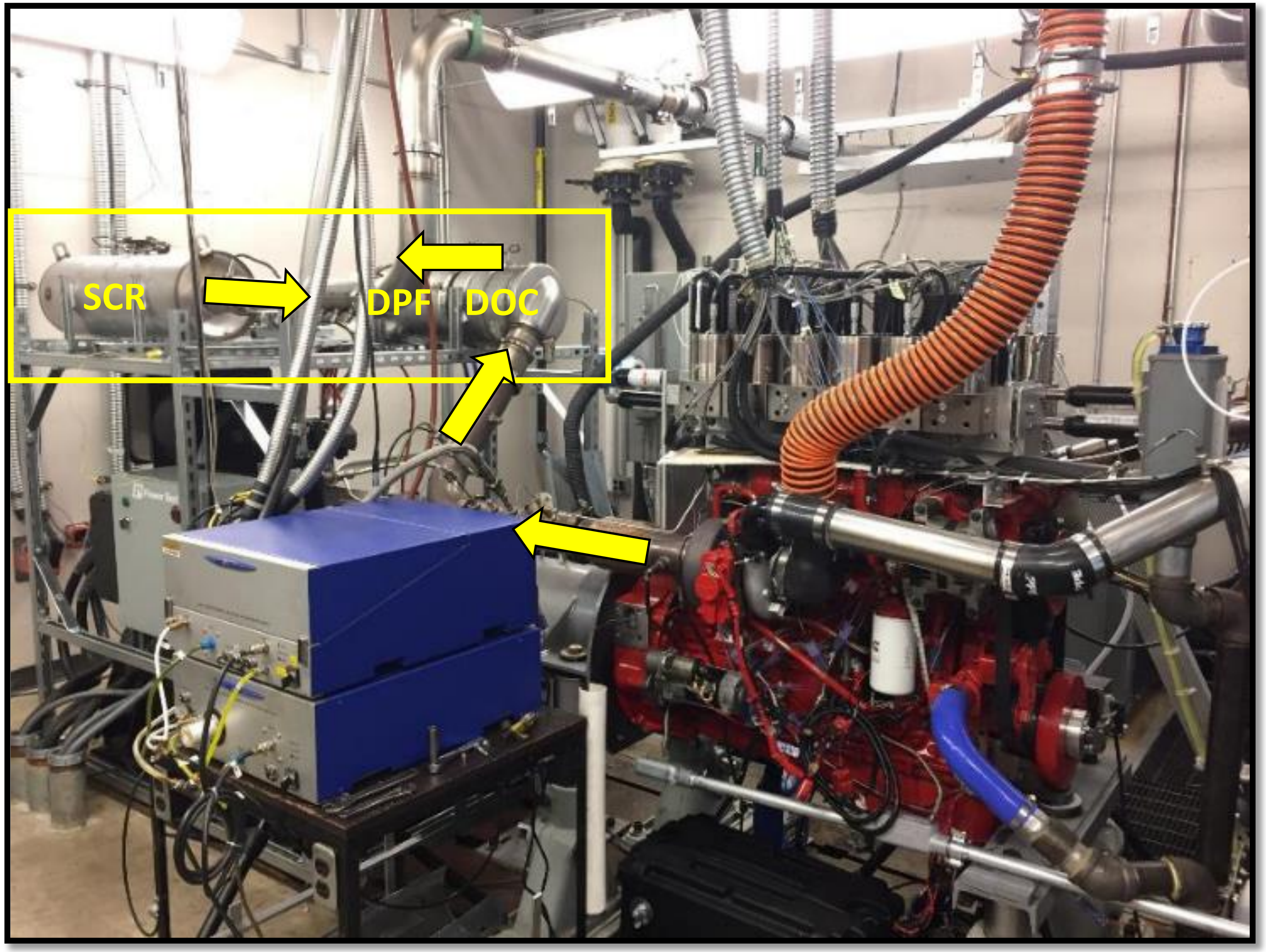

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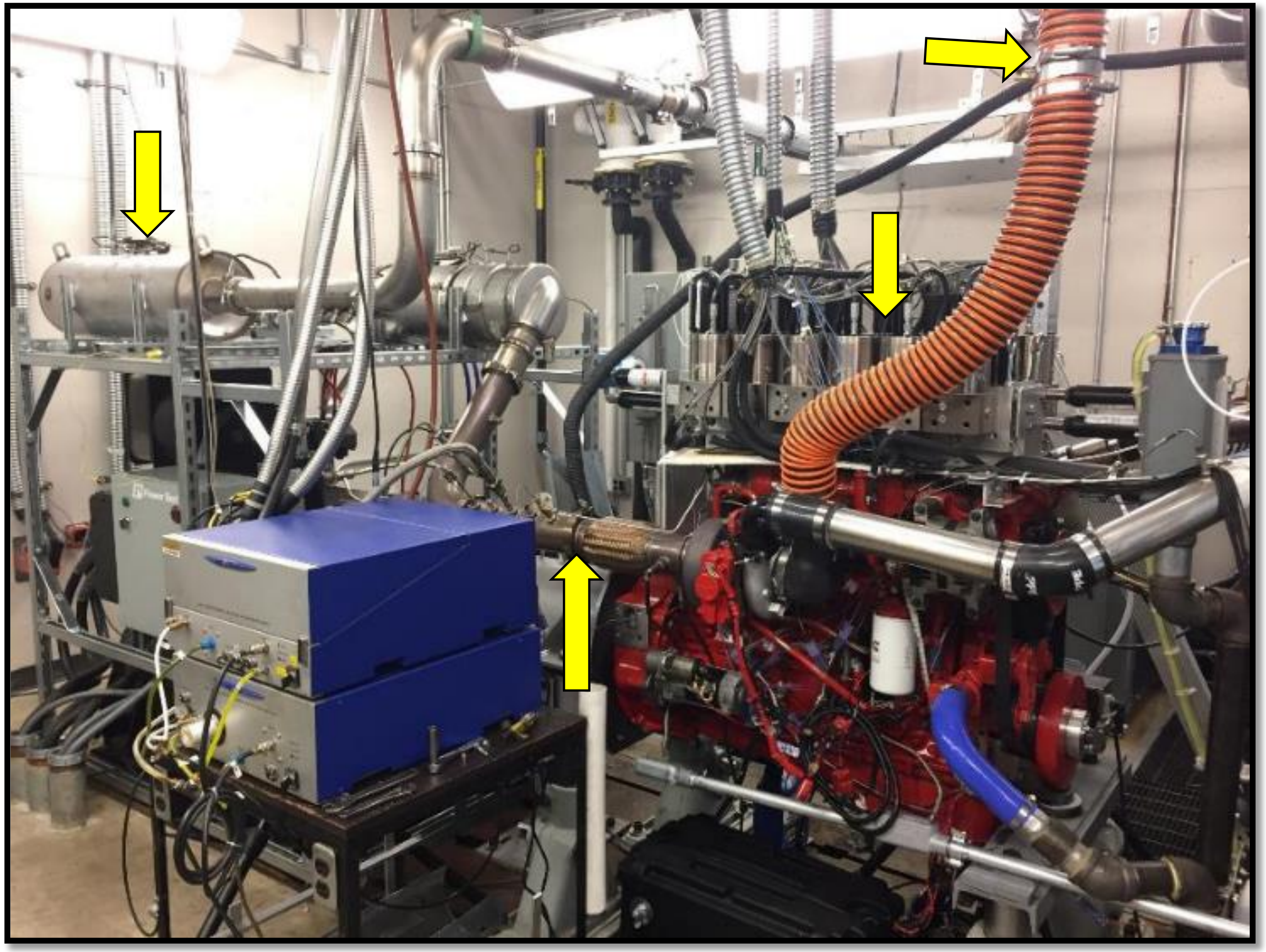

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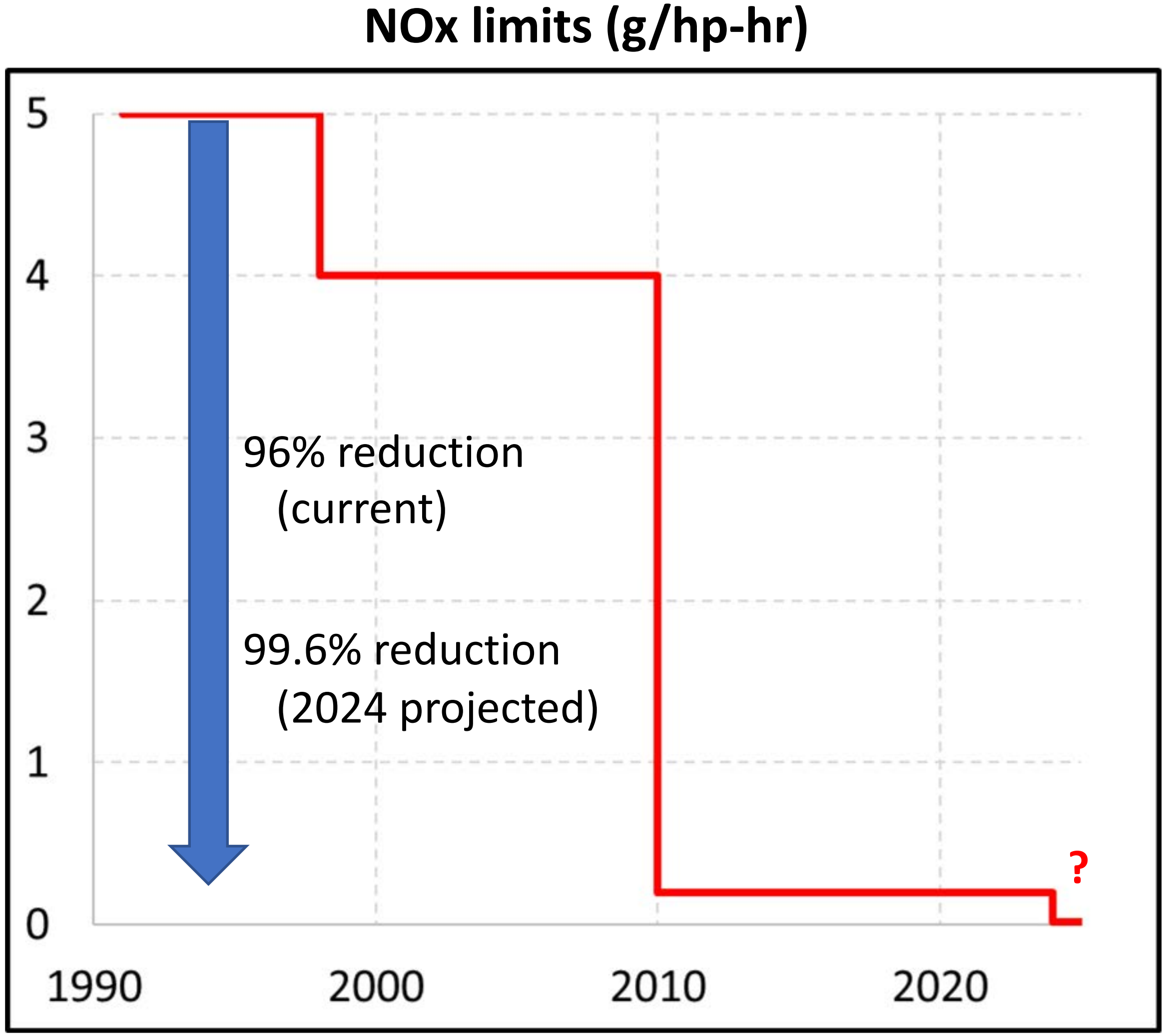
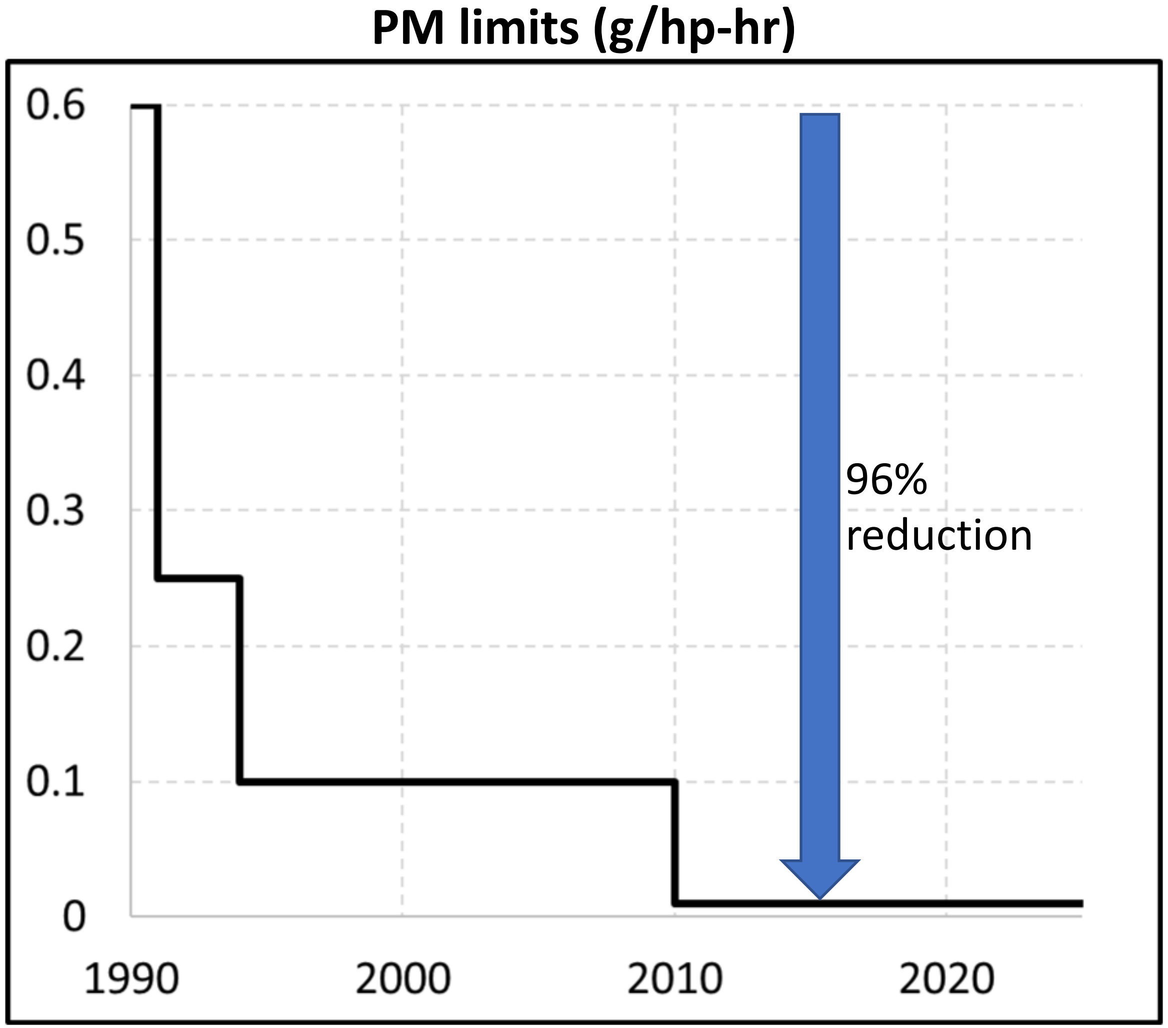
Measurements

Emissions, temperatures, pressures, flow rates etc.

Vehicular NOx and PM emissions are constrained by increasing stringent regulations (U.S. example here)





‘Heavy-Duty Highway Compression-Ignition Engines and Urban Buses: Exhaust Emission Standards’, United States Environmental Protection Agency

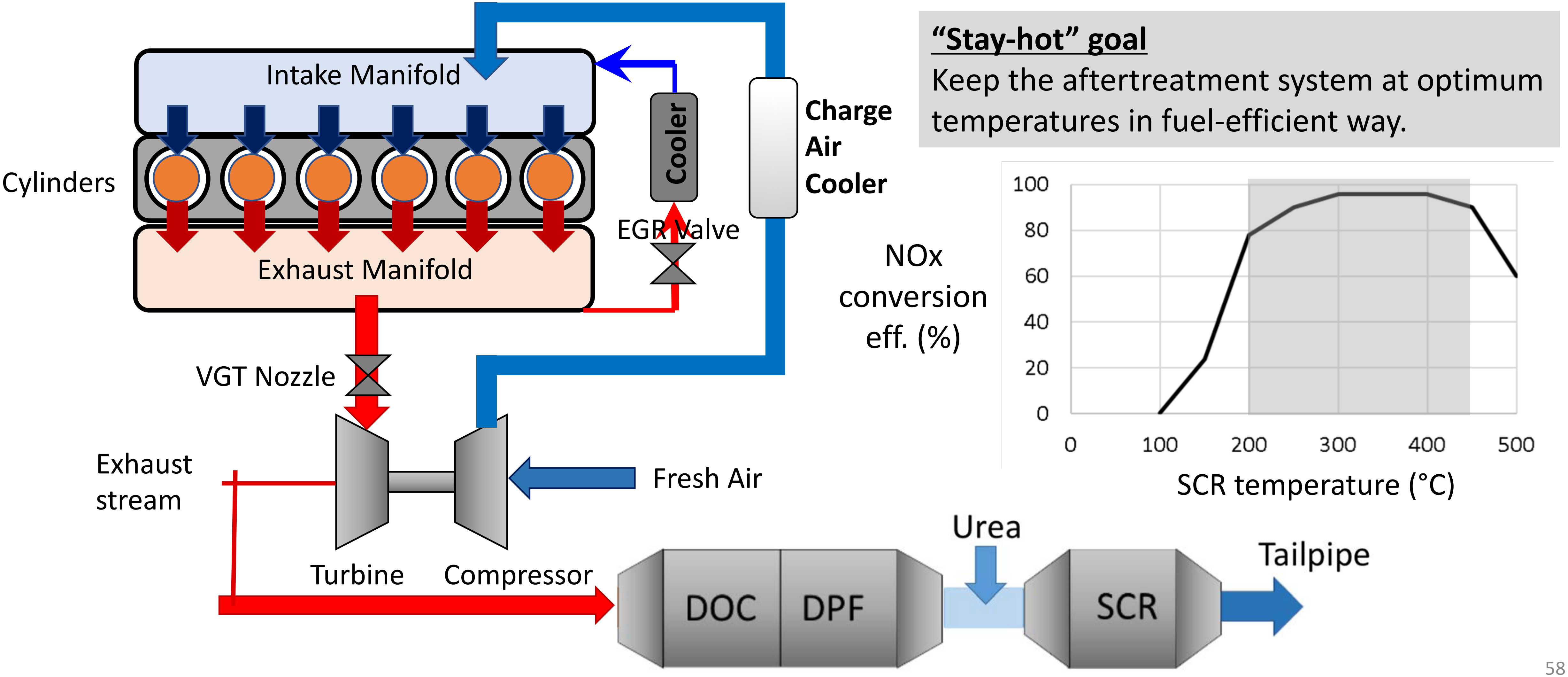
Modern Diesel engine systems incorporate complex engine/aftertreatment coupling

"Get-hot" goal

Get the aftertreatment system up to optimum temperatures as fast as possible

"Stay-hot" goal

Keep the aftertreatment system at optimum temperatures in fuel-efficient way.



