Engine-in-the-Loop Analysis of Series PHEV under 'Hot' Conditions

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Research Objective : Use Model Based Design (MBD) to Maximize Series PHEV Fuel Economy within Emissions Constraints

Vehicle selection and sizing in Autonomie.
Integration of engine emissions model.

Simulation study with focus on:

1. Engine ON/OFF.
2. Engine operating region.
3. Engine warm-up strategies torque transients.

Investigate promising simulation results using EIL

Iterate between EIL and simulation

Vehicle and Drive Cycle Assumptions

- Series PHEV SUV sized in Autonomie (Class – small SUV).
- Test cycle – consecutive UDDS cycles.

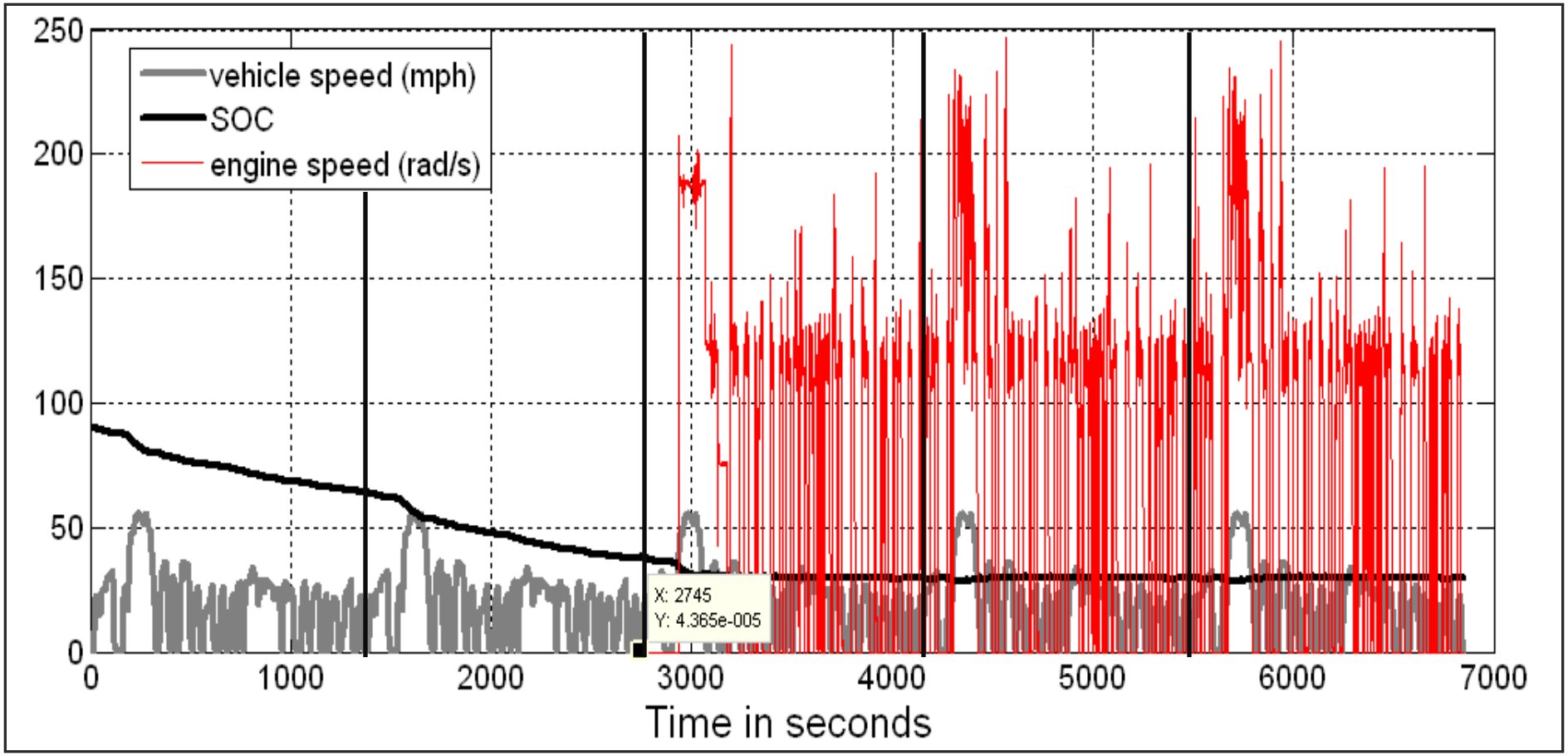
Performance Requirements

1. 0-60 = ~9sec
2. Vmax > 100 mph
3. 6% grade at 55 mph at GVW.
4. ~ 20 miles equivalent electric range on UDDS.
5. Use existing engine for hardware validation

