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Electrified Deceleration Cylinder Cutoff Engine Control Benefits and Strategies

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Speaker Information

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Agenda

- eDCCO/Hybrid++ introduction
- DCCO and eDCCO advantages
- Electric-only driving and algorithms
- Vehicle platform and fuel economy projections
- DCCO transitions
- Vehicle drive cycle results
- Value proposition and summary

Tula Technology SAE Presentations

- **2021-01-0459 Evaluation of a New High Efficiency Engine Concept with Atkinson cycle, Cooled EGR and Dynamic Skip Fire**
- **2021-01-0450 Application of Dynamic Skip Fire for NOx and CO2 Emissions Reduction of Diesel Powertrains**
- **2021-01-0446 Controls and Hardware Development of Multi-Level Miller Cycle Dynamic Skip Fire (mDSF) Technology**
- 2020-01-0313 Fast Catalyst Light-Off with Dynamic Skip Fire
- 2019-01-1245 Instrumentation and Processor in Loop Verification for Dynamic Skip Fire Technology
- 2019-01-1054 Vibration Rating Prediction using Machine Learning in a Dynamic Skip Fire Engine
- 2019-01-0549 Dynamic Skip Fire Applied to a Diesel Engine for Improved Fuel Consumption and Emissions
- 2019-01-0227 mDSF: Improved Fuel Efficiency, Drivability and NVH Via DSF and Miller Cycle Synergies
- 2018-01-1162 Method to Compensate Fueling for Individual Firing Events in a 4-Cylinder Engine Operated with Dynamic Skip Fire
- 2018-01-1158 Machine Learning for Misfire Detection in a Dynamic Skip Fire Engine
- 2018-01-0891 λDSF: Dynamic Skip Fire with Homogeneous Lean Burn for Improved Fuel Consumption, Emissions and Drivability
- 2018-01-0864 Electrified Dynamic Skip Fire (eDSF) - Design and Benefits
- 2016-01-0672 Fuel Economy Gains through Dynamic-Skip-Fire in Spark Ignition Engines
- 2015-01-1717 Modeling and Simulation of Airflow Dynamics in a Dynamic Skip Fire Engine
- 2015-01-0210 Misfire Detection in a Dynamic Skip Fire Engine
- 2014-01-1675 Methods of Evaluating and Mitigating NVH when Operating an Engine in DSF
- 2013-01-0359 Design and Benefits of Dynamic Skip Fire Strategies

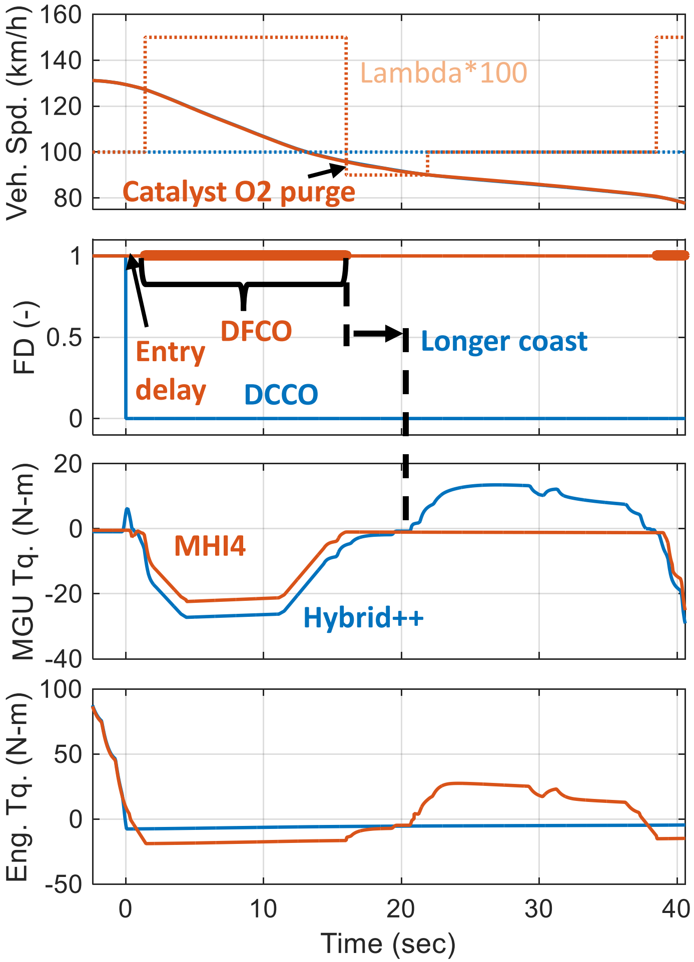
eDCCO/Hybrid++ Introduction

- All-at-once cylinder deactivation systems have lower cost and are attractive to customers
- DCCO extends coasting by eliminating retarding pumping torque encountered in typical DFCO, and prevents catalyst oxygenation
- Opportunity for electric driving with fully deactivated engine when torque demand is low
  - Electric driving doubles fuel cutoff time in WLTC
- Torque bump on exiting DCCO managed through use of MGU torque; more efficient than other methods