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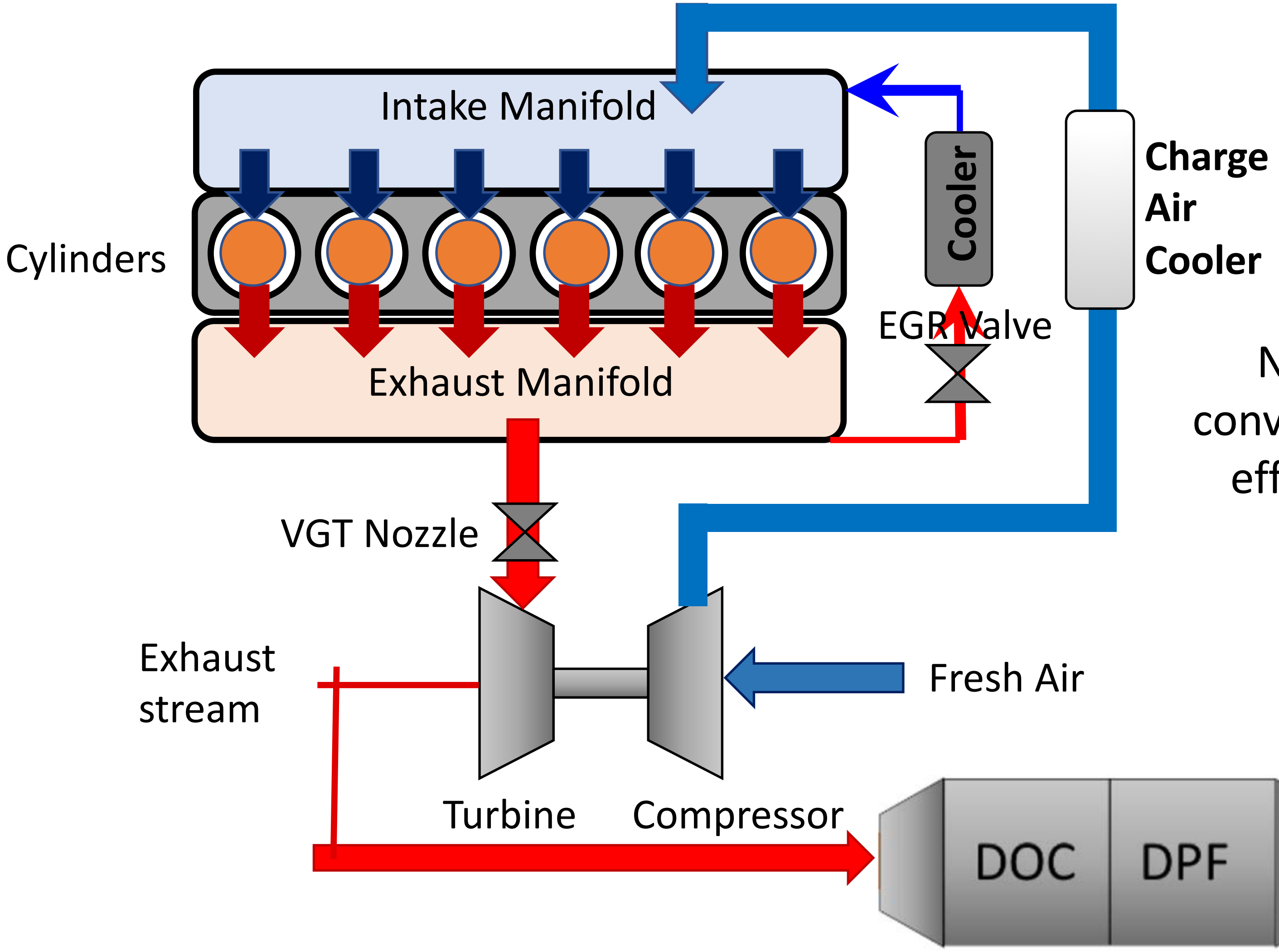
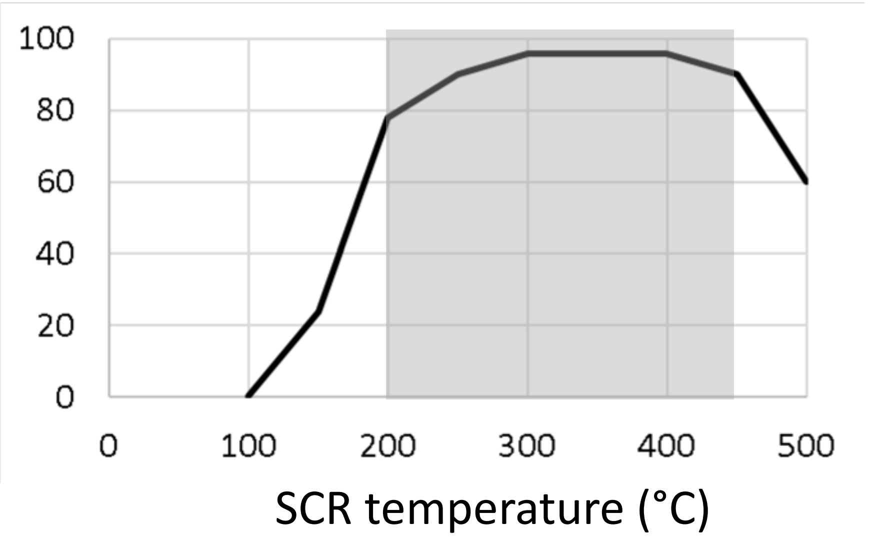


"Get-hot" goal
Get the aftertreatment system up to optimum temperatures as fast as possible

Desired:

- Elevated engine-out temperatures
- Elevated exhaust flow



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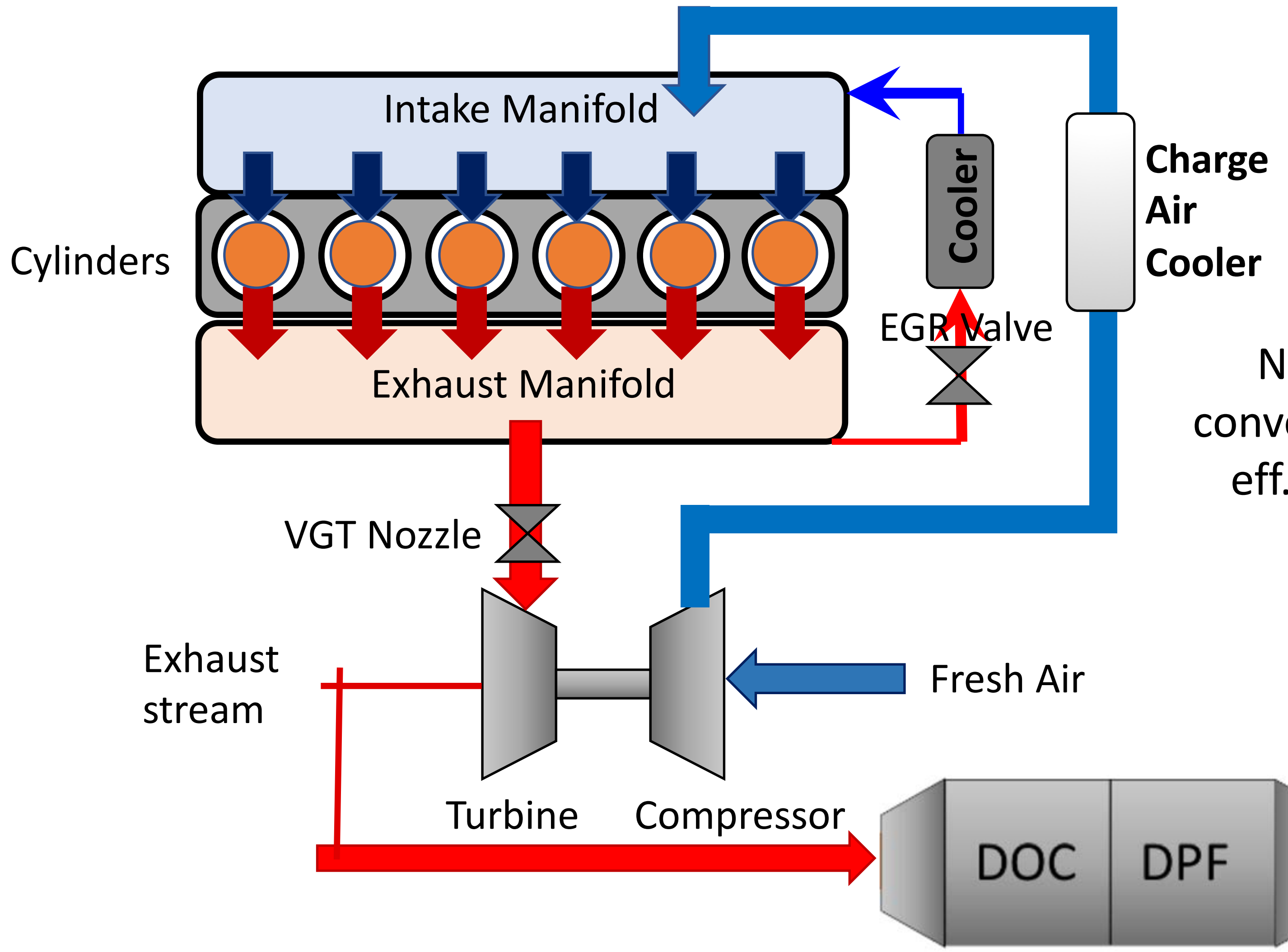
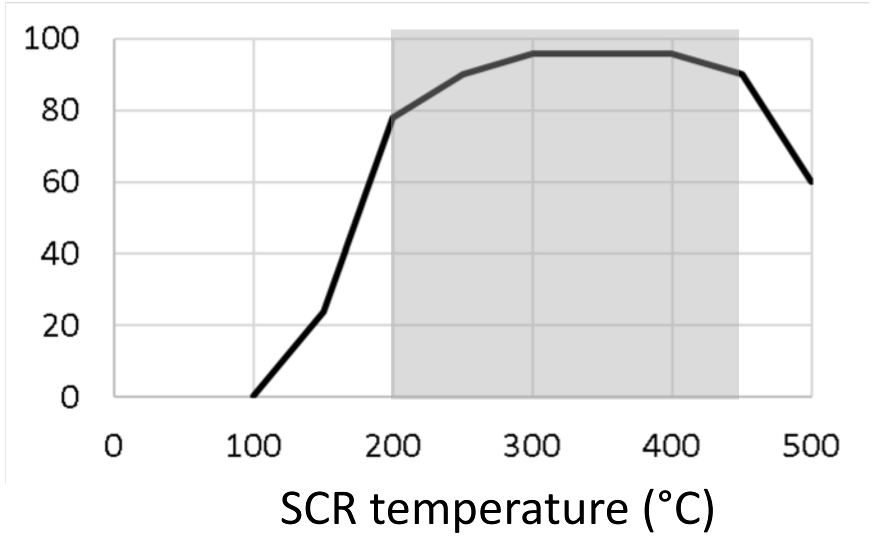


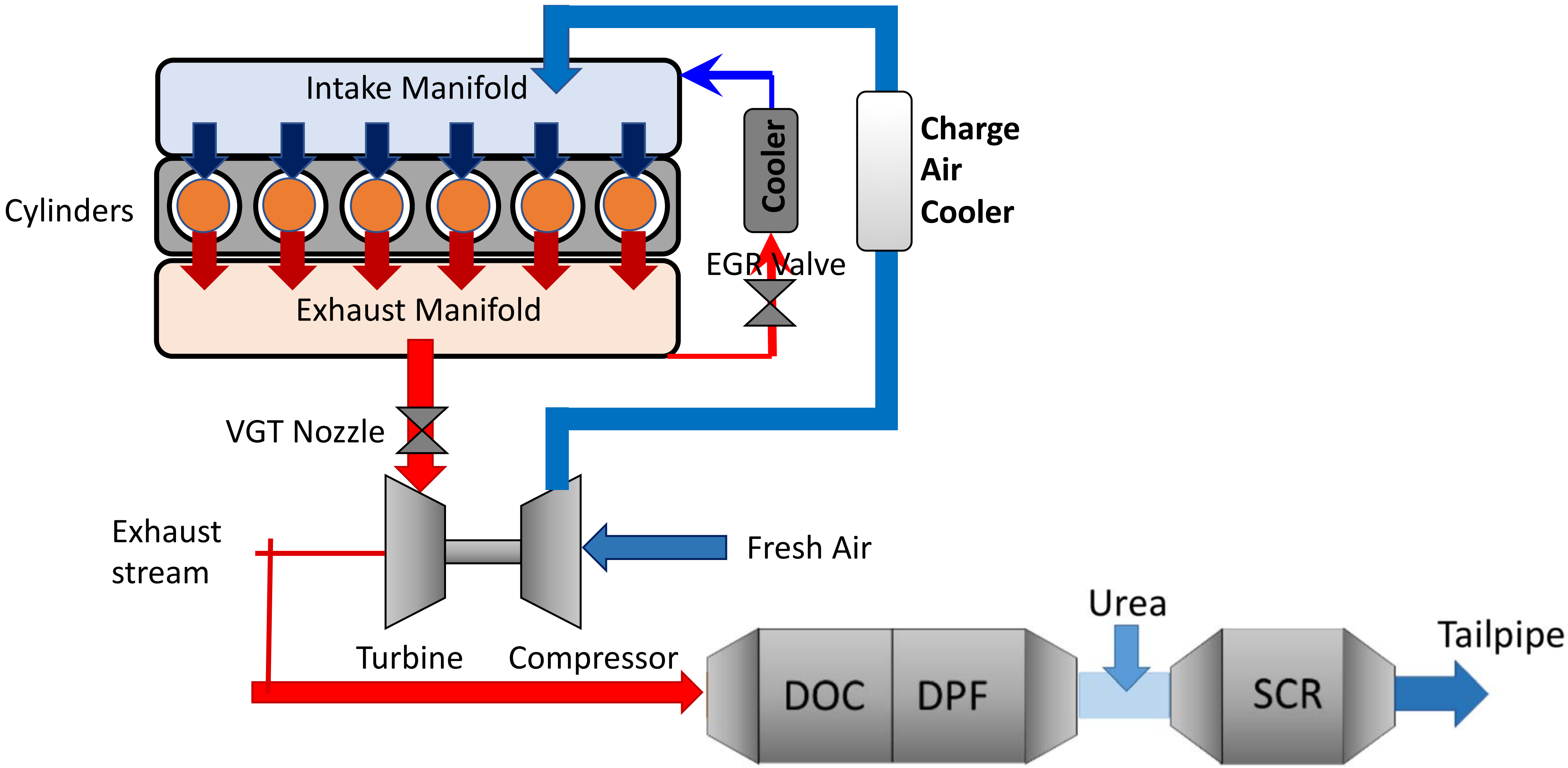
Desired:

- Elevated engine-out temperatures
- Higher engine efficiency

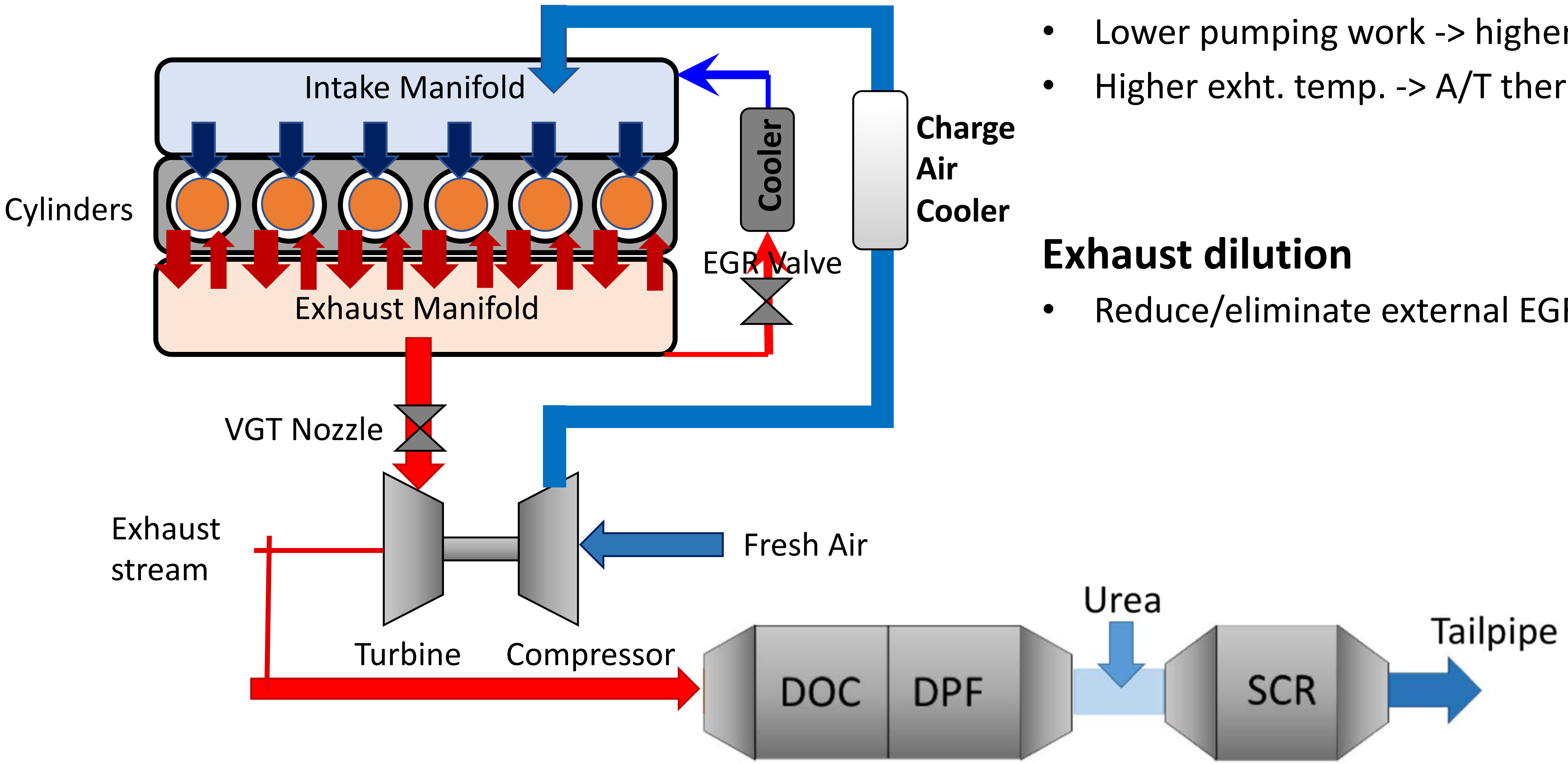
"Stay-hot" goal
Keep the aftertreatment system at optimum temperatures in fuel-efficient way.



Gas exchange & combustion - conventional



Gas exchange & combustion – exhaust reinduction



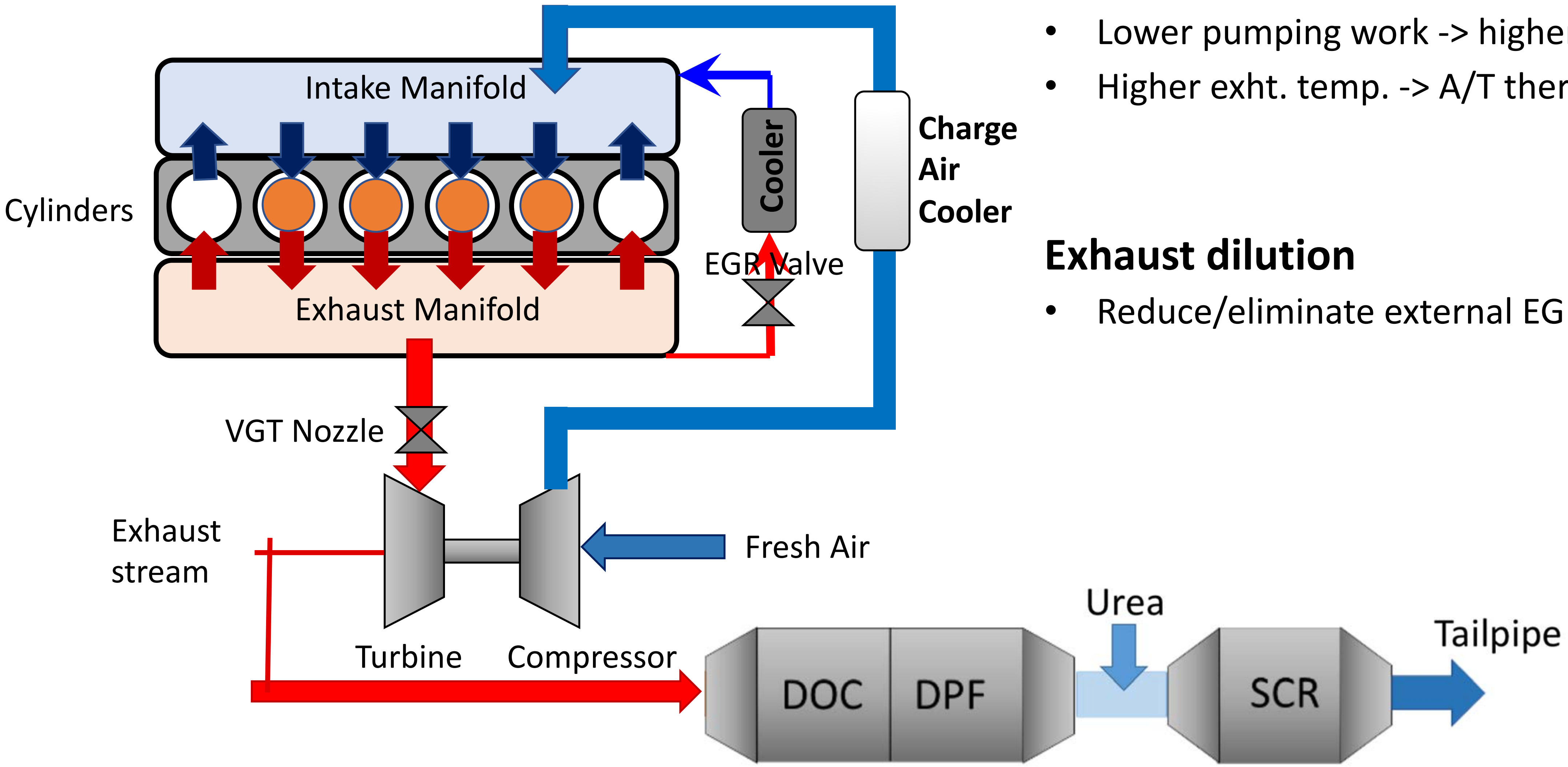
Reduce airflow

- Lower pumping work -> higher efficiency
- Higher exht. temp. -> A/T thermal control

Exhaust dilution

- Reduce/eliminate external EGR

Gas exchange & combustion – "non-fired reverse breathing"