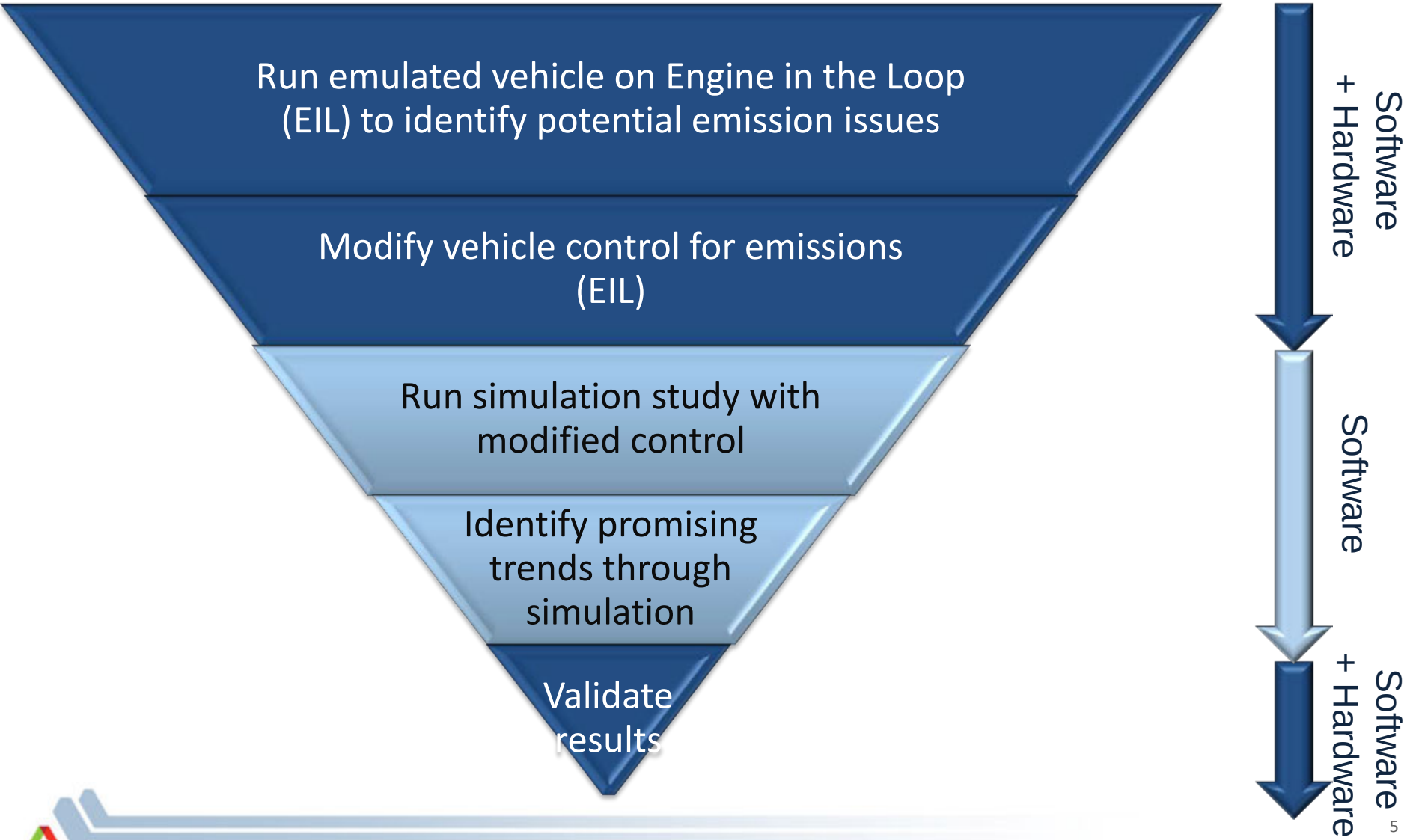
Hardware

Parameter	Value
Curb weight	1800 kg
GVW	2440 kg
Engine	110 kW , 2.2 L SIDI engine
Electric Machine Power	130 kW / 13000 rpm
Generator Power	110 kW / 6000 rpm
Battery	41 Ah, 10 kWh Li-ion
Cd	0.37
FA	2.54 m2
Tire	P225_75_R15 (0.359)
Fixed ratio	1.6
Final drive ratio	4

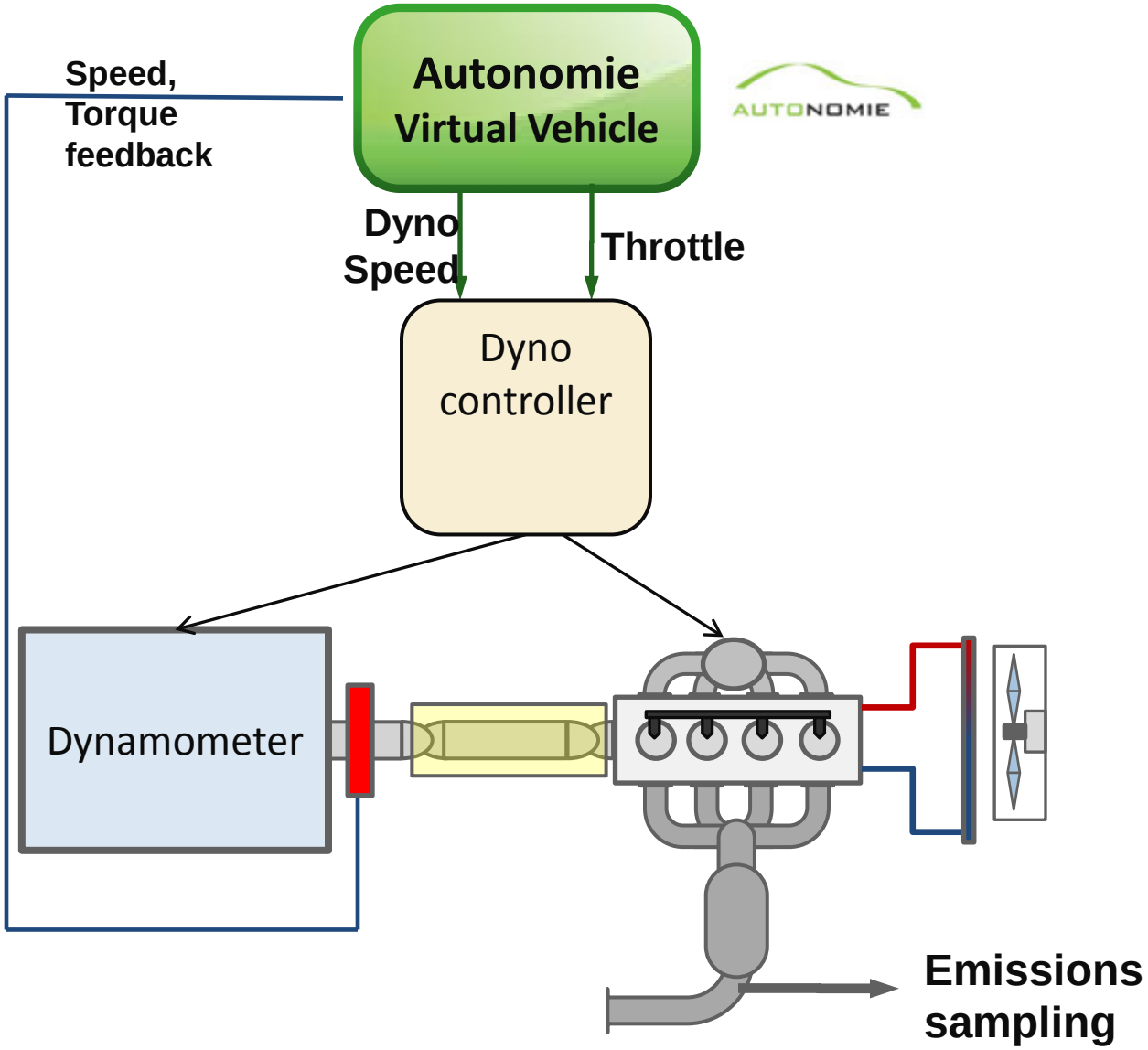
Vehicle Control Strategy Based on EV Mode Followed by CS Mode (with warm-up before CS)