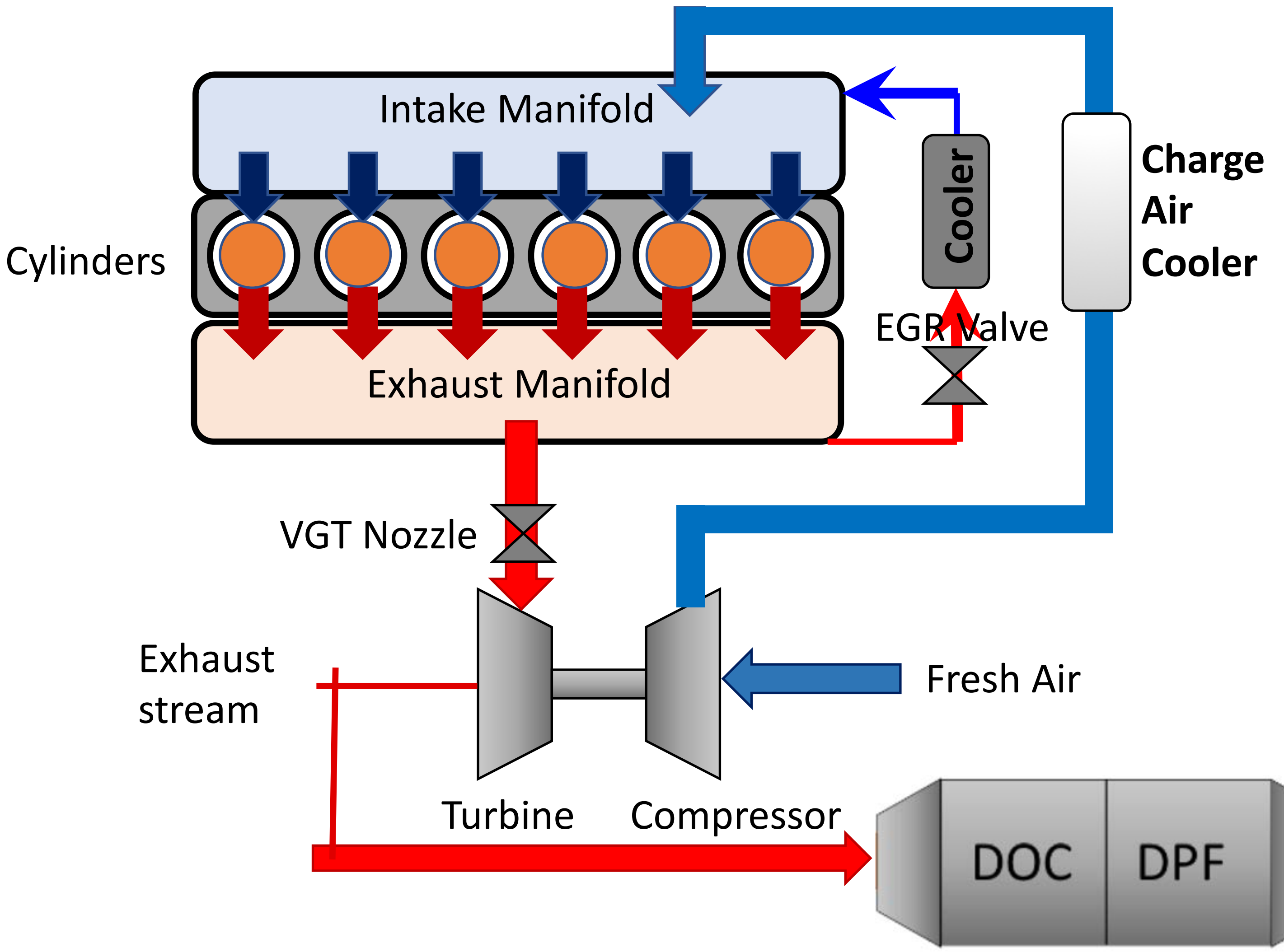
Reduce airflow

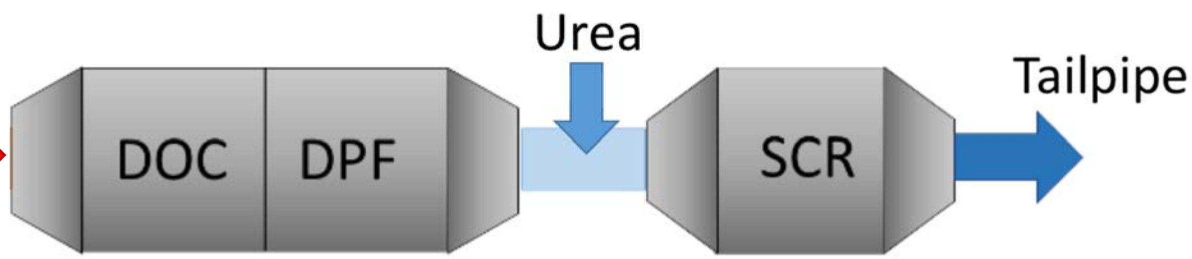
- Lower pumping work -> higher efficiency
- Higher exht. temp. -> A/T thermal control

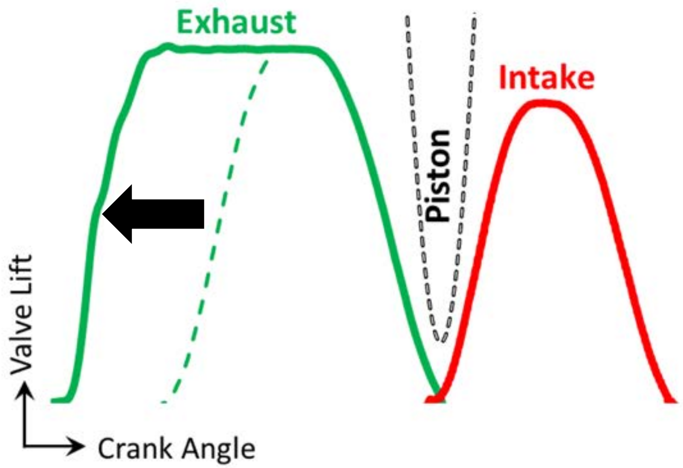
Exhaust dilution

- Reduce/eliminate external EGR

Gas exchange & combustion – early exht vlv opening (EEVO)





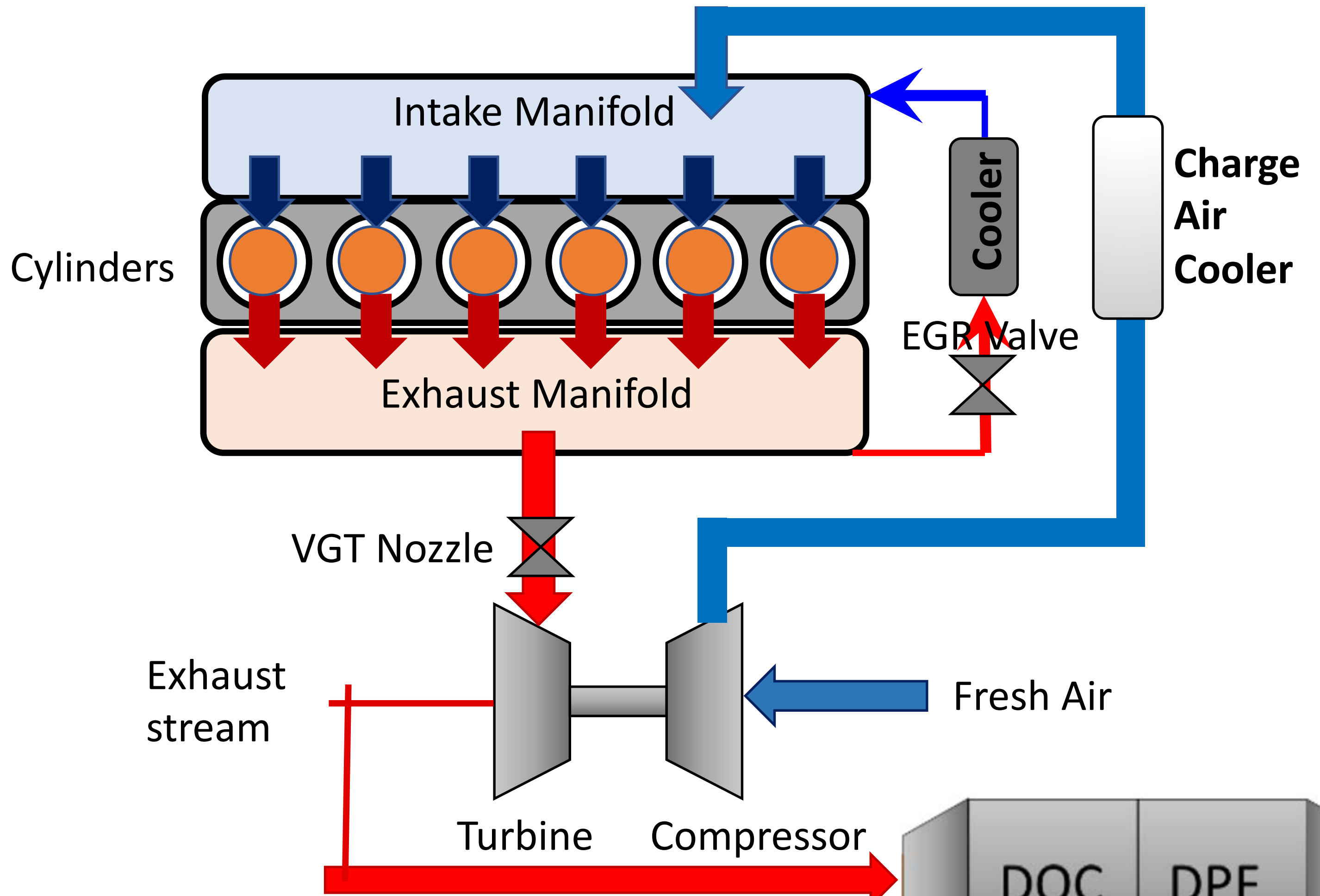


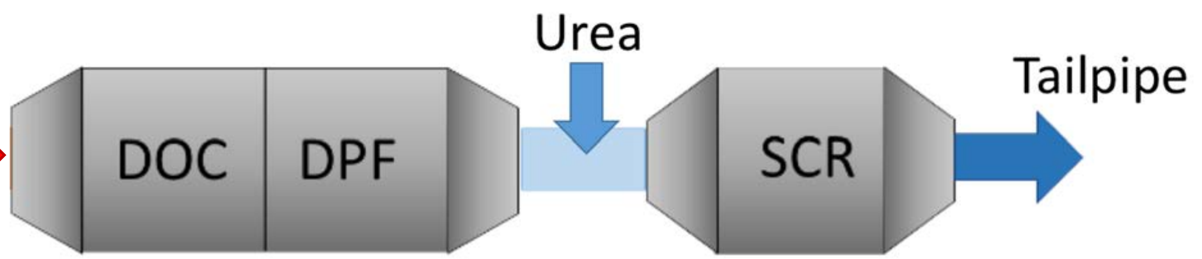
Early Exhaust Valve Opening

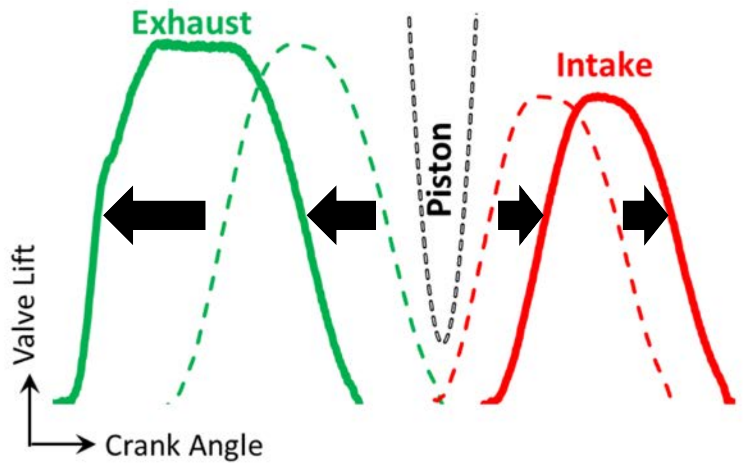
Early blowdown

- Higher exht. temp. -> A/T thermal control

Gas exchange & combustion – EEVO + exhaust gas trapping





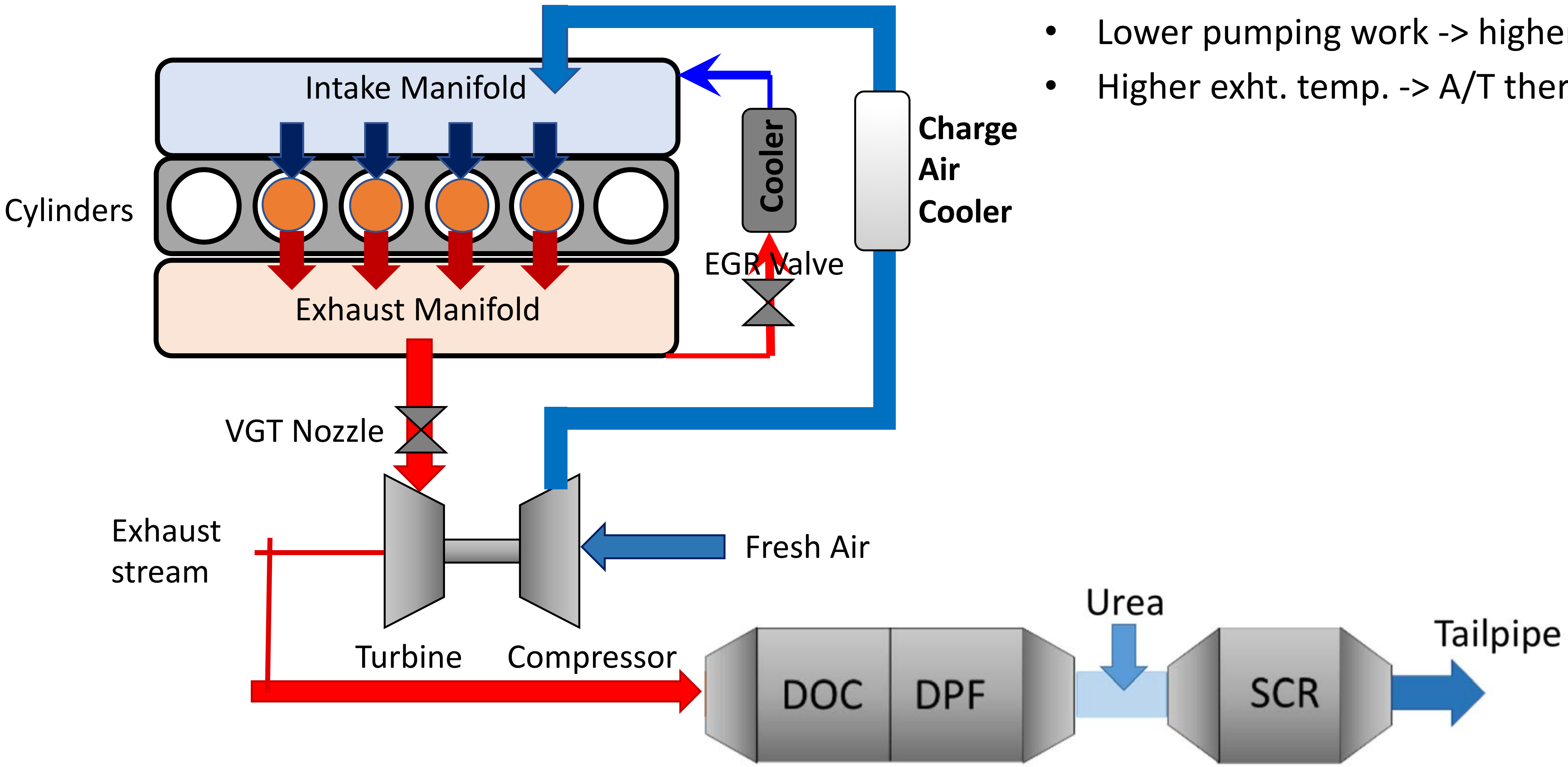


Early Exhaust Valve Opening
with Internal EGR

Early blowdown & no EGR cooling

- Higher exht. temp. -> A/T thermal control

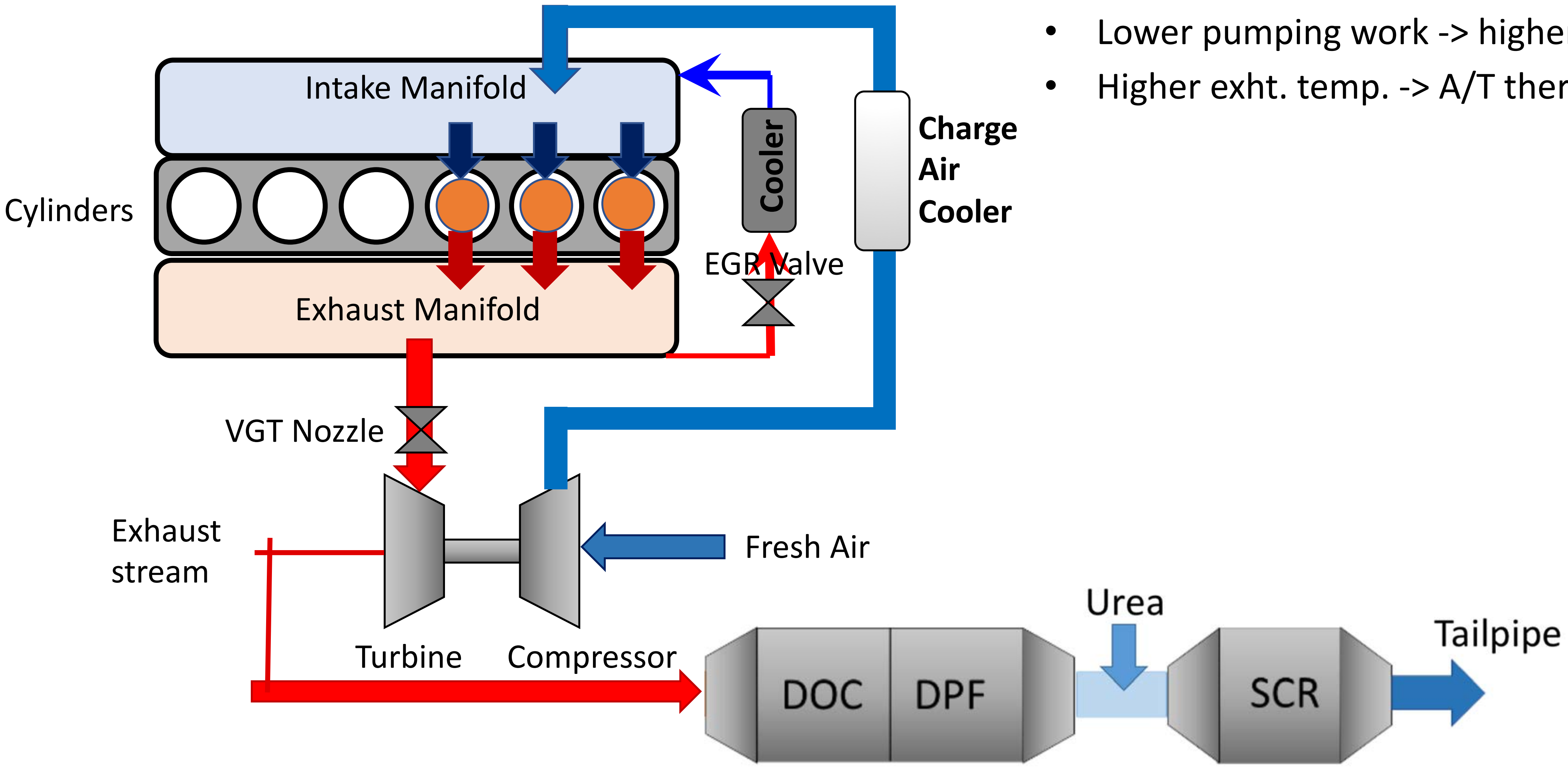
Gas exchange & combustion – cylinder deactivation



Reduce airflow

- Lower pumping work -> higher efficiency
- Higher exht. temp. -> A/T thermal control

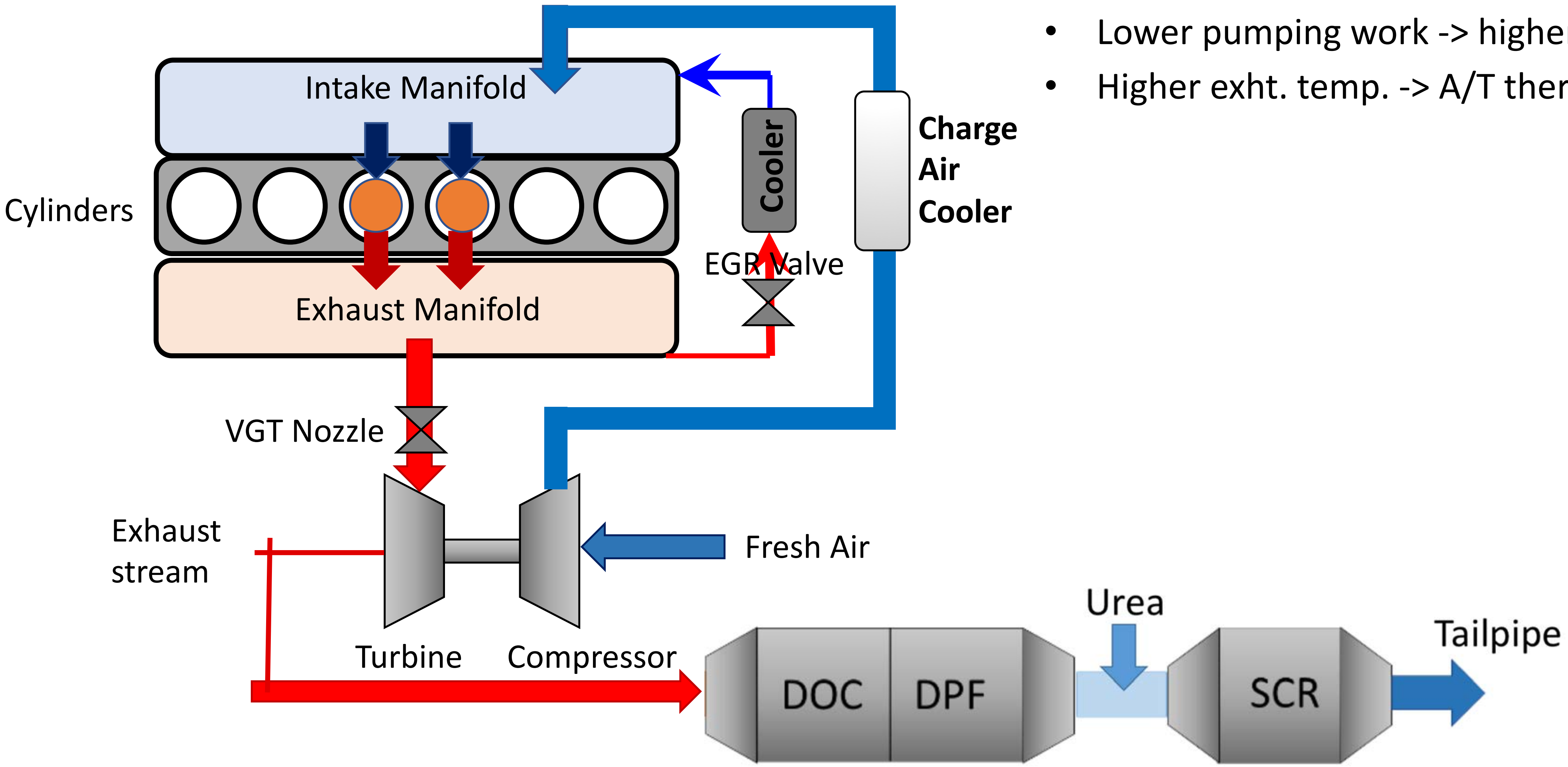
Gas exchange & combustion – cylinder deactivation



Reduce airflow

- Lower pumping work -> higher efficiency
- Higher exht. temp. -> A/T thermal control

Gas exchange & combustion – cylinder deactivation



Reduce airflow

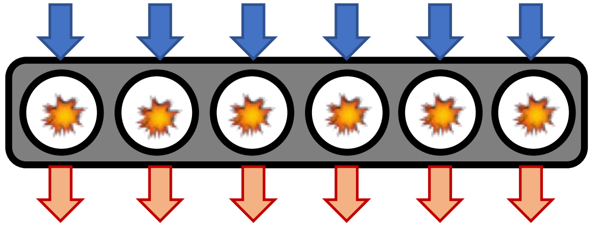
- Lower pumping work -> higher efficiency
- Higher exht. temp. -> A/T thermal control

Challenges (& opportunities) for combustion (& gas exchange) control w/ VVA

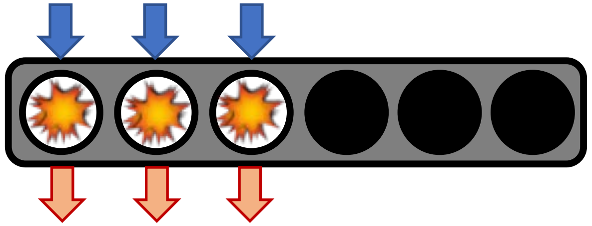
- Not every cylinder has to be doing the same thing
- Combustion modes & gas exchange strategies could (should) change depending on thermal state of the aftertreatment system.
- Higher EGR dilution possible
- External EGR might not be necessary
- Variable geometry turbocharging may not be necessary
- Effective compression ratios and volumetric efficiency modulation
- Higher engine-out NOx possible w/ improved aftertreatment thermal control
- More gas exchange levers -> more flexibility -> model-based controls/estimation/OBD even more important
- More options for in-cylinder charge motion control
- More difficult to know the in-cylinder dilution for non-external EGR strategies
- And more….

Cylinder Deactivation

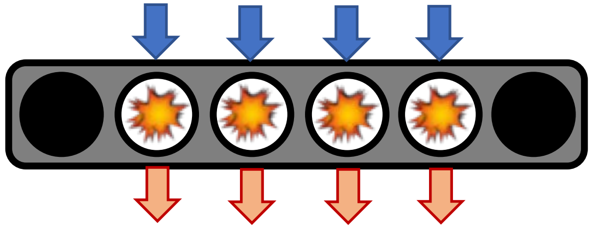
Conventional six-cylinder operation



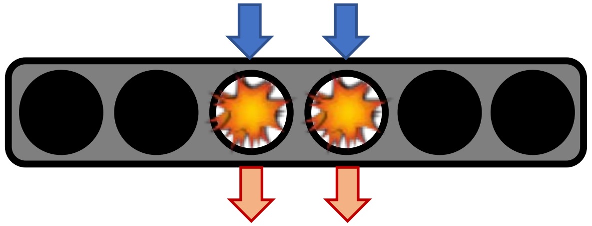
Fixed CDA – 3 cylinders firing (3 CF)



Fixed CDA – 4 cylinders firing (4 CF)



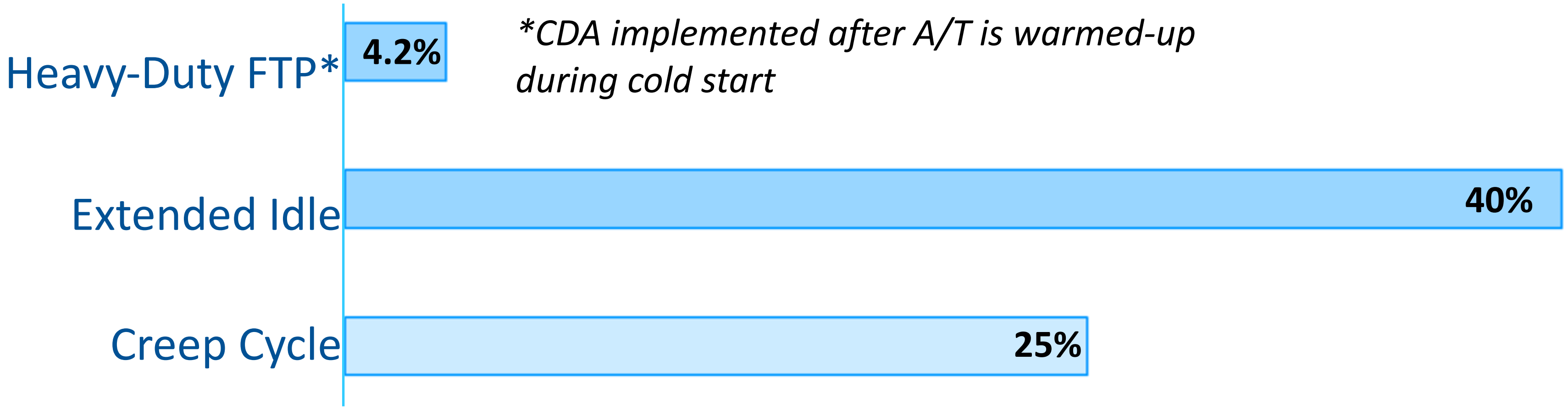
Fixed CDA – 2 cylinders firing (2 CF)



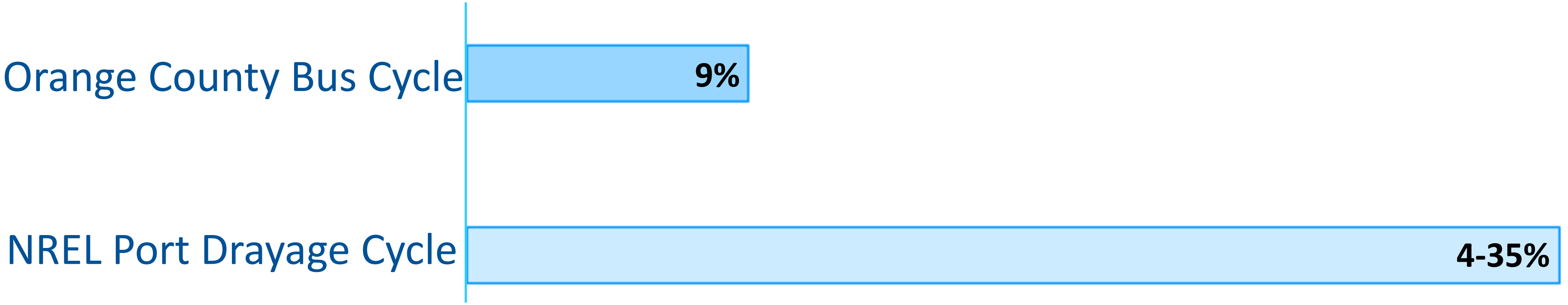
- Both valve actuation and fuel injection are disabled
- Fuel injected in the active cylinders is increased to meet torque/power
- Fixed set of cylinders are deactivated every engine cycle

3CF CDA implemented up to 1.3 bar BMEP over engine and vehicle drive cycles

Engine drive cycles – Experimentally demonstrated

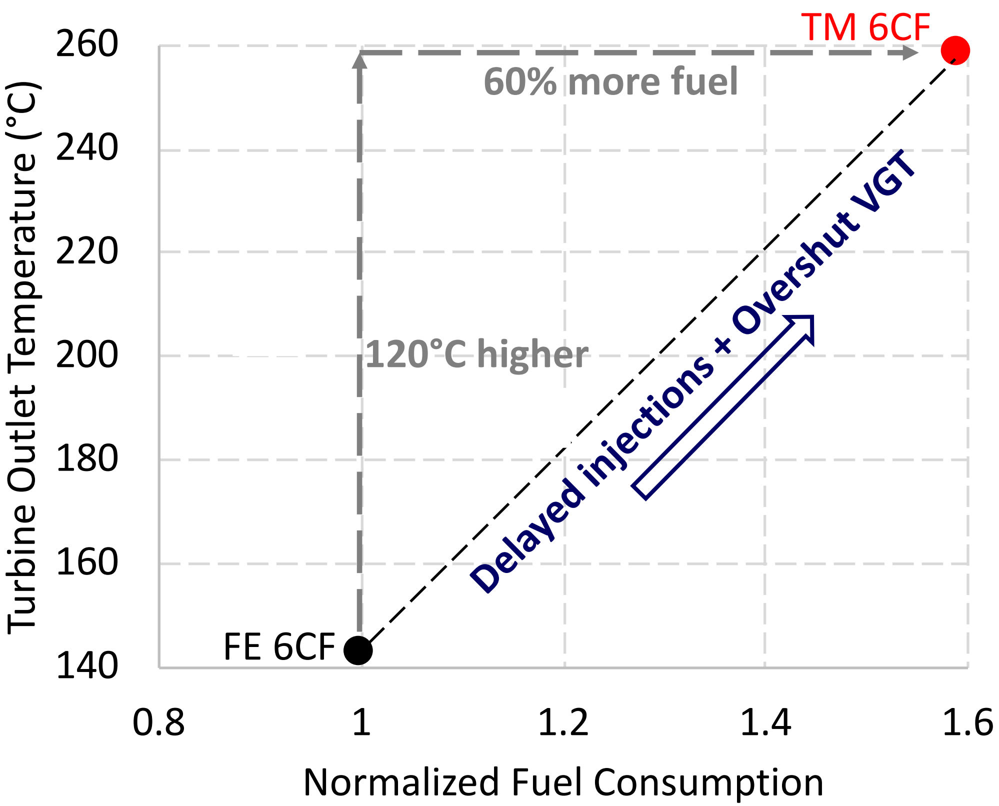


Vehicle drive cycles – Predicted

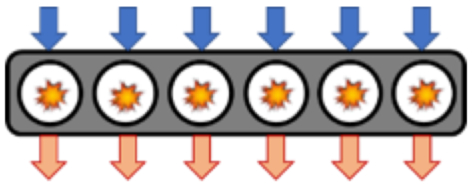


Fixed CDA (3 CF) shows 4.2% – 40% fuel savings, while maintaining elevated A/T temperatures, when implemented below 3 bar BMEP

Cylinder Deactivation – 800 rpm, 1.3 bar (curb idle)



6 cylinder operation (6CF)

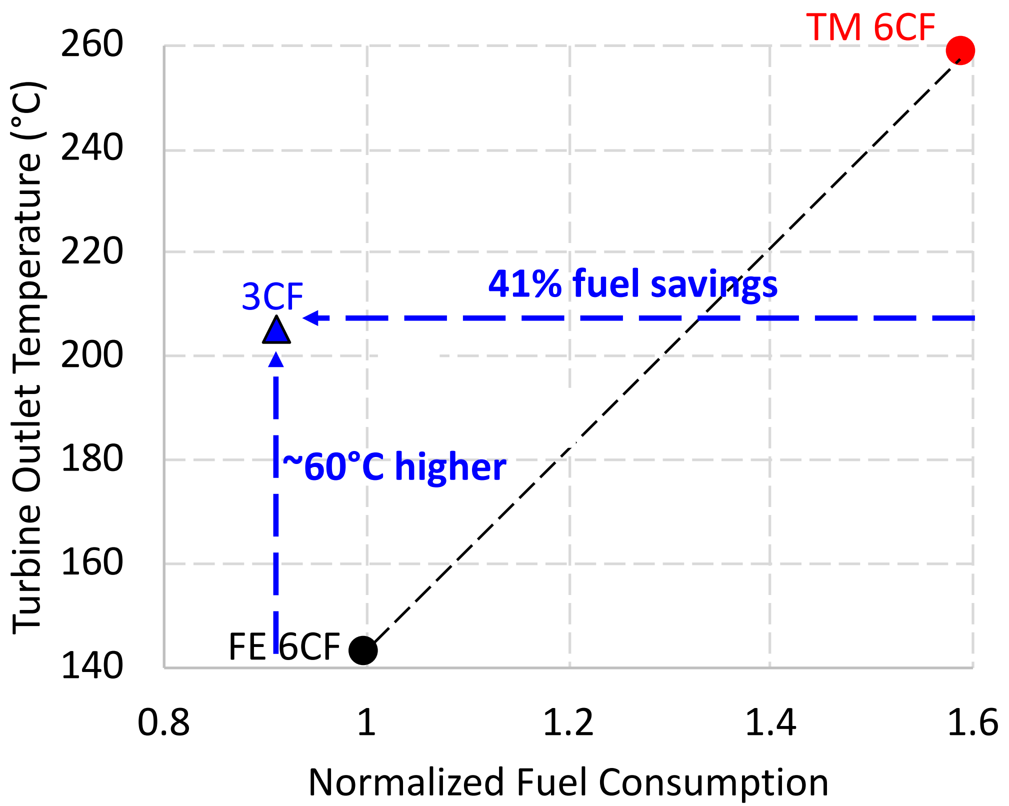


TM – conventional thermal management mode

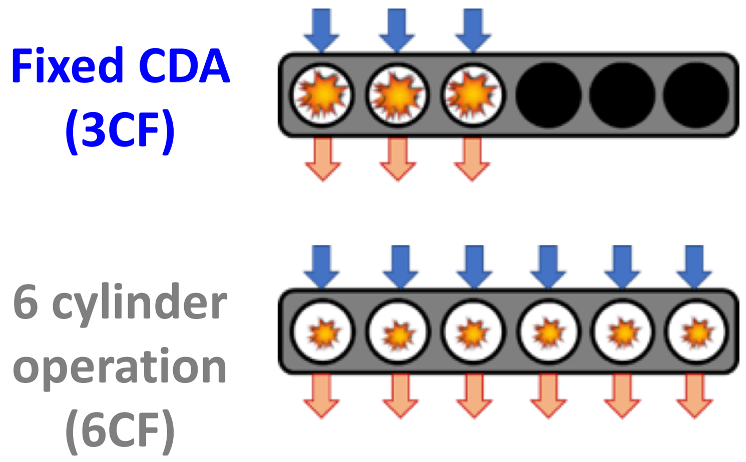
FE – conventional fuel efficient mode

(Experimental results)

Cylinder Deactivation – 800 rpm, 1.3 bar (curb idle)

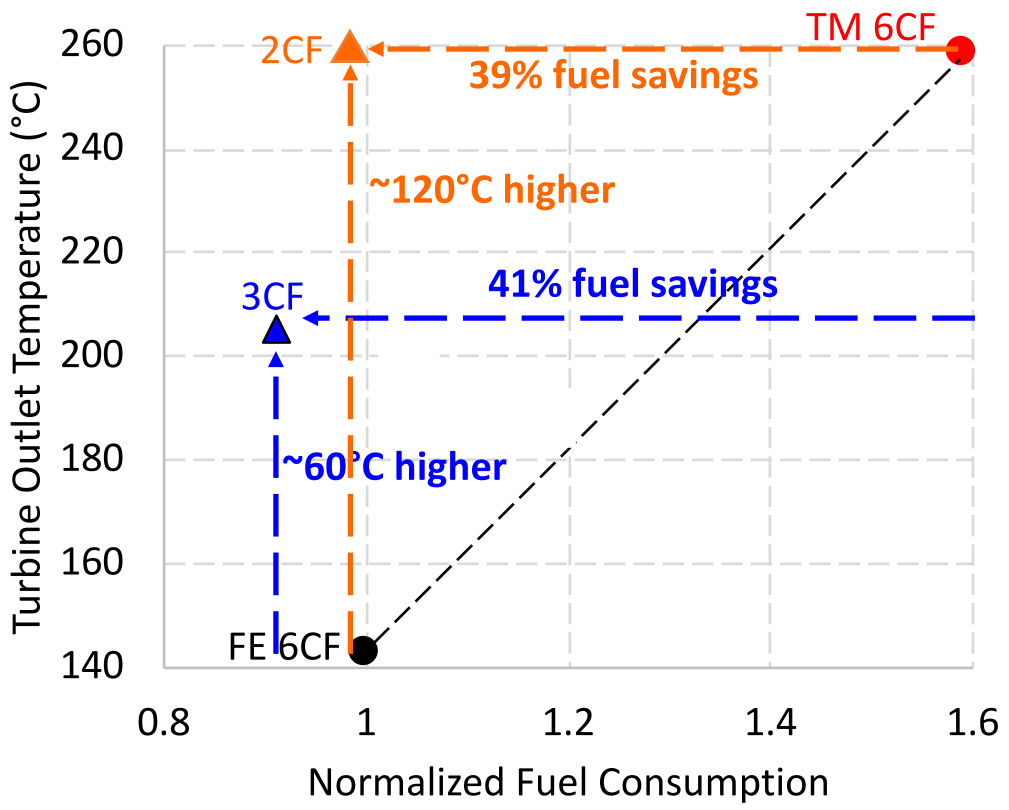


CDA achieves elevated engine-out temperatures at lower fuel consumption

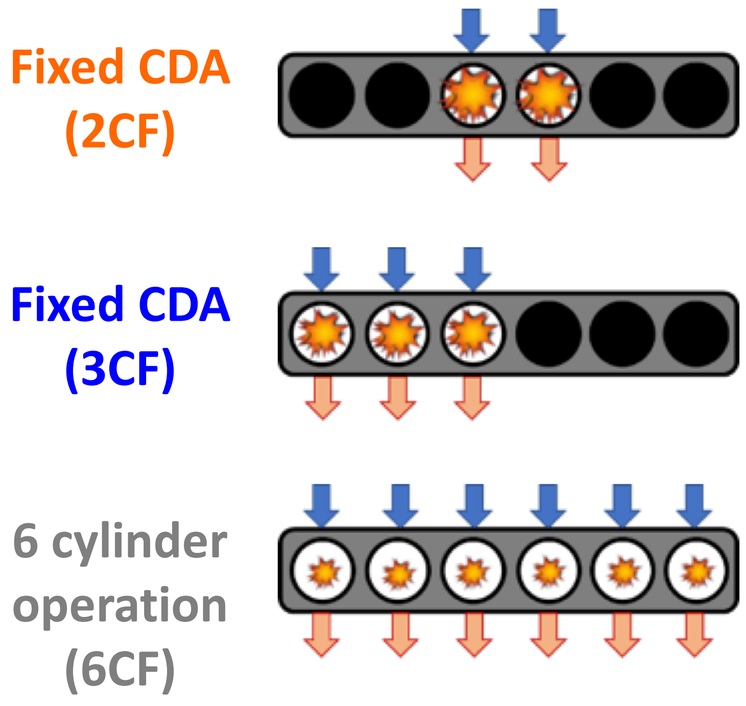


(Experimental results)

Cylinder Deactivation – 800 rpm, 1.3 bar (curb idle)

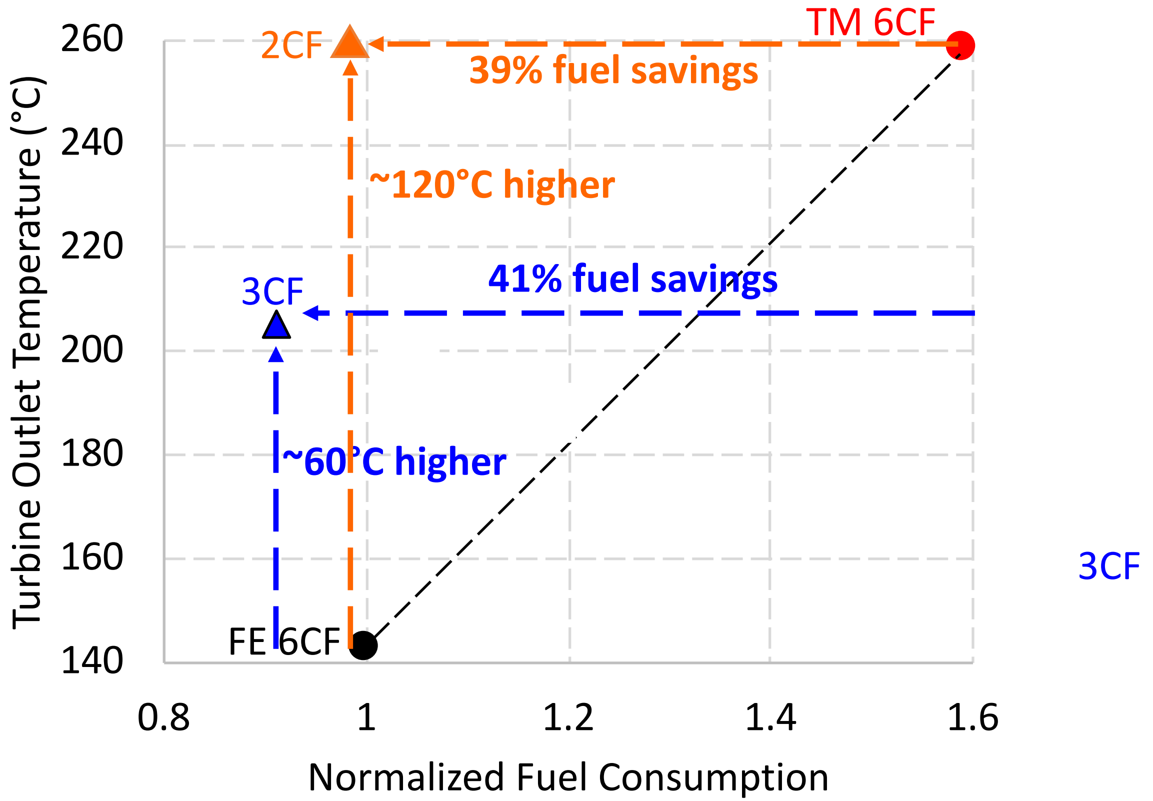


CDA achieves elevated engine-out temperatures at lower fuel consumption

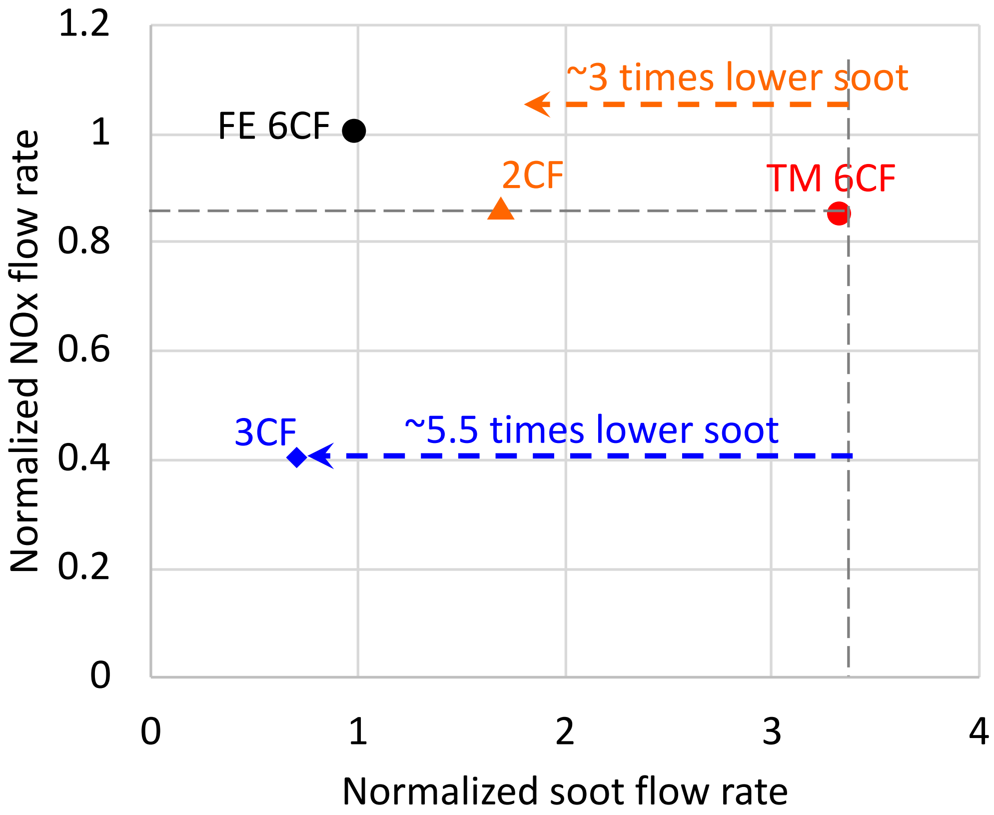


(Experimental results)