Model Based Design Approach



Engine-In-The-Loop Block Diagram



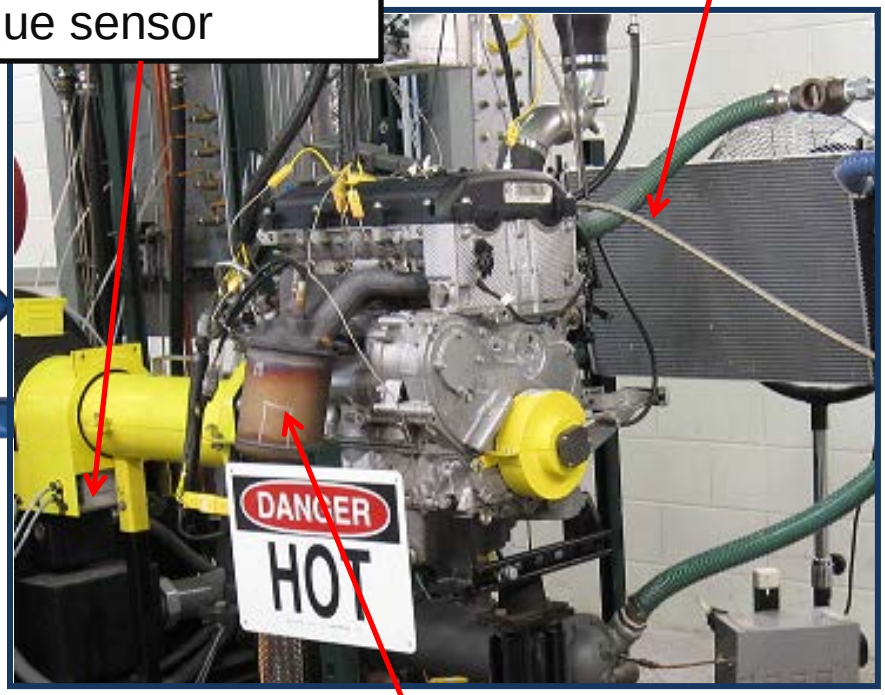
Actual Hardware

Torque command to engine

Torque feedback propels the vehicle

Contactless hi-fidelity torque sensor

Engine cooling



Catalytic converter

Modular dSPACE system with Analog, Digital, RS232, CAN measurement.

Default Vehicle on EIL Shows High NOx, CO.

Step 1: Run Default Vehicle on EIL

Engine Turns ON above 10 kW wheel power demand.

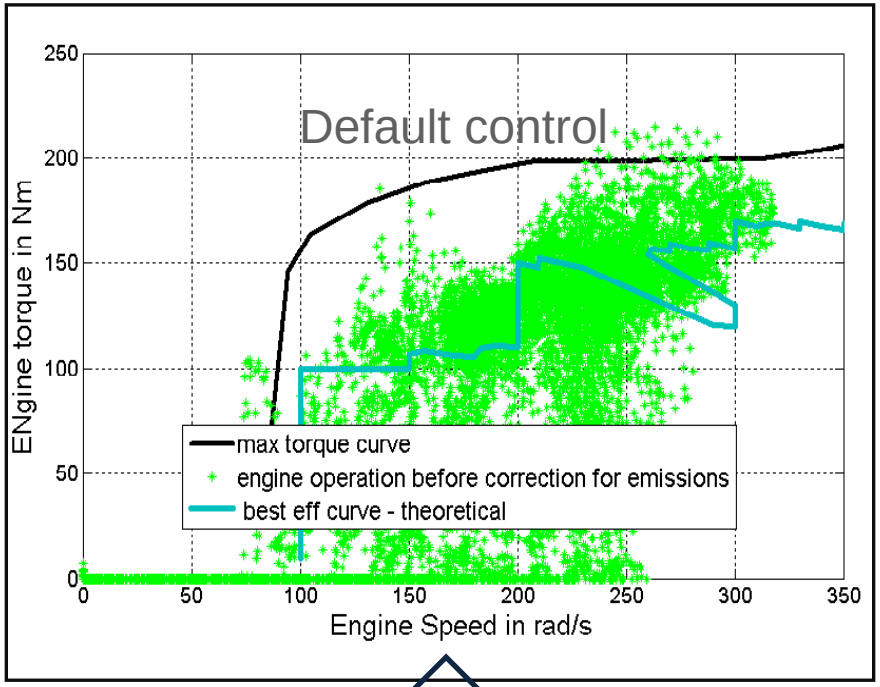
	Fuel Economy (mpg)	NOx(g/mi)	THC (g/mi)	CO (g/mi)
Conventional vehicle	24	0.01	0.0492	1.27
Series vehicle, CS operation	38	0.17	0.0074	1.55

Tier II Bin 5

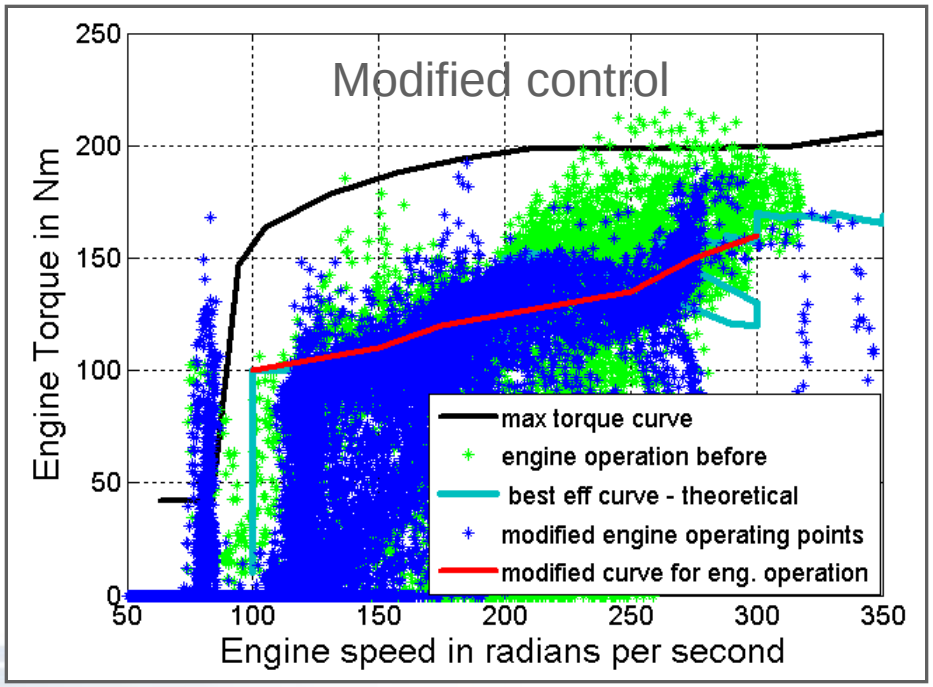
High NOx!