Cylinder Deactivation – 800 rpm, 1.3 bar (curb idle)

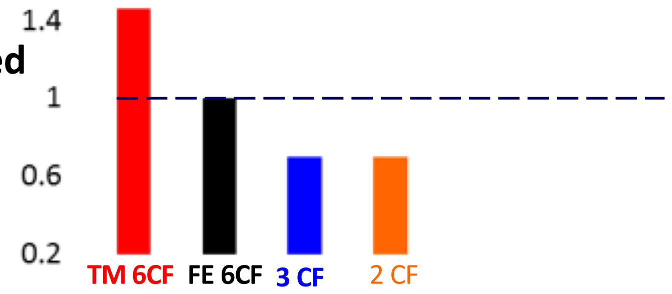


CDA achieves elevated engine-out temperatures at lower fuel consumption

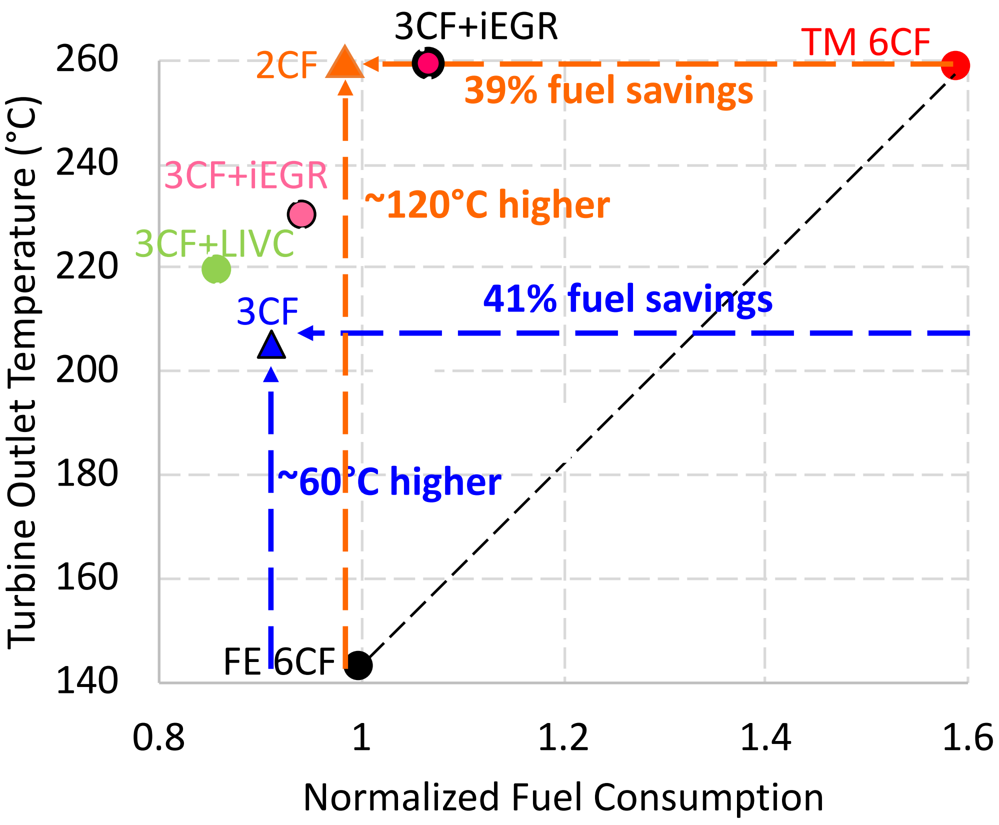


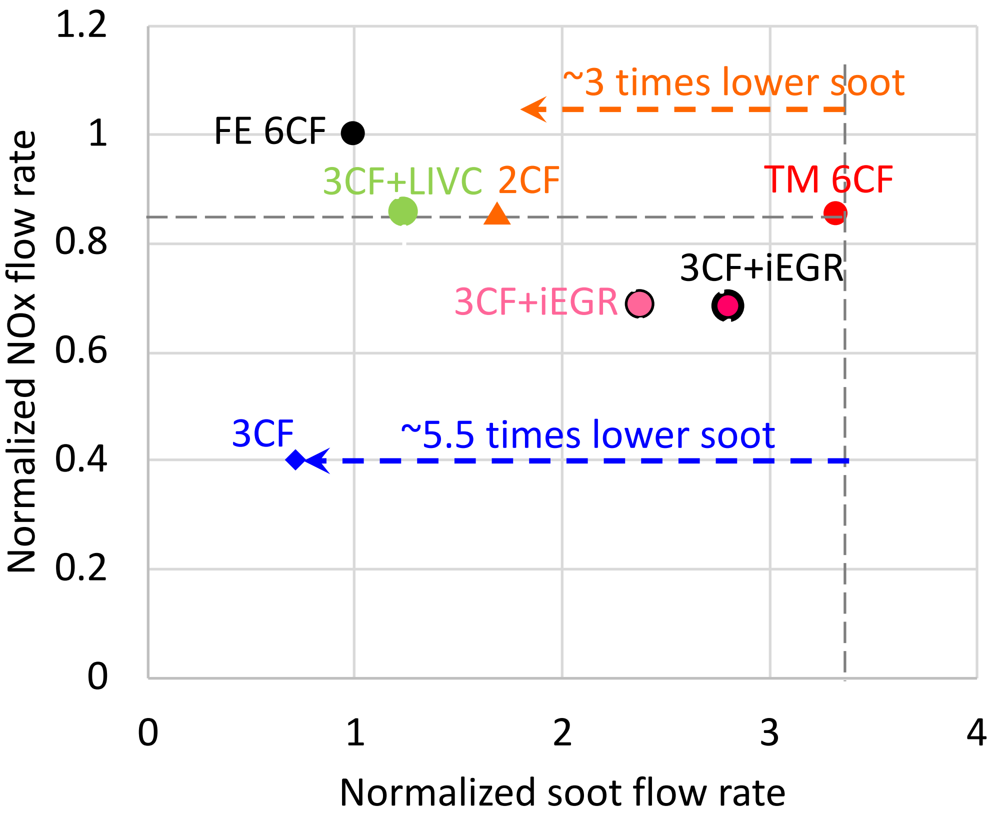
CDA shows lower engine-out NOx and soot emissions than conventional 6-cylinder thermal management operation

Normalized exhaust flow rates



Cylinder Deactivation – CDA+LIVC and CDA+iEGR at 800 rpm, 1.3 bar (curb idle)





- CDA+LIVC : Higher TOT, lower fuel consumption than 3CF
- CDA+iEGR : Enables improved TOT vs FC tradeoff

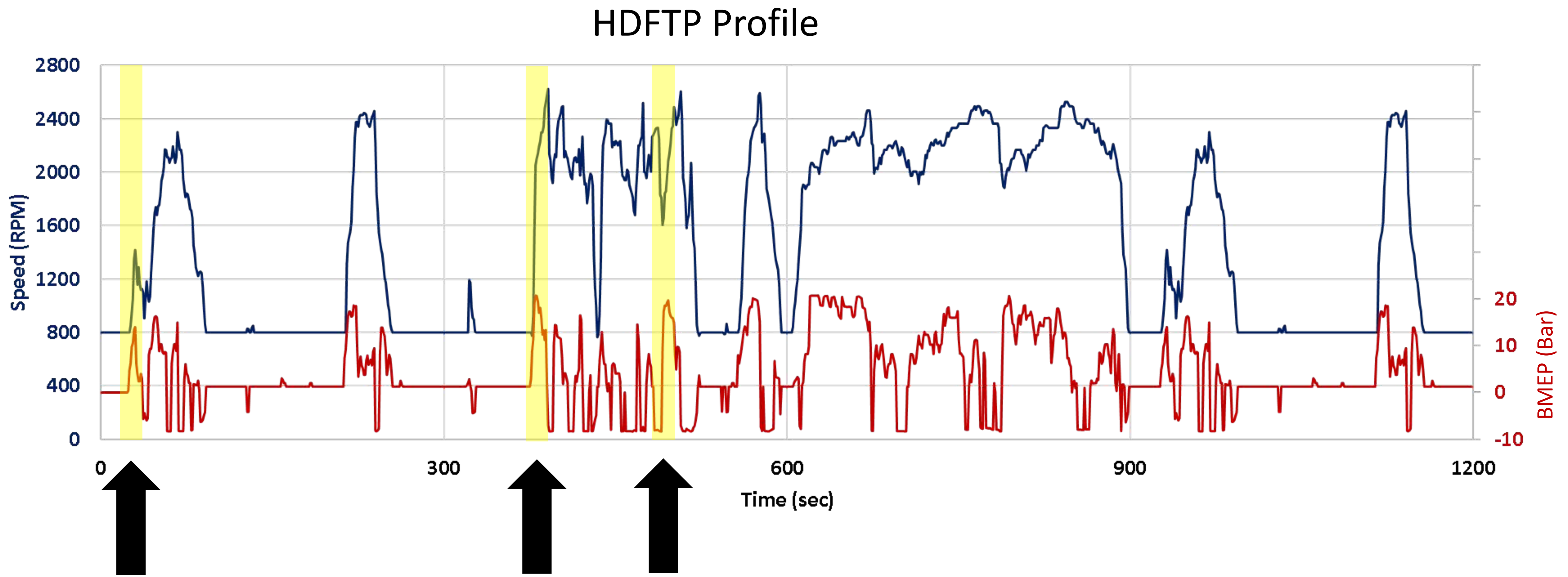
- CDA+LIVC
- CDA+iEGR

} Within desired emission constraints

(Experimental results)

Load Response Challenges for CDA?

Transient response with CDA – load increase



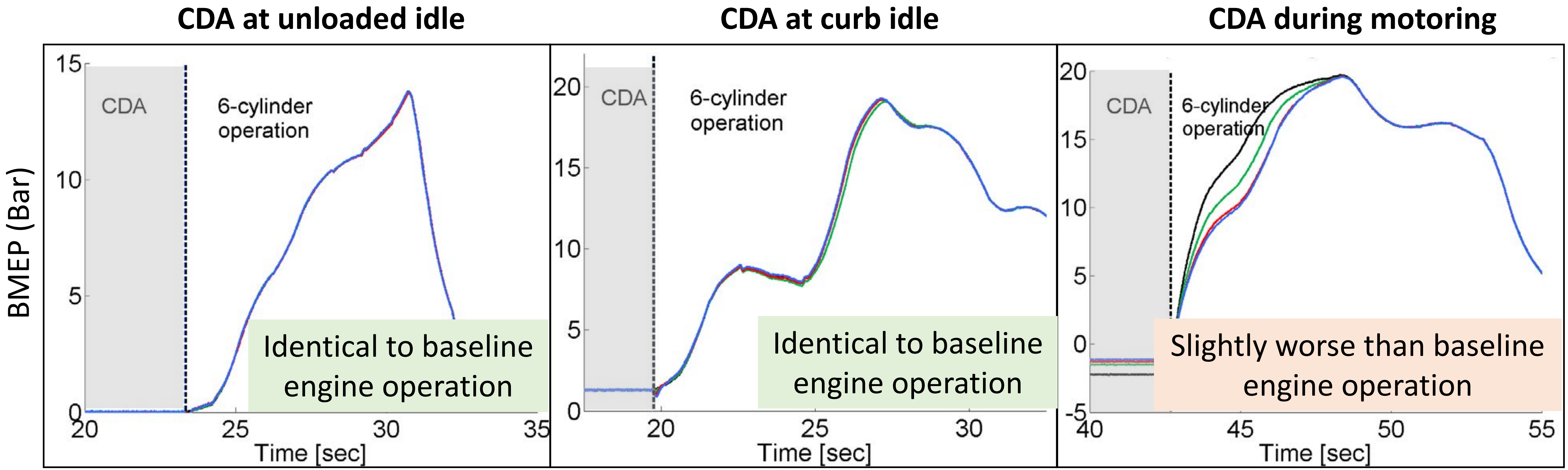
Unloaded idle initial condition

Curb idle initial condition

Motoring initial condition

Transient response evaluated with stock engine calibration, which is not optimized for CDA

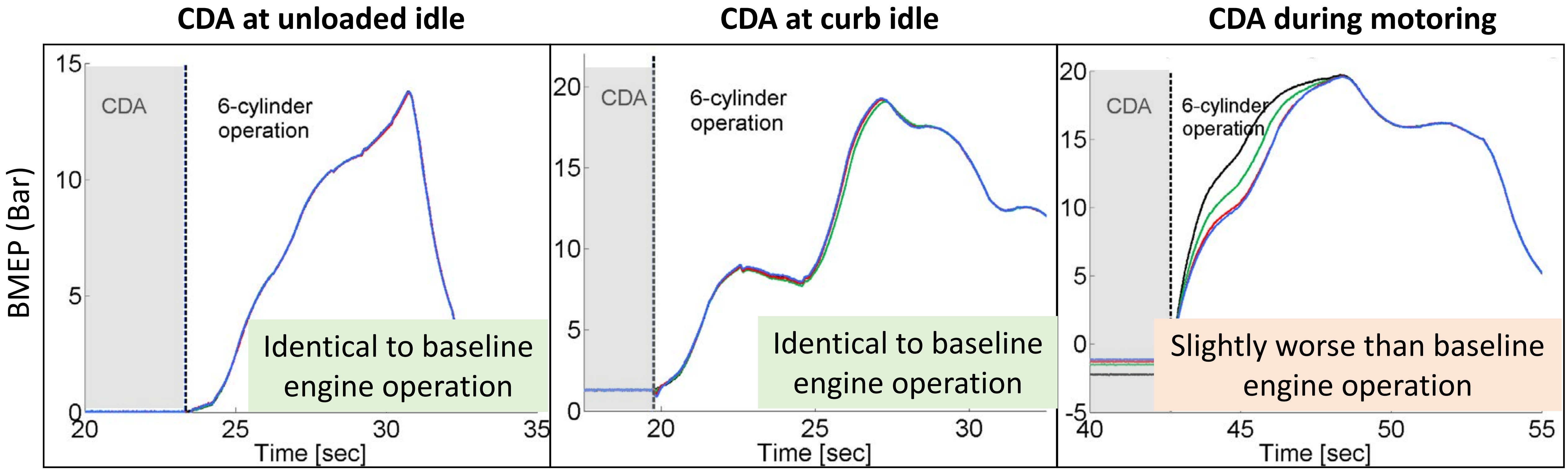
Transient response with CDA – load increase



6 cyl active ; 4 cyl active → 6 cyl active; 3 cyl active → 6 cyl active; 2 cyl active → 6 cyl active

Transient response evaluated with stock engine calibration, which is not optimized for CDA

Transient response with CDA – load increase



6 cyl active ; 4 cyl active → 6 cyl active; 3 cyl active → 6 cyl active; 2 cyl active → 6 cyl active

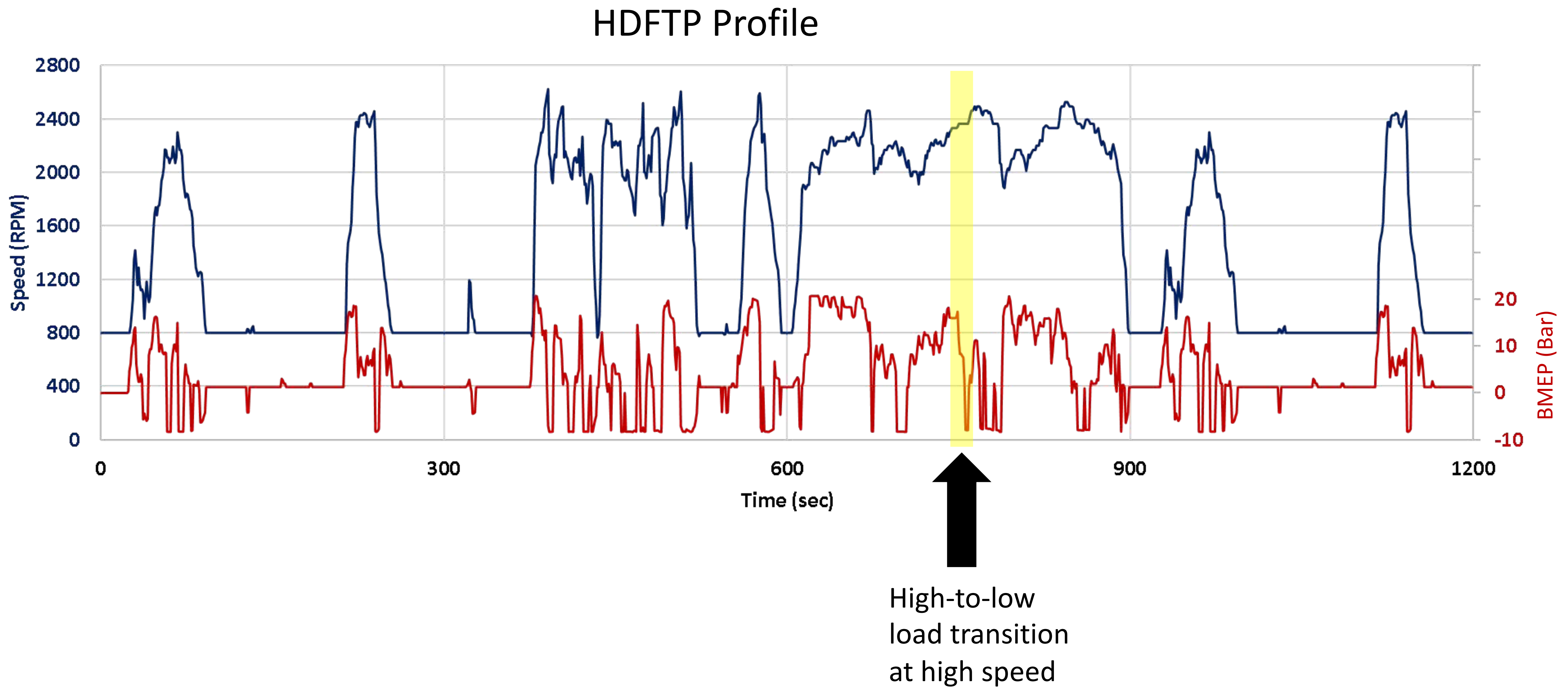
CDA at elevated speeds → Lower boost than baseline operation → Relatively slower transient response → CDA transient response at elevated speeds can likely be improved via model-based controls and/or look-ahead controls.