High CO!

NOx Reduced by Decreasing Engine High Load Operation

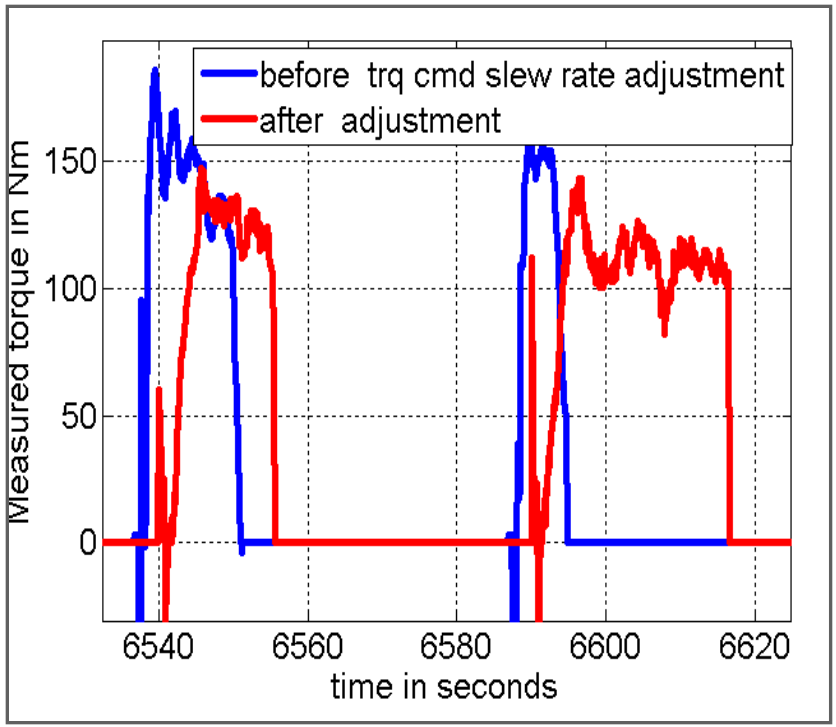


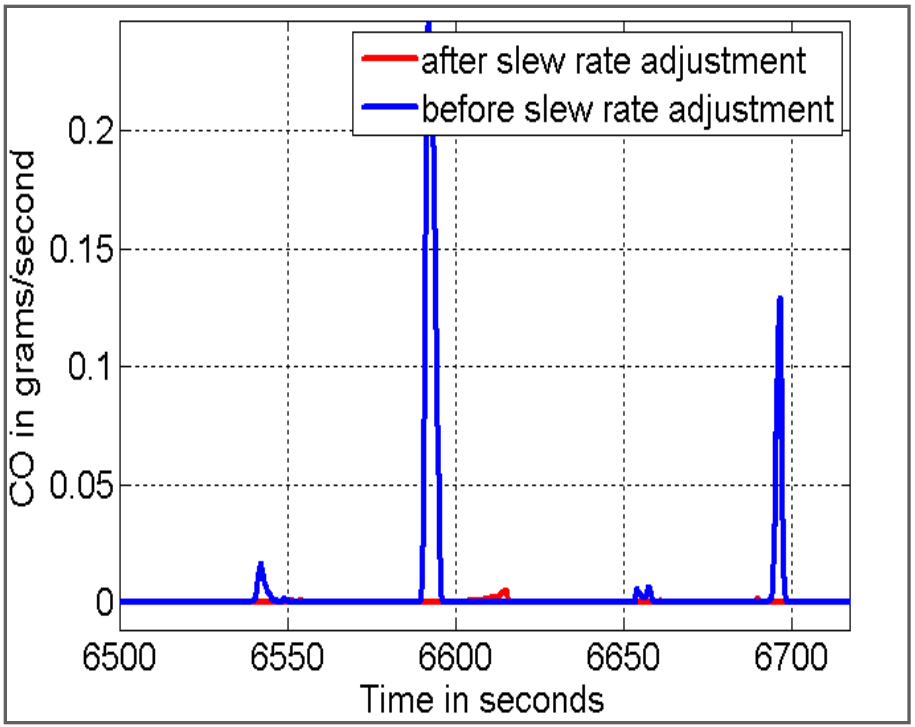
Engine operation at high loads restricted to reduce NOx.



High load operation leads to high combustion temperature which results in increased NOx.