Transient response evaluated with stock engine calibration, which is not optimized for CDA

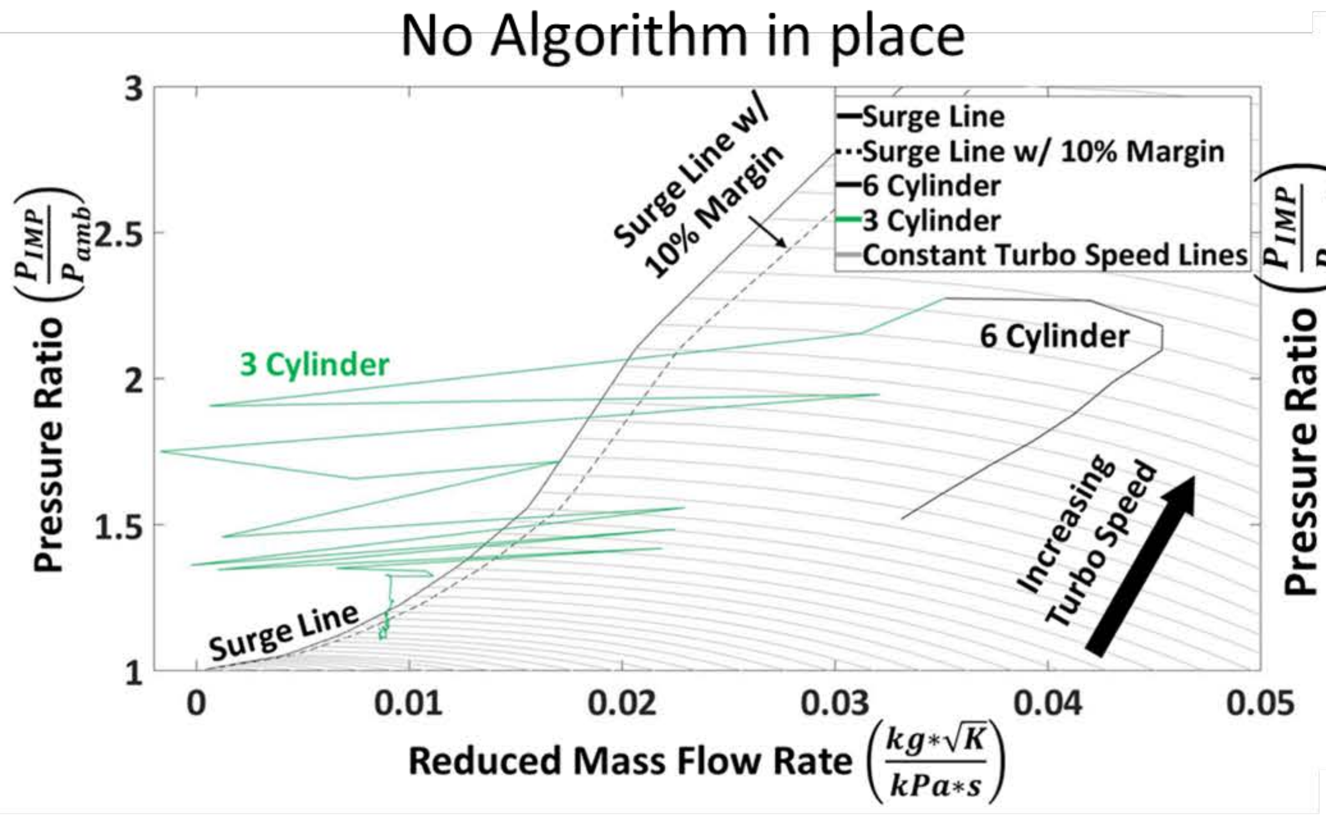
Experimental assessment of diesel engine cylinder deactivation performance during low-load transient operations, Int. J. of Eng. Res., June 2019

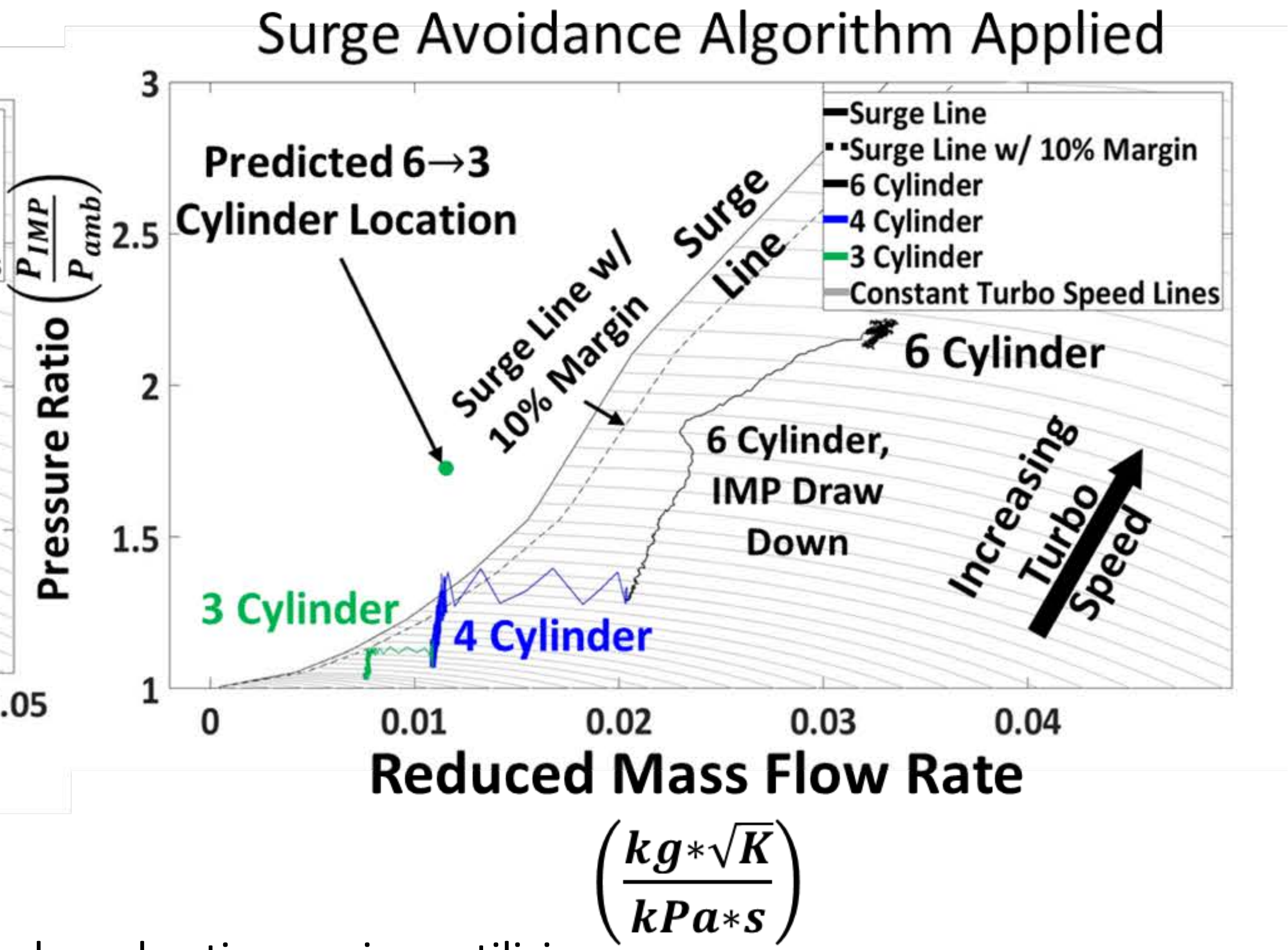
Surge avoidance when transiting into CDA from high load.

Transient response with CDA – surge avoidance



Transient response with CDA – surge avoidance





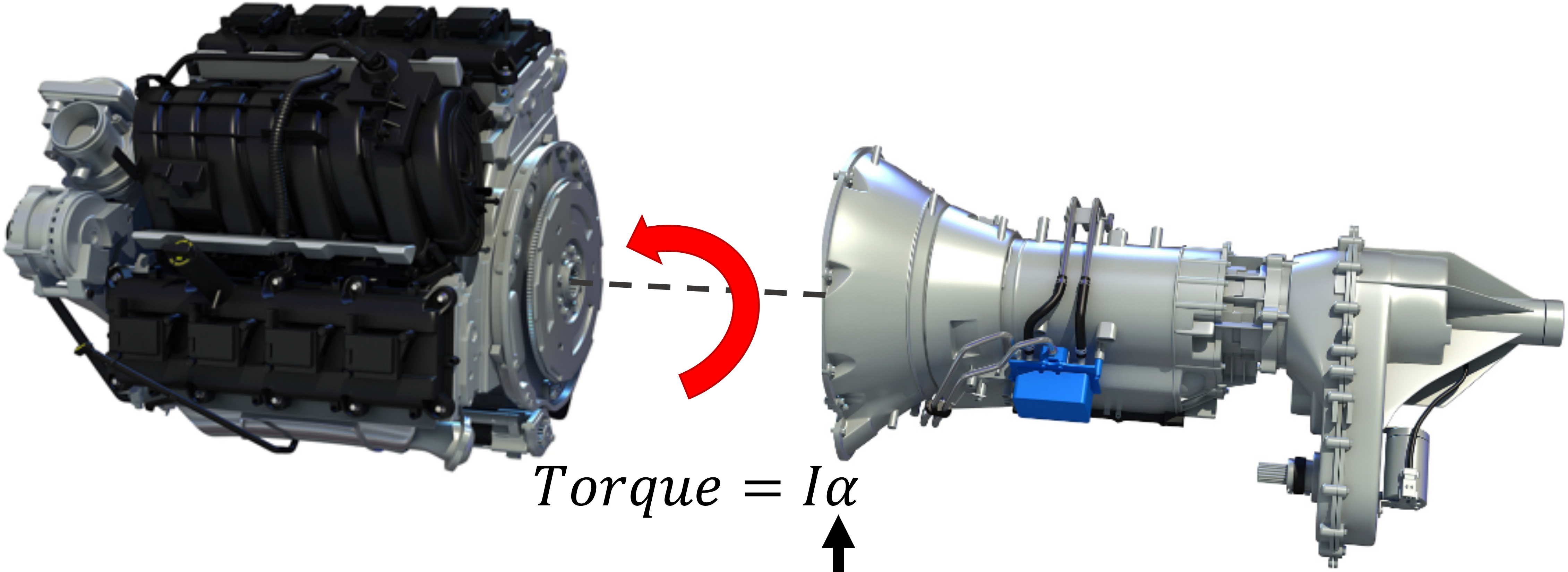
Model-based compressor surge avoidance algorithm for internal combustion engines utilizing cylinder deactivation during motoring conditions, Intl. J. of Engine Research, Oct. 2019

Torsional vibration challenges (?) and solutions (?) for CDA

Torsional vibrations

Too much acceleration can cause gear rattle, driveline noise

- Driveline manufacturers can design around this though



$$Torque = I\alpha$$

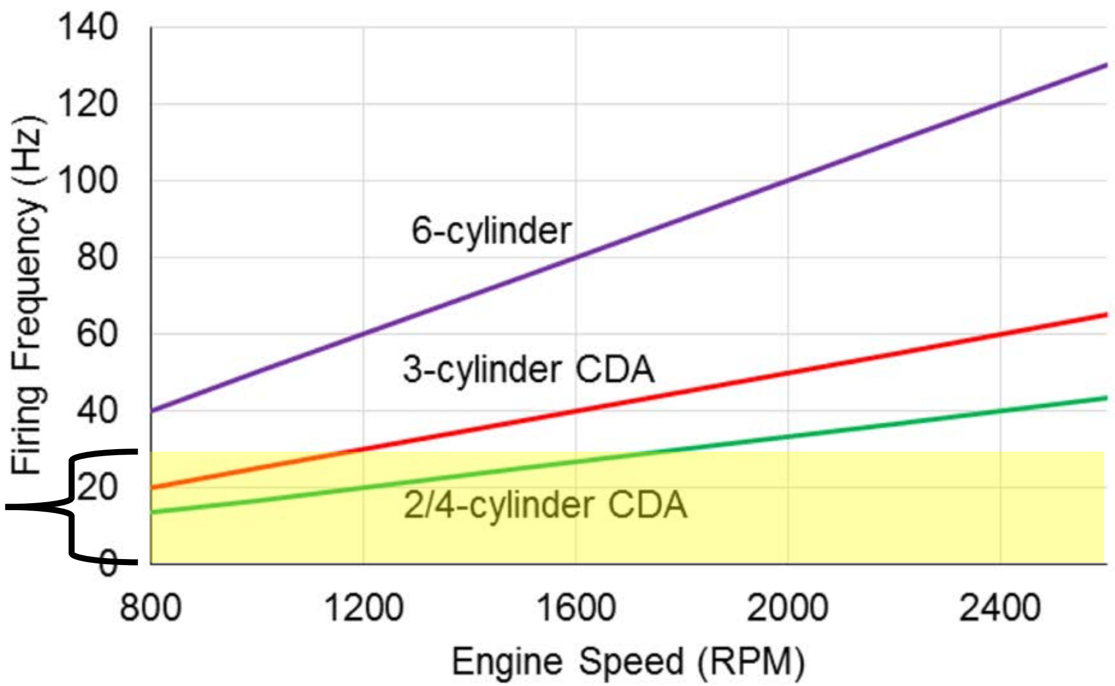
Want to assess variation in angular acceleration (and velocity and displacement)

Original image taken from: www.gandoza.com

Torsional vibrations

- Firing frequency is directly proportional to speed
- 6-cylinder operation stays above resonance frequencies
- CDA drops the firing frequency into the resonance range at/around idle
  - But at/around idle is where many CDA benefits happen
  - Need to characterize not only frequency, but amplitude of torsional vibrations for CDA modes compared to 6-cylinder operation

Typical driveline and body resonance frequencies*

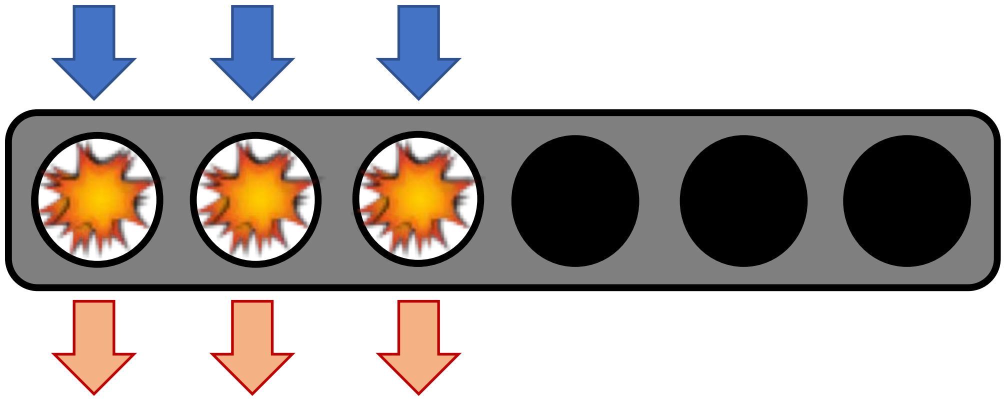


*Leone et al. Fuel Economy Benefit of Cylinder Deactivation Sensitivity to Vehicle Application and Operating Constraints. SAE Technical Paper Series, 1645(724):10{11, 2001.
*Wellman et al. Aspects of Driveline Integration for Optimized Vehicle NVH Characteristics. SAE Technical Paper, (724), 2007.
*Lee et al. Active tuned absorber for displacement-on-demand vehicles. In SAE 2005 Noise and Vibration Conference and Exhibition. SAE International, may 2005.
*Serrano et al. Methods of Evaluating and Mitigating NVH when Operating an Engine in Dynamic Skip Fire. SAE International Journal of Engines, 7(3), 2014.

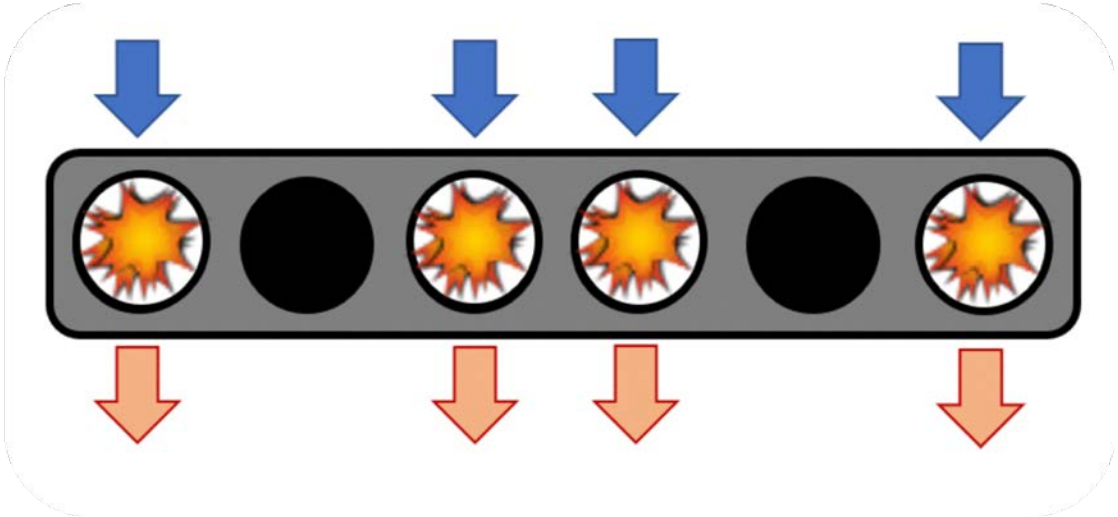
Dynamic Cylinder Activation (DCA)

Form of CDA with a different set of active cylinders each engine cycle

Fixed Cylinder Deactivation
Fixed CDA (3 CF)

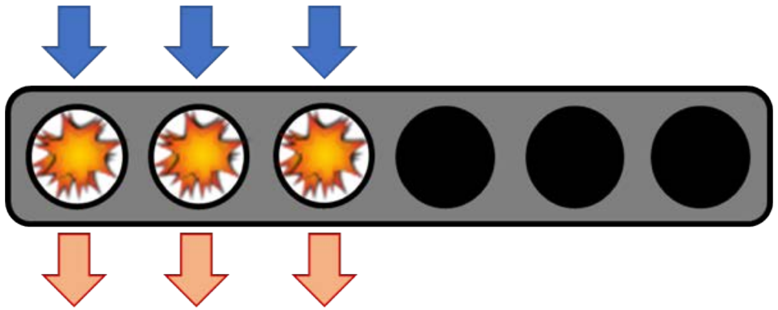


Dynamic Cylinder Activation
DCA (3 CF equivalent)

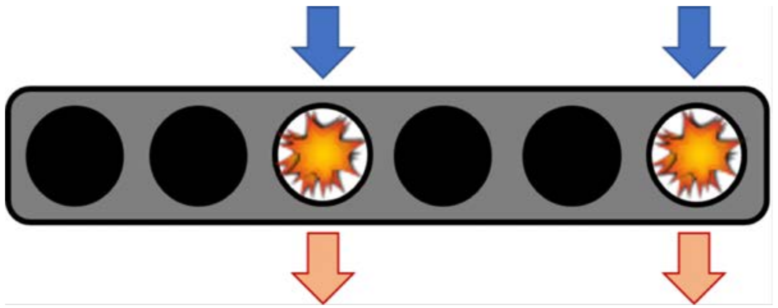


DCA is studied using different "recipes"

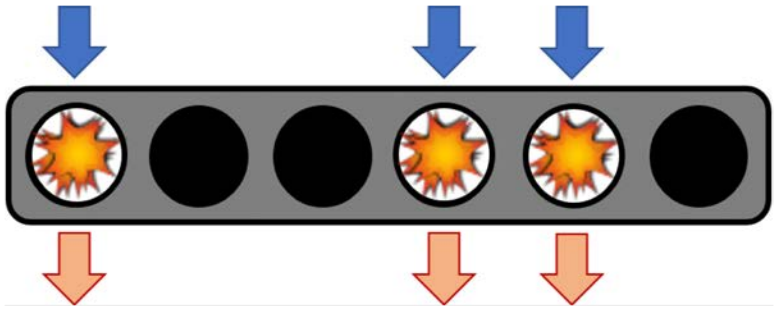
Fixed CDA



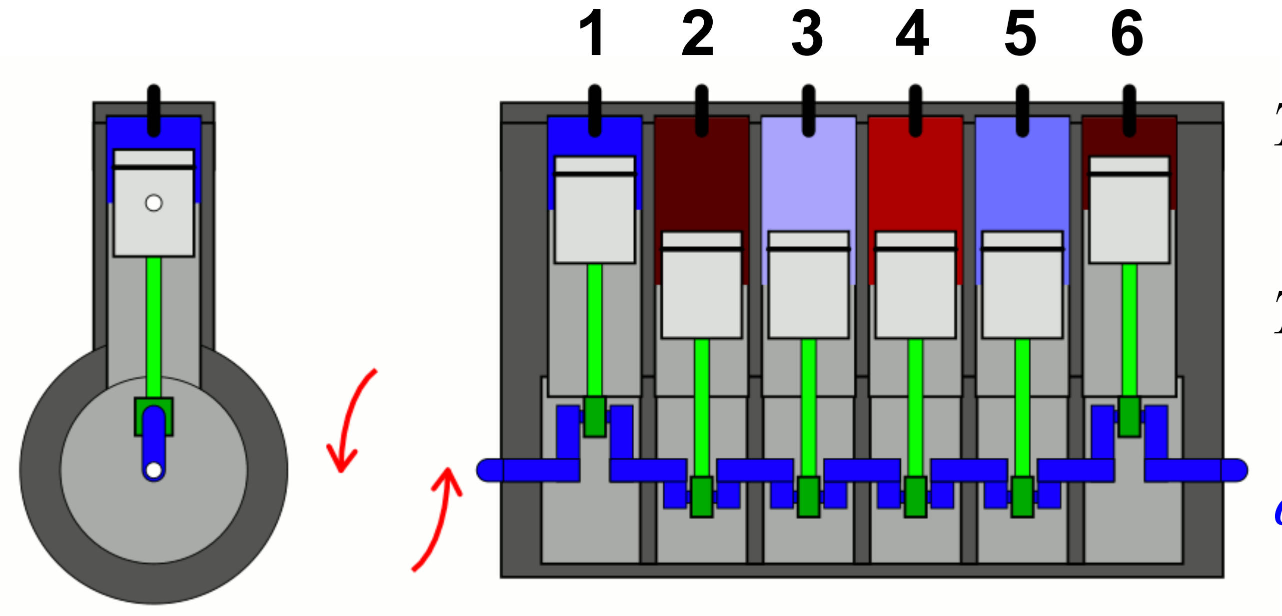
DCA
alternating pattern



DCA
aperiodic pattern



Angular acceleration at the flywheel was simulated using a rigid crankshaft kinematics model



$$T_{inertia,i} = \frac{1}{2} m_{rec} r^2 \omega^2 \left(\frac{r}{2l} \sin\theta - \sin 2\theta - \frac{3r}{2l} \sin 3\theta \right)$$

$$T_{gas,i} = P_{cyl} A_{piston} r \sin\theta \left(1 + \frac{r}{2} \cos\theta \right)$$

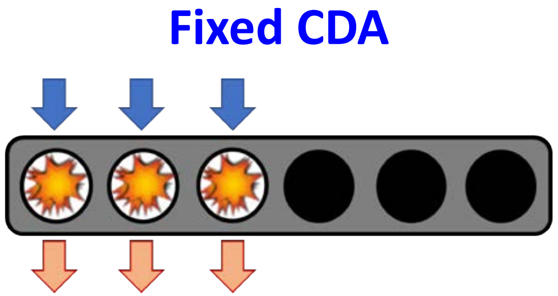
$$T_{crankshaft} = \sum_{i=1}^{6} \left(T_{inertia,i} + T_{gas,i} \right)$$