CO Reduced by Slower Torque (Throttle) Tip-Ins



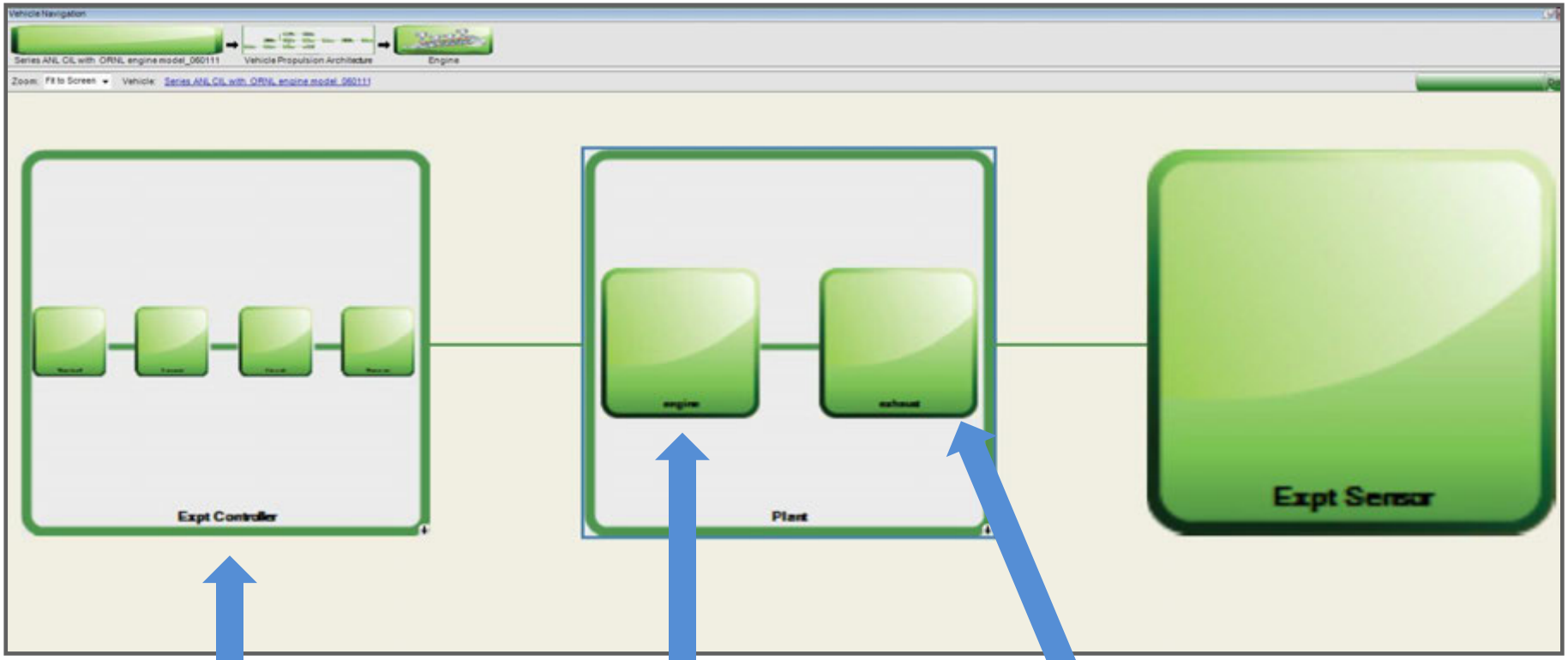


High slew rates on the throttle caused rich engine operation and high CO.

Modified Control Shows Significant Reduction in Both NOx and CO.

	Fuel Economy (mpg)	NOx(g/mi)	THC (g/mi)	CO (g/mi)
Conventional vehicle	24	0.01	0.0492	1.27
			Tier II Bin 5	
Series, Default Control	38	0.17	0.0074	1.55
Series, Modified Control	35	0.04	0.0062	0.29
			Tier II Bin 5	

For Accuracy, Low Level EIL Control and Emulation of Hardware Behavior Implemented in Autonomie



Same low level control as used in EIL.

Plant model reflects hardware
Delays and noise.

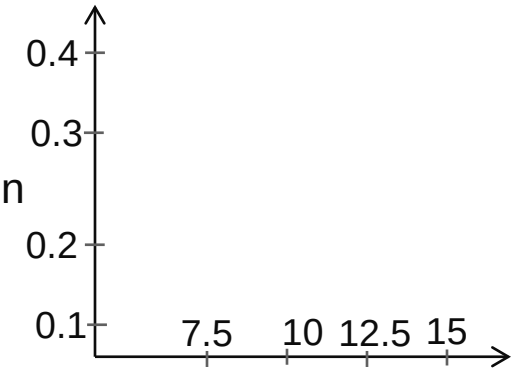
After-treatment model accounts for cold start and emissions.

Two Parameters Selected for the Design of Experiment

Objective – Minimize fuel consumption while maintaining SOC balance.

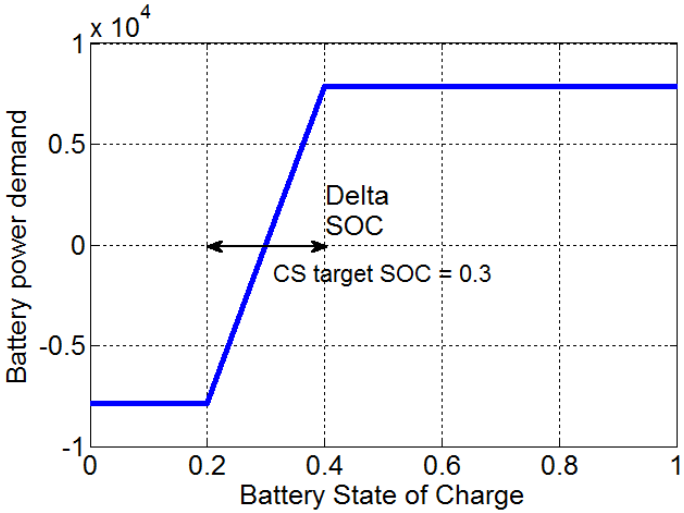
Simulation study matrix

SOC window for CS operation (delta SOC)

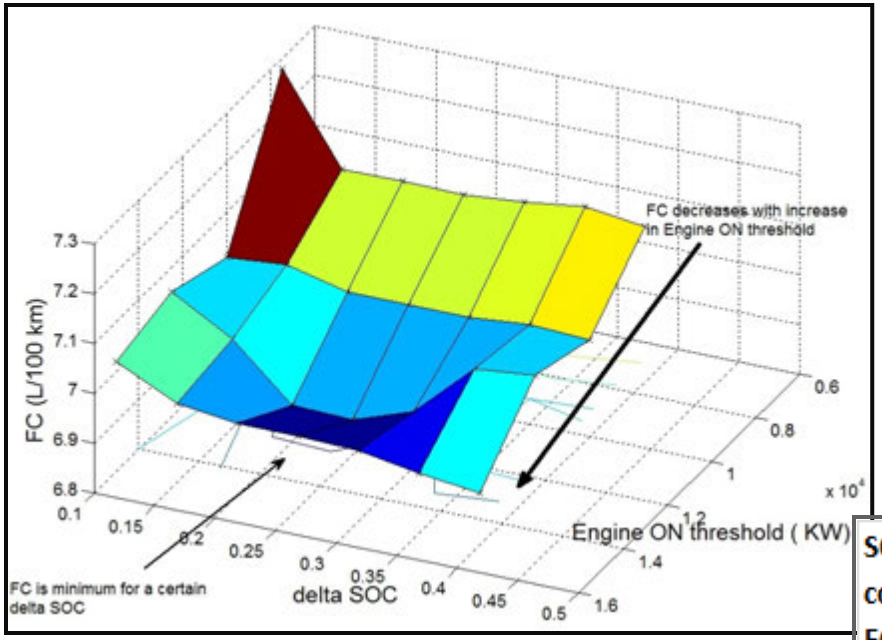


Engine ON threshold based on wheel power demand (kW)

Delta SOC concept



Simulation Results – Minimum Fuel Consumption at Engine ON Threshold of 12.5 kW with 20% Useable SOC.



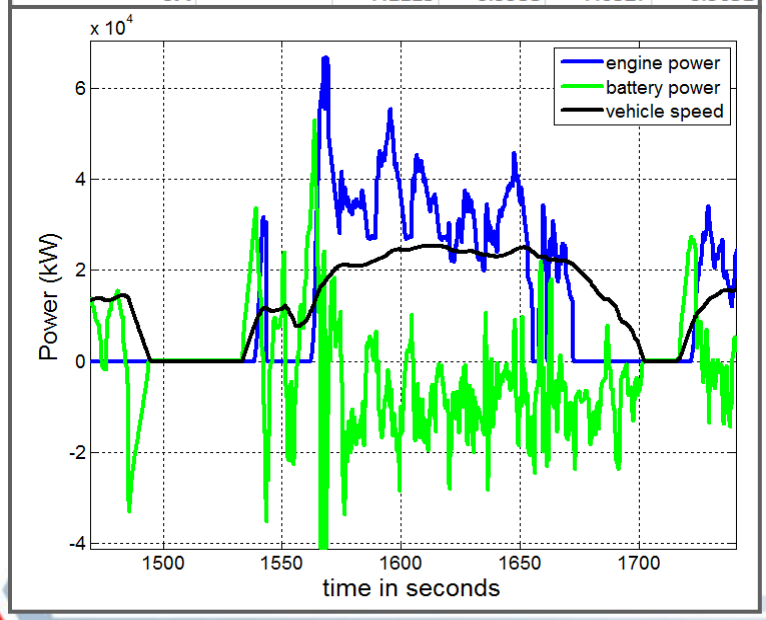
SOC correctedsimu FC	Engine ON Threshold				
delta SOC	5000	7500	10000	12500	15000
0.1		7.28	7.0741	7.05	7.0214
0.15		7.1018	7.0199	6.98	6.9608
0.2	7.16	7.1037	6.99	6.8726	6.946
0.25		7.1013	6.99	6.8687	6.9451
0.3		7.1106	6.99	6.91	6.9404
0.35		7.1127	7	7.0213	6.9215
0.4		7.1113	6.9938	7.0327	6.9051

Fuel consumption minimum

Eliminate High Engine Speed Cases and Aggressive SOC Control.

SOC correctedsimu FC	Engine ON Threshold				
delta SOC	5000	7500	10000	12500	15000
0.1		7.28	7.0741	7.05	7.0214
0.15		7.1018	7.0199	6.98	6.9608
0.2	7.16	7.1037	6.99	6.8726	6.946
0.25		7.1013	6.99	6.8687	6.9451
0.3		7.1106	6.99	6.91	6.9404
0.35		7.1127	7	7.0213	6.9215
0.4		7.1113	6.9938	7.0327	6.9051

Not considered
for EIL validation due to engine speeds greater than 380 rad/s

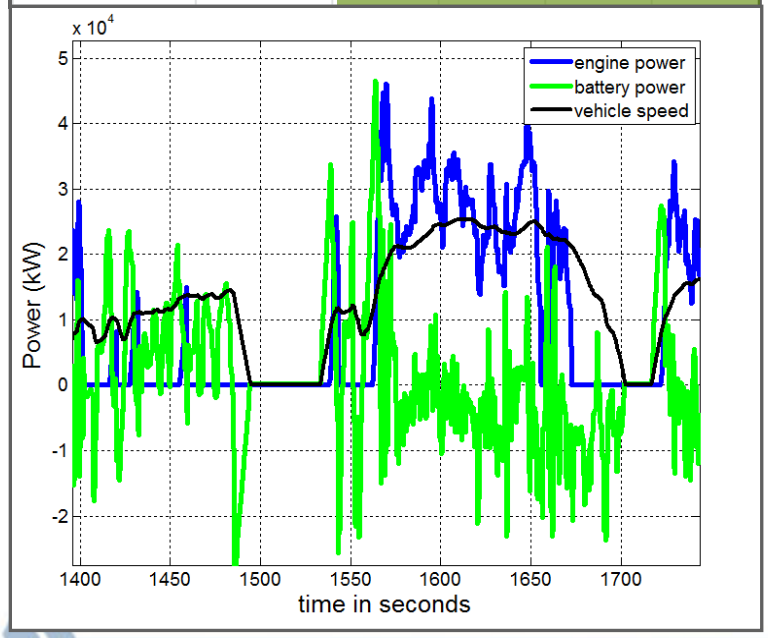


High engine ON threshold , along with aggressive battery SOC control, result in high engine power (speed) demand when engine is turned on.

Eliminate Cases where SOC Dropt to Very Low Values

SOC correctedsimu FC	Engine ON Threshold				
delta SOC	5000	7500	10000	12500	15000
0.1		7.28	7.0741	7.05	7.0214
0.15		7.1018	7.0199	6.98	6.9608
0.2	7.16	7.1037	6.99	6.8726	6.946
0.25		7.1013	6.99	6.8687	6.9451
0.3		7.1106	6.99	6.91	6.9404
0.35		7.1127	7	7.0213	6.9215
0.4		7.1113	6.9938	7.0327	6.9051

Not considered
for EIL validation due to low SOC in CS mode (e.g. 24%).



'Lazy' battery SOC control results in CS operation at low SOC, and large SOC swings.

Eliminate Cases where Test to Test Variation is Higher Than Simulation Results

SOC correctedsimu FC	Engine ON Threshold				
delta SOC	5000	7500	10000	12500	15000
0.1		7.28	7.0741	7.05	7.0214
0.15		7.1018	7.0199	6.98	6.9608
0.2	7.16	7.1037	6.99	6.8726	6.946
0.25		7.1013	6.99	6.8687	6.9451
0.3		7.1106	6.99	6.91	6.9404
0.35		7.1127	7	7.0213	6.9215
0.4		7.1113	6.9938	7.0327	6.9051

Simulation results with FC difference less than EIL test to test variation (1%).