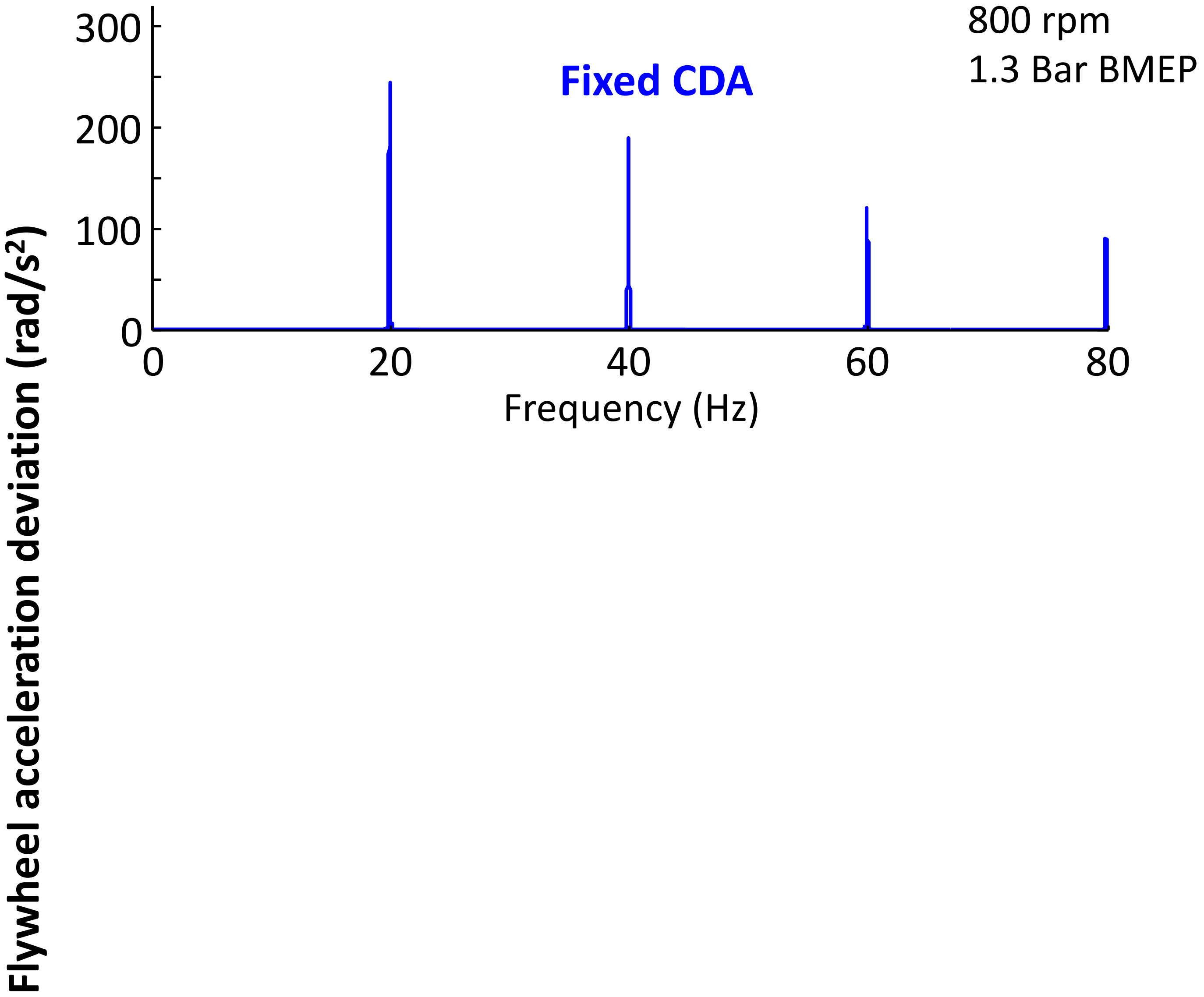
$$\alpha_{crankshaft} = \frac{T_{crankshaft}}{J}$$