Four Simulation Cases Selected for EIL Validation

SOC correctedsimu FC	Engine ON Threshold				
delta SOC	5000	7500	10000	12500	15000
0.1		7.28	7.0741	7.05	7.0214
0.15		7.1018	7.0199	6.98	6.9608
0.2	7.16	7.1037	6.99	6.8726	6.946
0.25		7.1013	6.99	6.8687	6.9451
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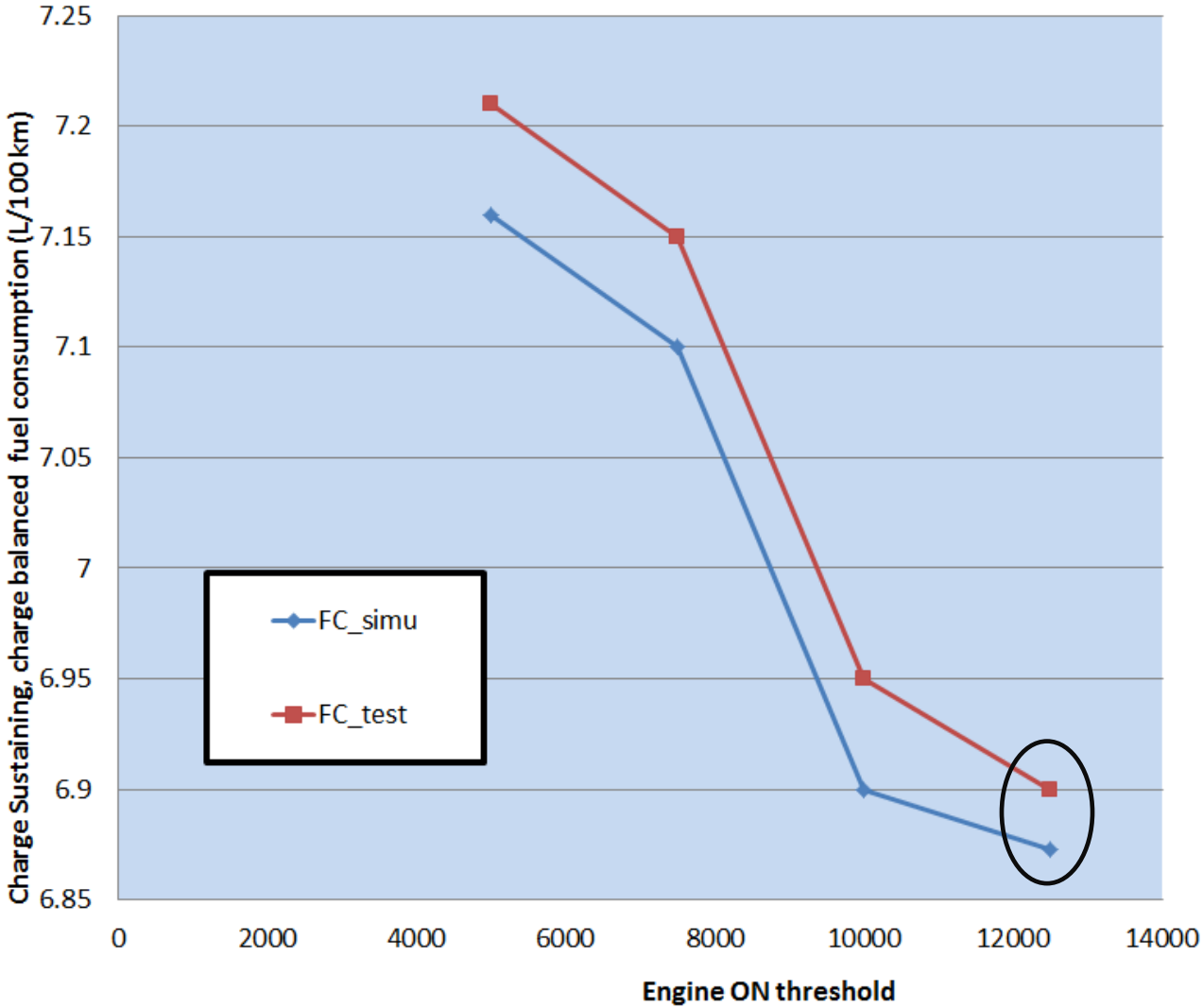
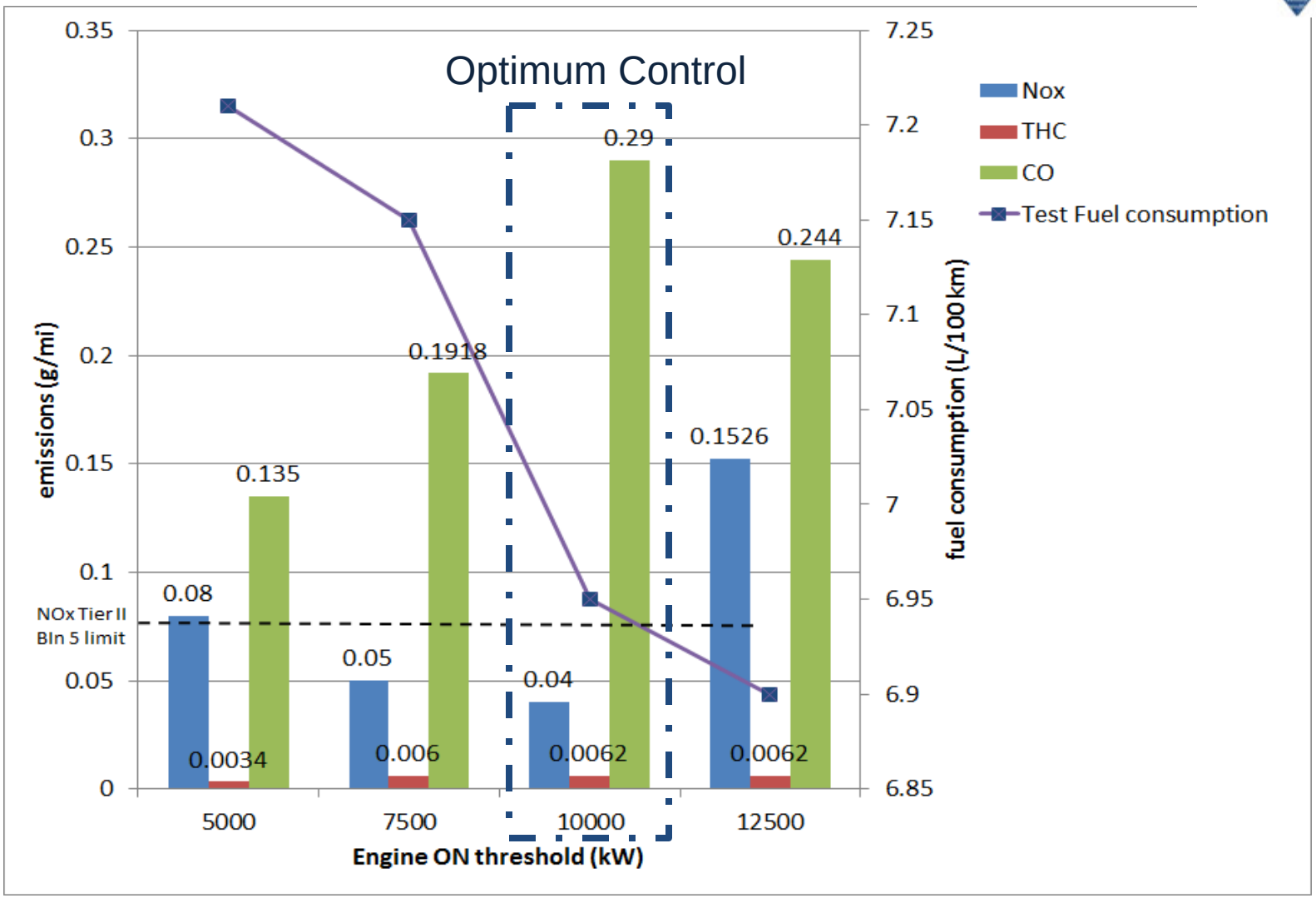
0.35		7.1127	7	7.0213	6.9215
0.4		7.1113	6.9938	7.0327	6.9051

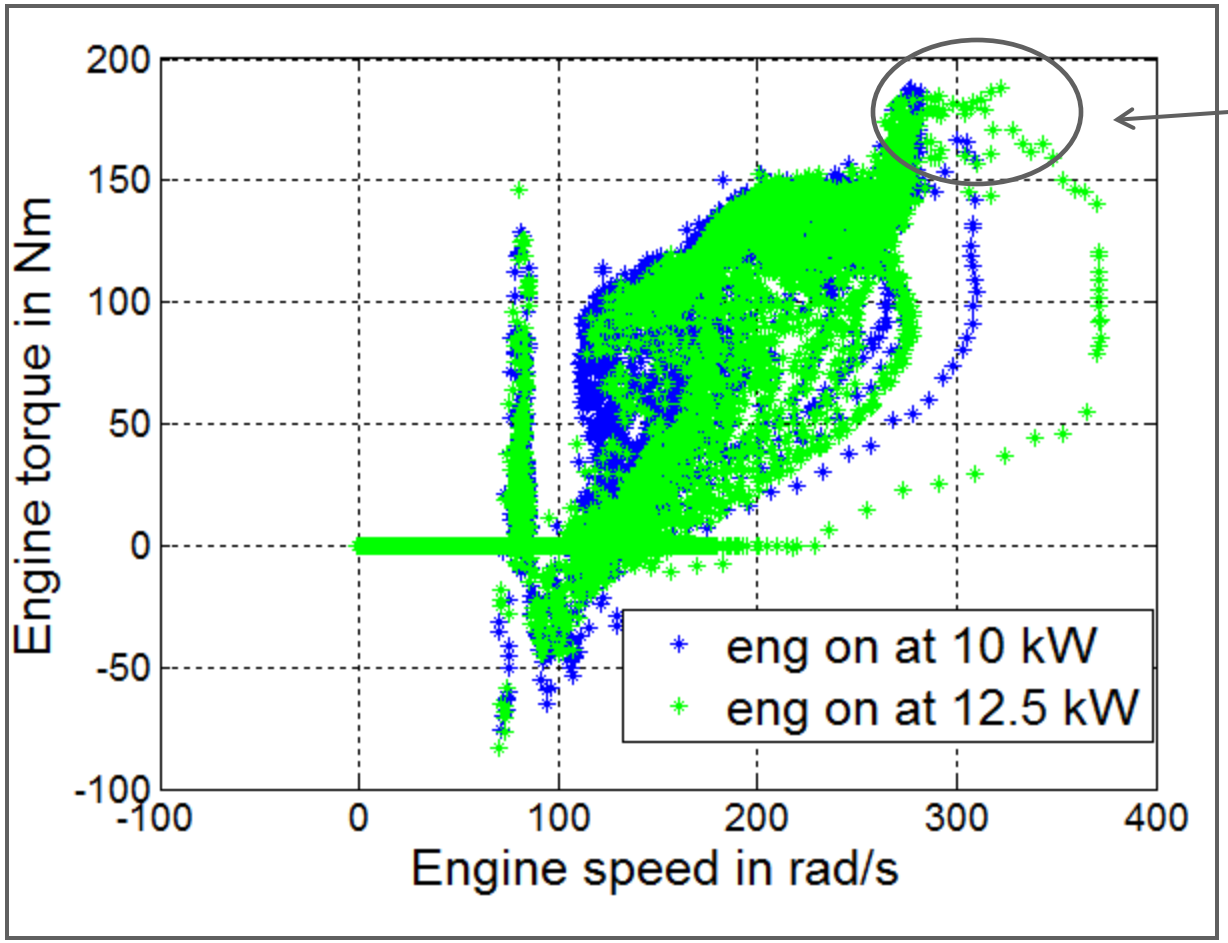
EIL Fuel Consumption Results Validate Simulation Trends.



However, Lowest Fuel Consumption Shows High NOx Emissions



Even with Modified Control, High Engine Load for the 12.5 kW Case Causes NOx Increase.



High load operation.

Summary

- Model based design approach used to maximize charge sustaining fuel economy while having emissions comparable to a conventional vehicle.
- The default vehicle level control of the series PHEV was modified to reduce CO and NOx emissions.
- Simulation study with the modified controls was performed to identify maximum charge sustaining fuel economy over a UDDS cycle
- Optimum fuel consumption obtained from simulation was validated using EIL and final result was selected taking emissions into account
- Use of MBD approach has resulted in study being performed with minimal use of EIL tests.
- The vehicle level algorithms modified to take emission into account (i.e., high load operation, tip-ins…) will be used to support other studies to avoid over-estimating technology benefits