↓

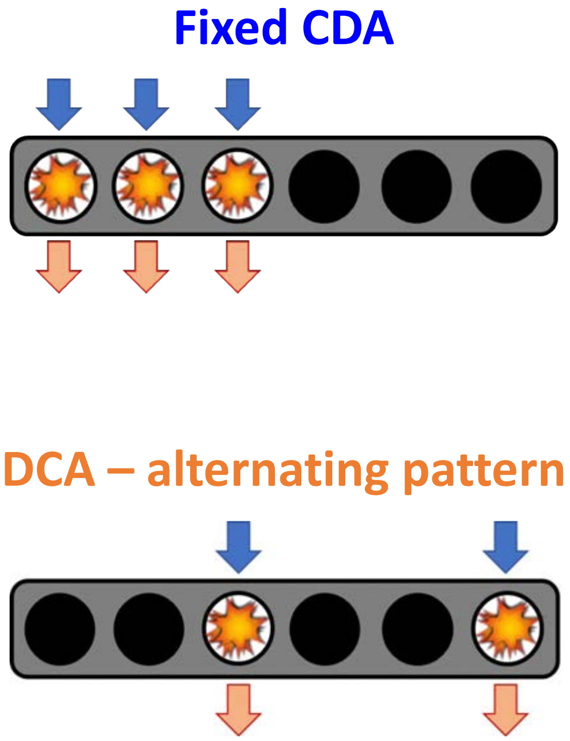
FFT

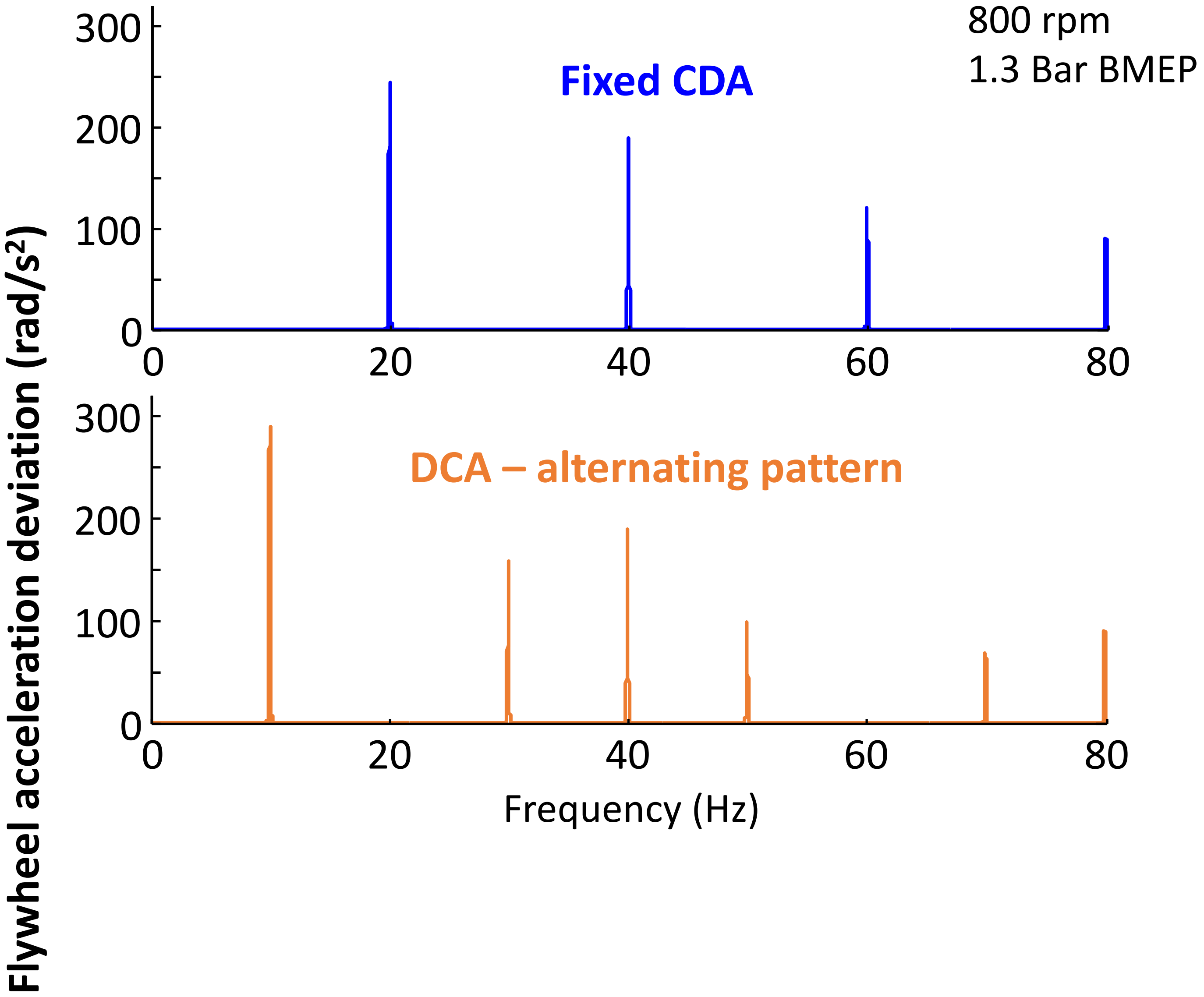
Simulation Results





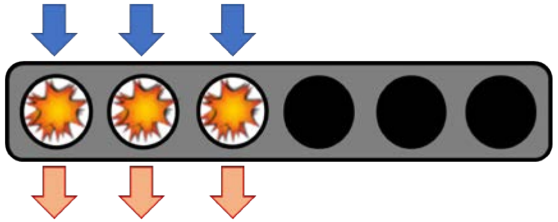
Simulation Results



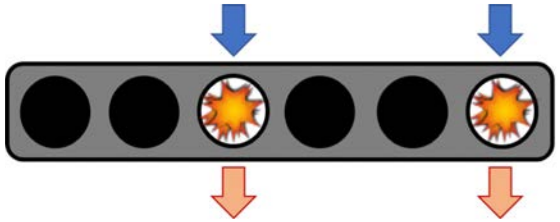


Simulation Results

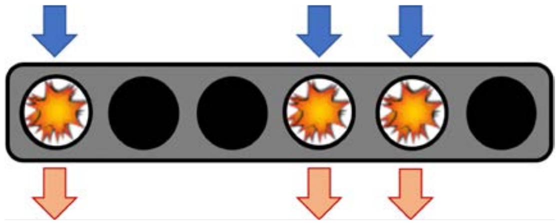
Fixed CDA

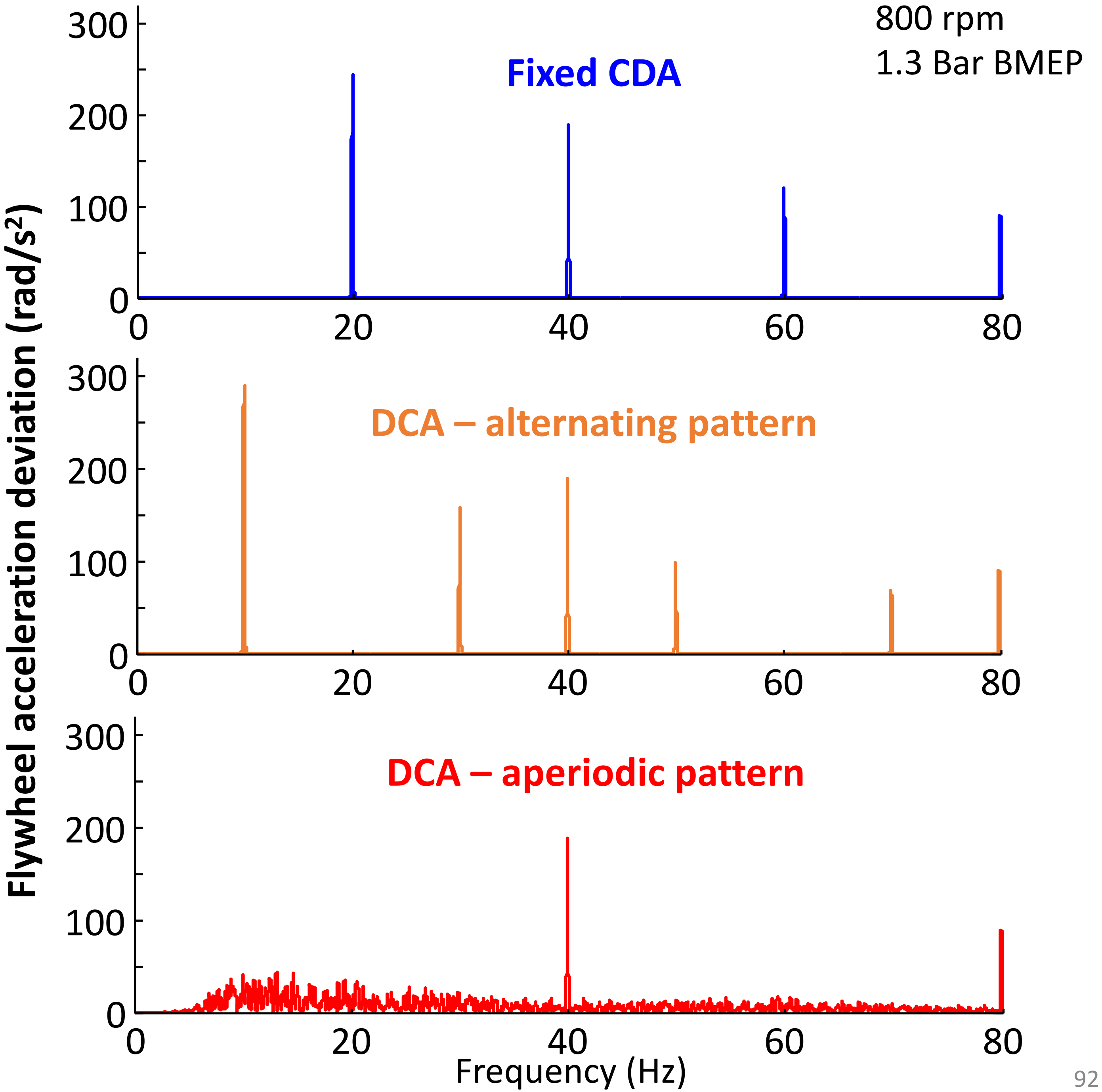


DCA – alternating pattern

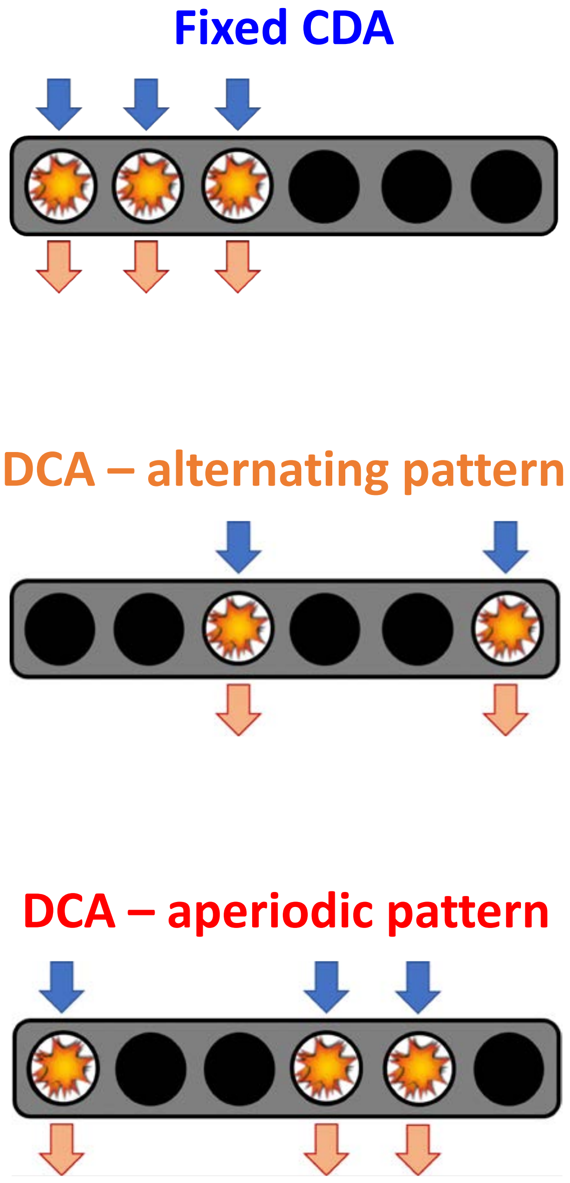


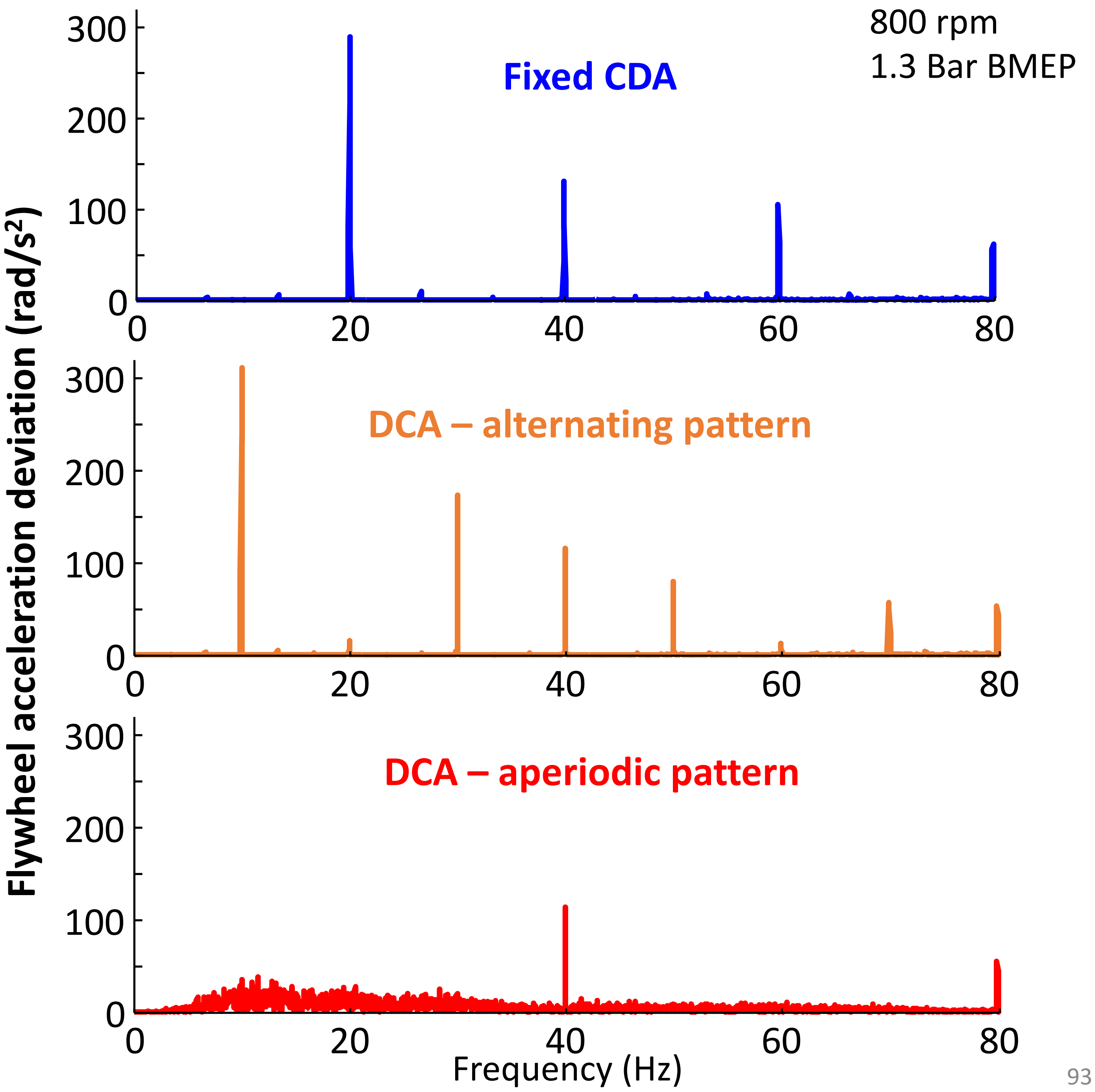
DCA – aperiodic pattern





Experimental Results





DCA can modulate the forcing frequencies…

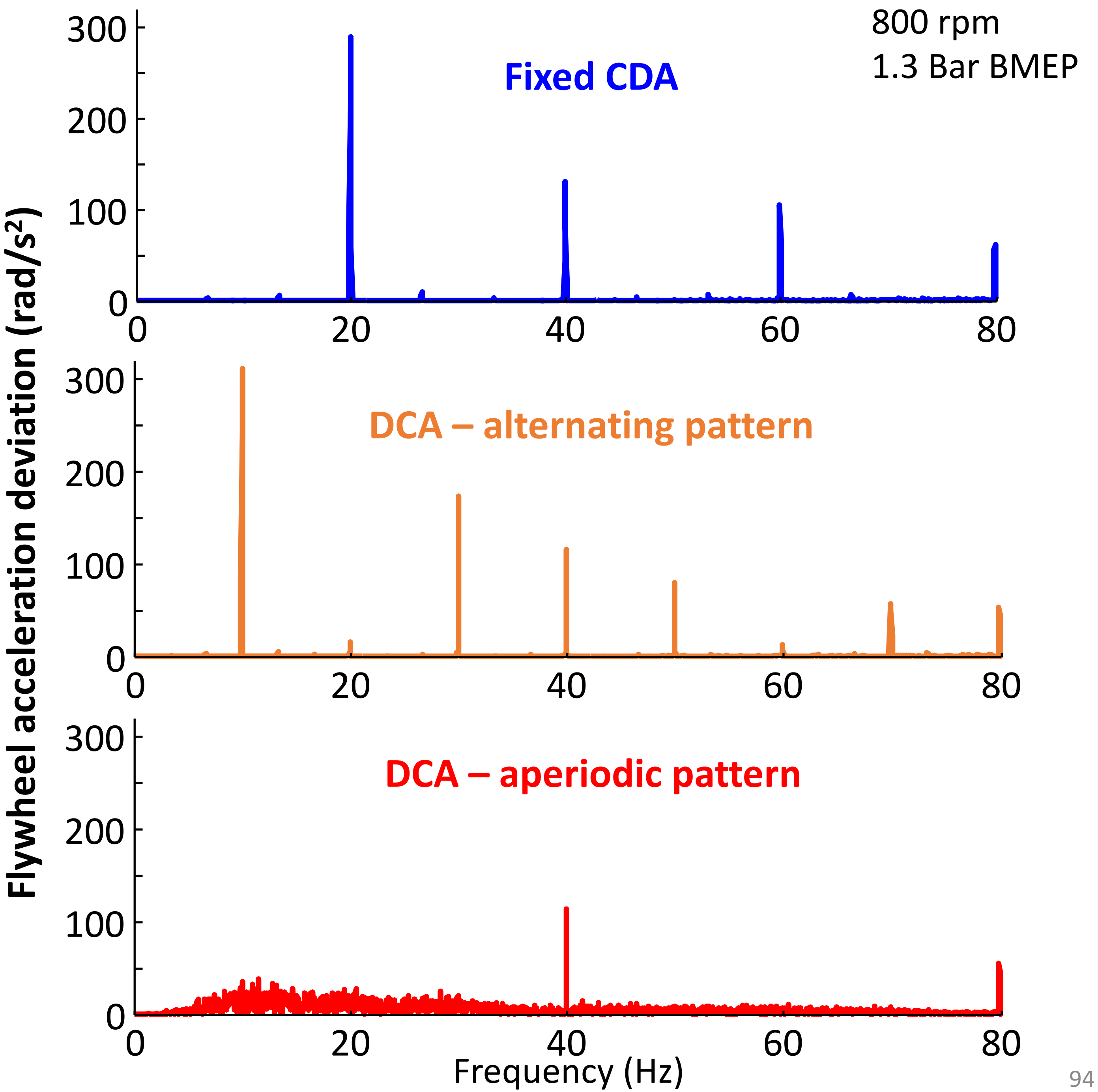
… to different, distinct frequencies

or

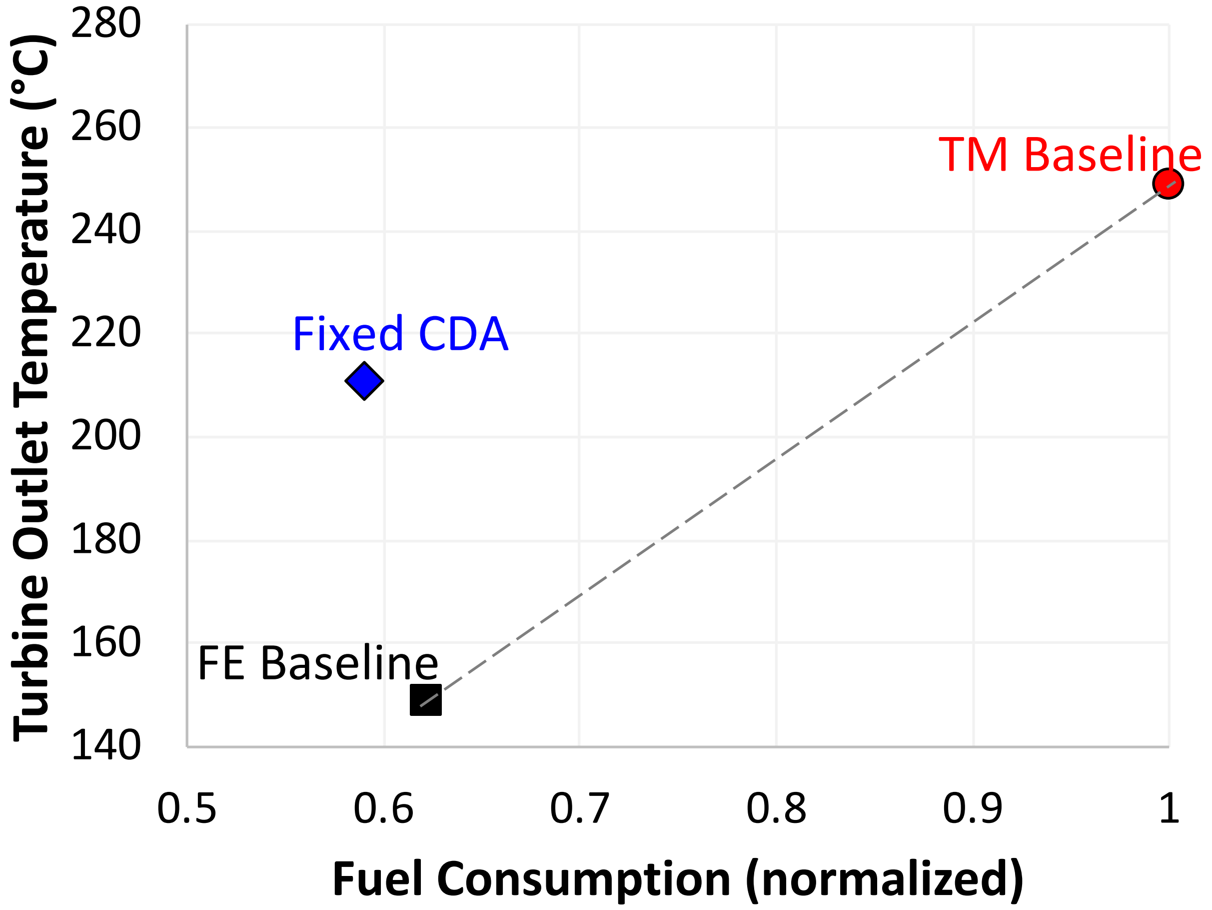
… to low amplitudes across a range of low frequencies

… in a deterministic, controllable way

Model-Based Design of Dynamic Firing Patterns for Supervisory Control of Diesel Engine Vibration, IFAC Control Engr. Practice, Feb. 2021

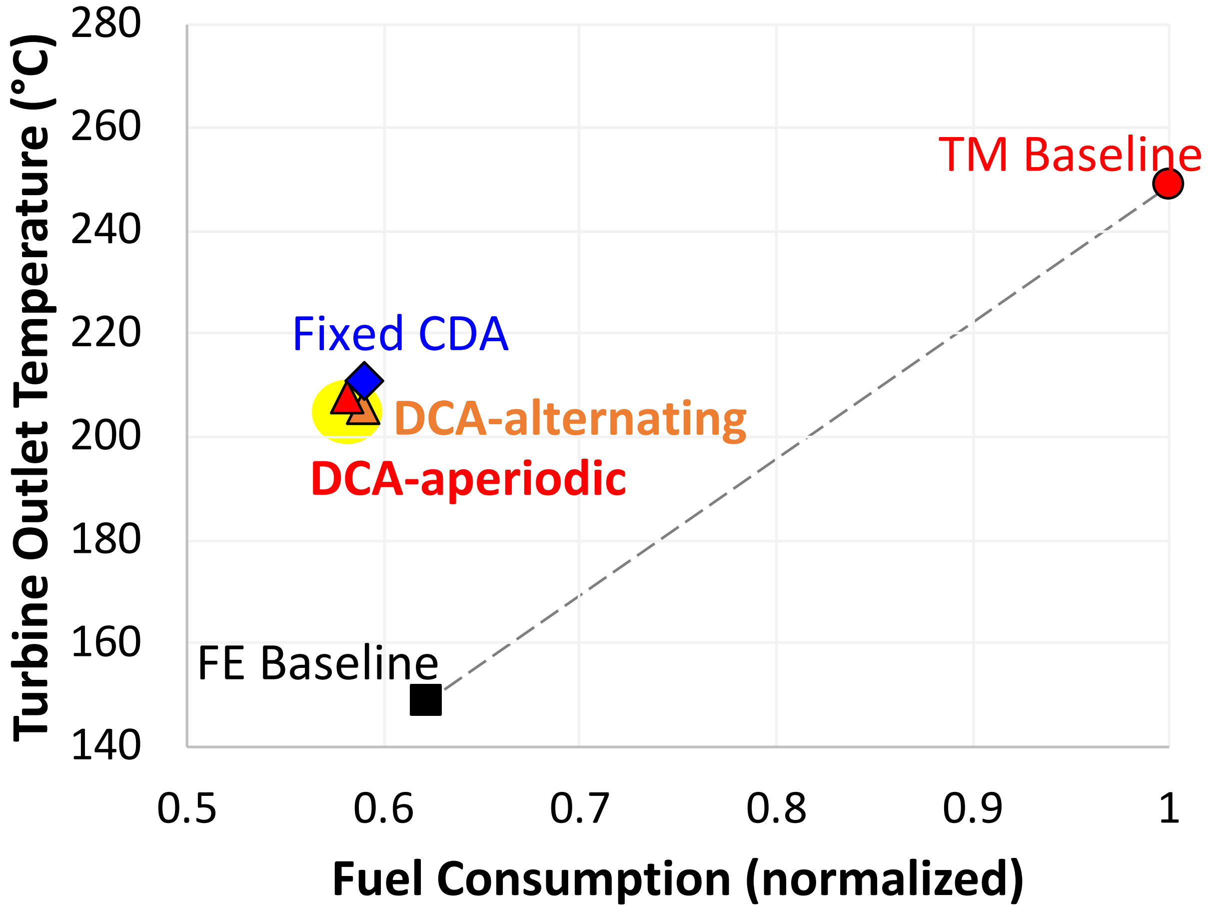


DCA

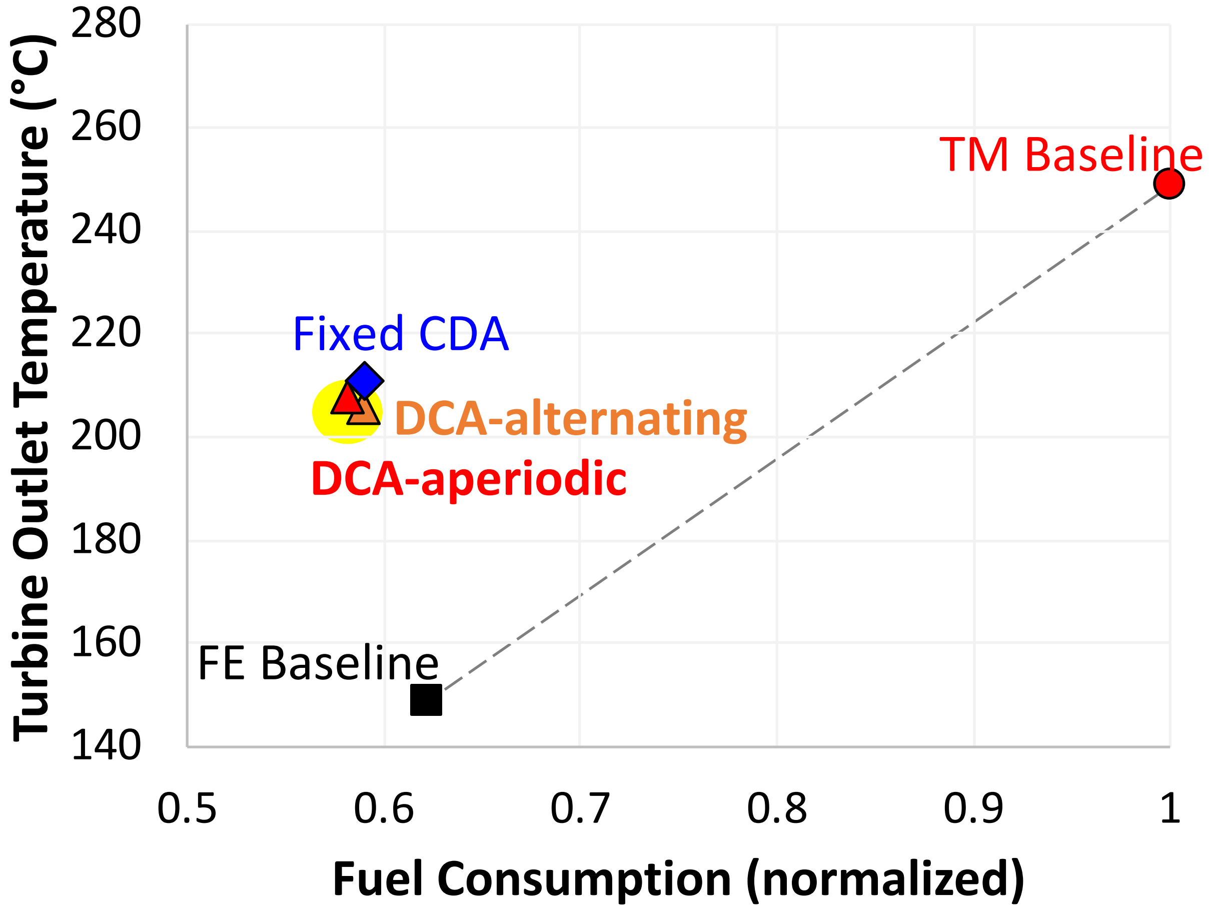


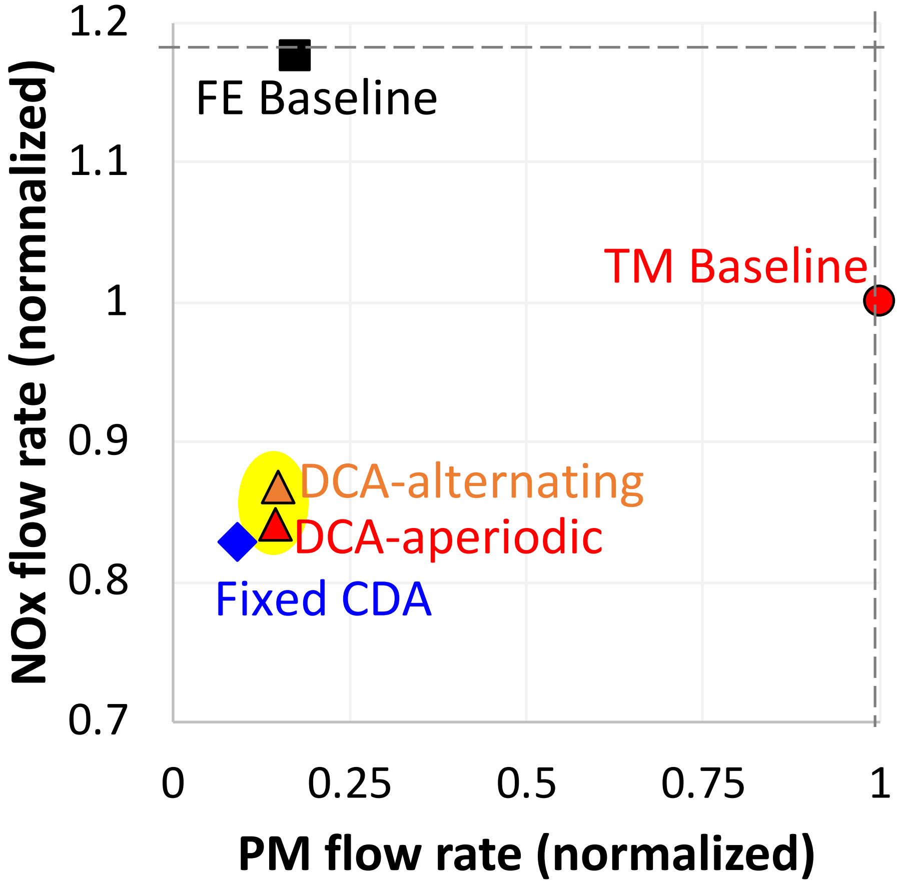
Turbine Outlet Temperature (°C)
280
260
240
220
200
180
160
140
TM Baseline
Fixed CDA
FE Baseline
0.5
0.6
0.7
0.8
0.9
1
Fuel Consumption (normalized)

DCA – Similar fuel consumption, TOT as fixed CDA

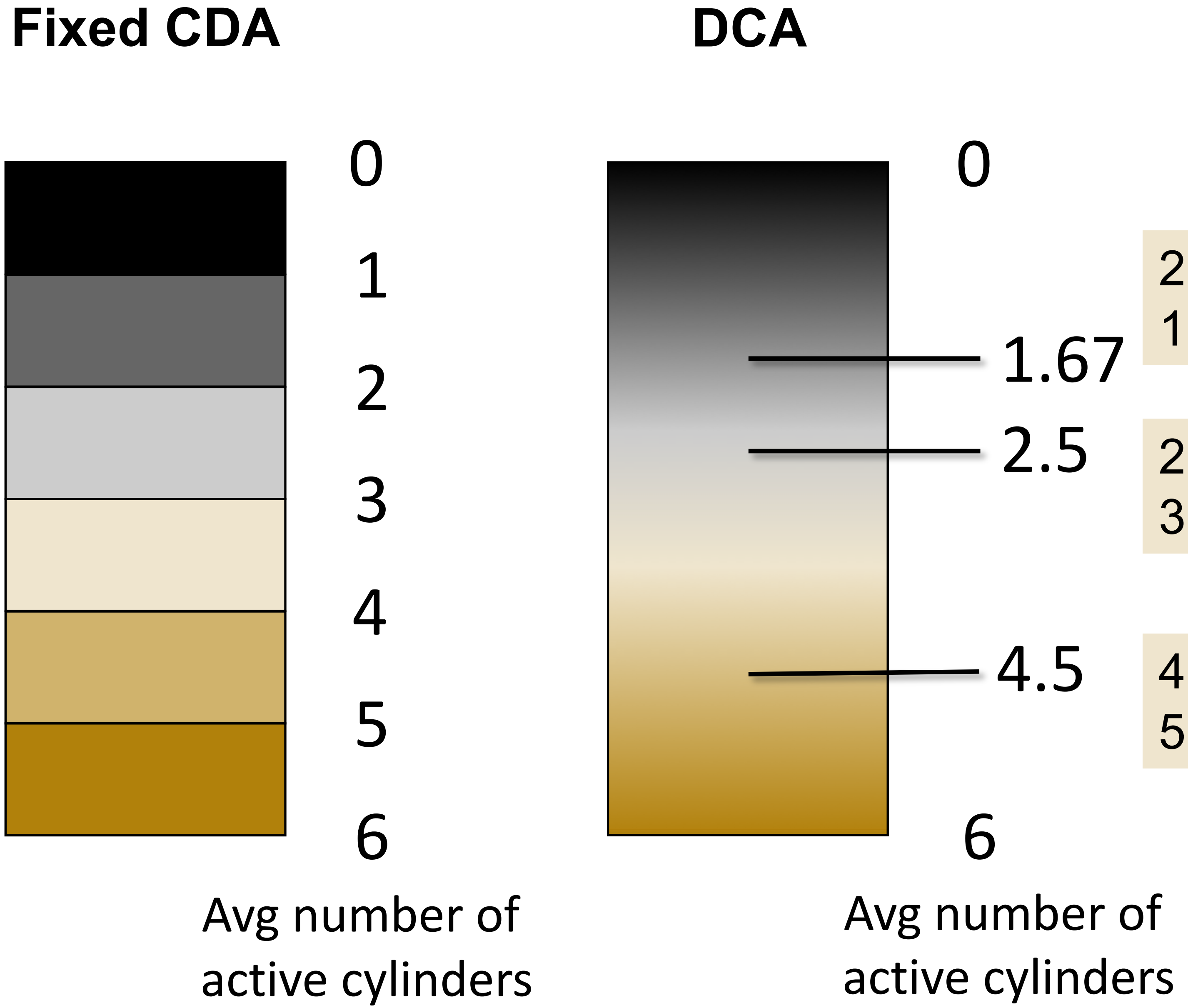


DCA – Similar fuel consumption, TOT and emissions as fixed CDA





DCA can realize a continuous set of firing densities



2 cylinders in two cycles +
1 cylinder in every third cycle

2 cylinders in one cycle
3 cylinders in the next cycle

4 cylinders in one cycle
5 cylinders in the next cycle

Commercial Vehicle Powertrains of the Future -- Conclusions

- The IC Engine will continue to play a key role:
  - Lower/low/no-carbon fuels:
    - Very high efficiency diesel – lean-burn engines
    - Natural gas – stoichiometric engines
    - Hydrogen – stoichiometric and lean-burn engines
    - Bio-derived fuels
  - Use in hybrids electric drivetrains – coordinated control is critical
  - Electrification of some engine functions – EGR pumping, eBoosting, etc.

- Model-based controls is critical
  - Very high demand for this talent in industry

Shaver Research Group

18 Graduate Students (9 Phd, 9 MSME)

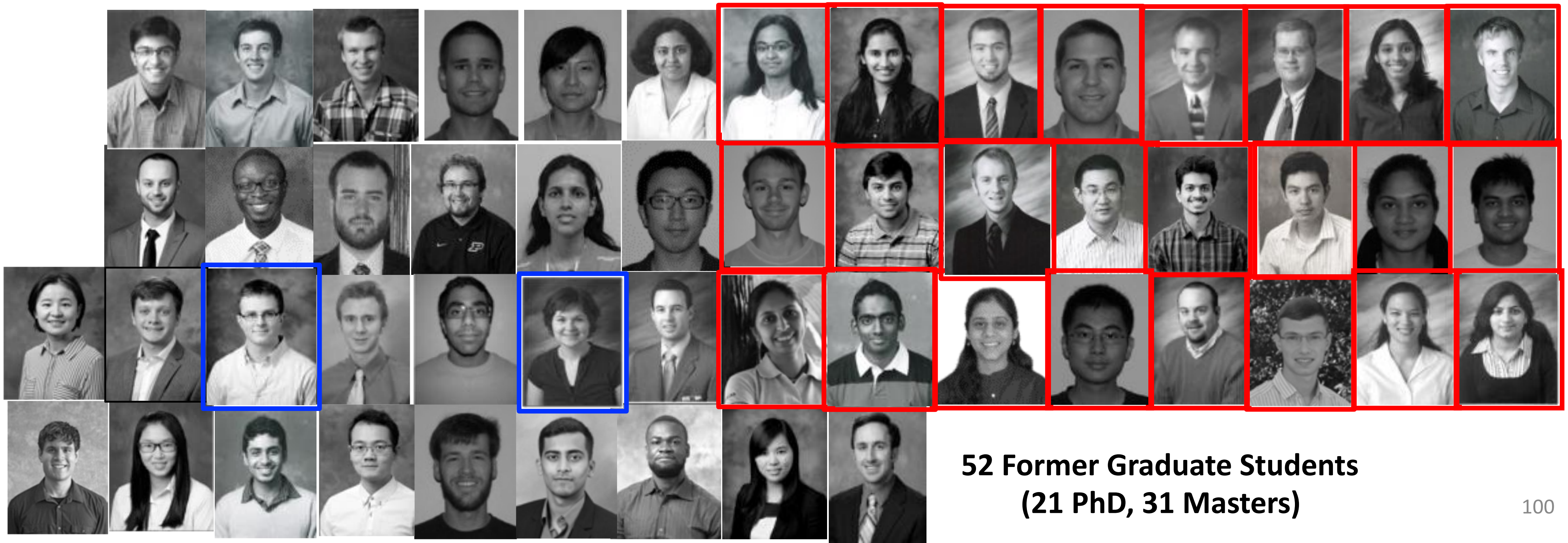
Greg Shaver, PhD
Faculty Lead

Eric Holloway, PhD
Project management for select projects

Ryan Thayer
Testcell & vehicle leadership

Employed at industry partner companies.

Tenure-track faculty.



52 Former Graduate Students (21 PhD, 31 Masters)