DCCO Advantages over DFCO

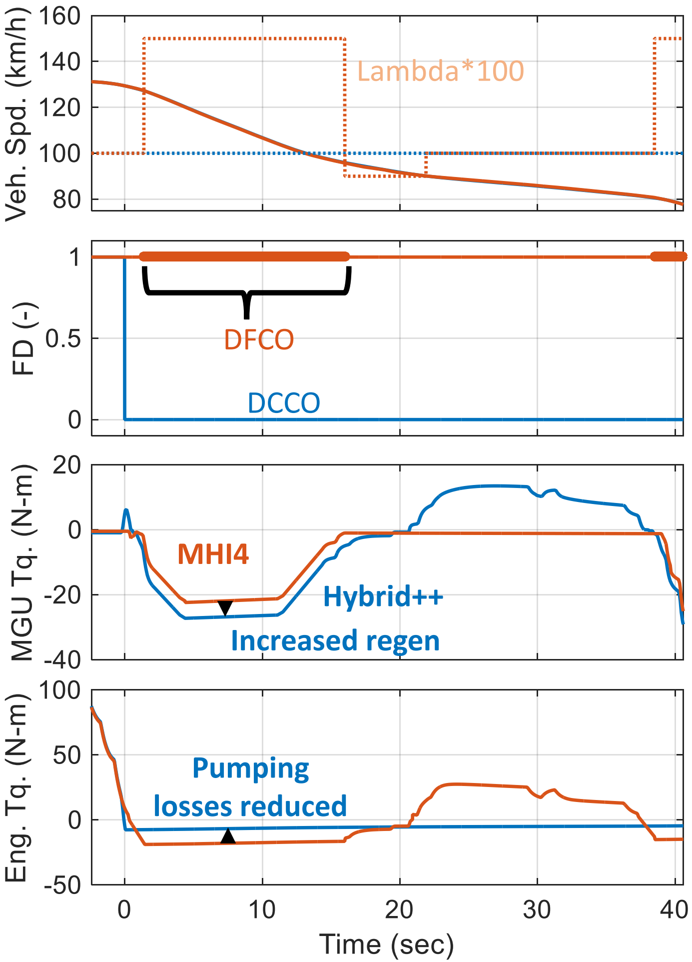
- ***Catalyst oxygen management:*** avoids air pumping through catalyst during decelerations, eliminates need for O2 purge with rich combustion

- ***Increased fuel off time:*** no entry delays, increased coasting time



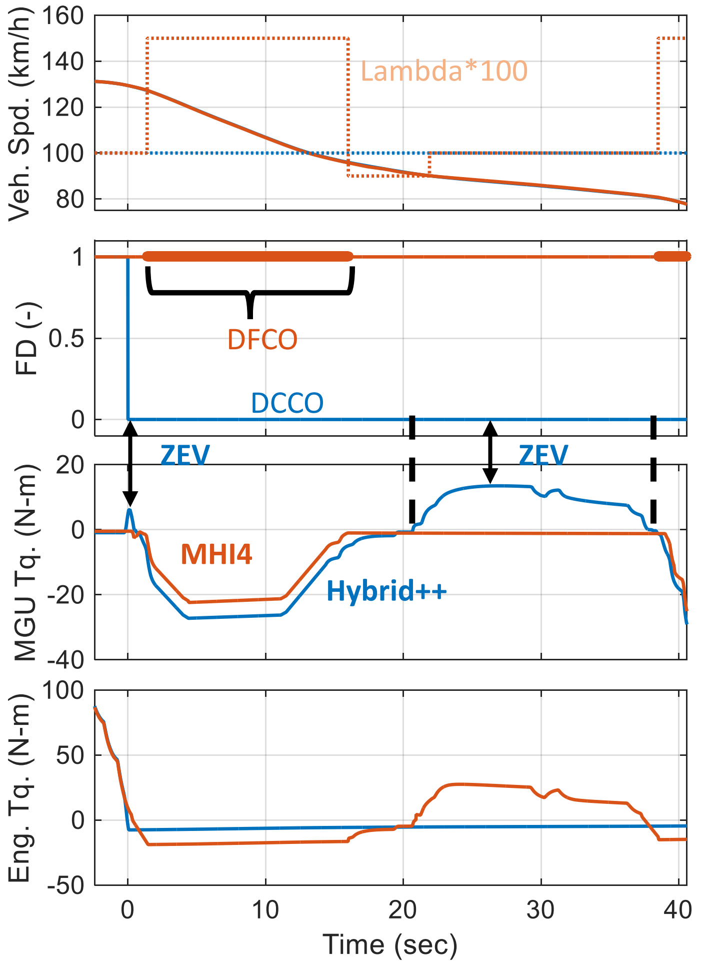
Synergy of DCCO with Mild Hybrid

- ***Increased regeneration*** by reducing pumping losses
- ***High value torque assist*** in using the energy through electric driving



Synergy of DCCO with Mild Hybrid

- ***Increased regeneration*** by reducing pumping losses
- ***High value torque assist*** in using the energy through electric driving
- ***Electric driving mode or ZEV mode***
  - Lengthens DCCO events with earlier entry and delayed exit
  - During low torque maneuvers including coasting or mild decel leading to additional ZEV events



Additional Benefits

- Engine stop in DCCO
  - Avoids return to idle and associated fueling
  - Increases inertia energy recuperation by eliminating pumping

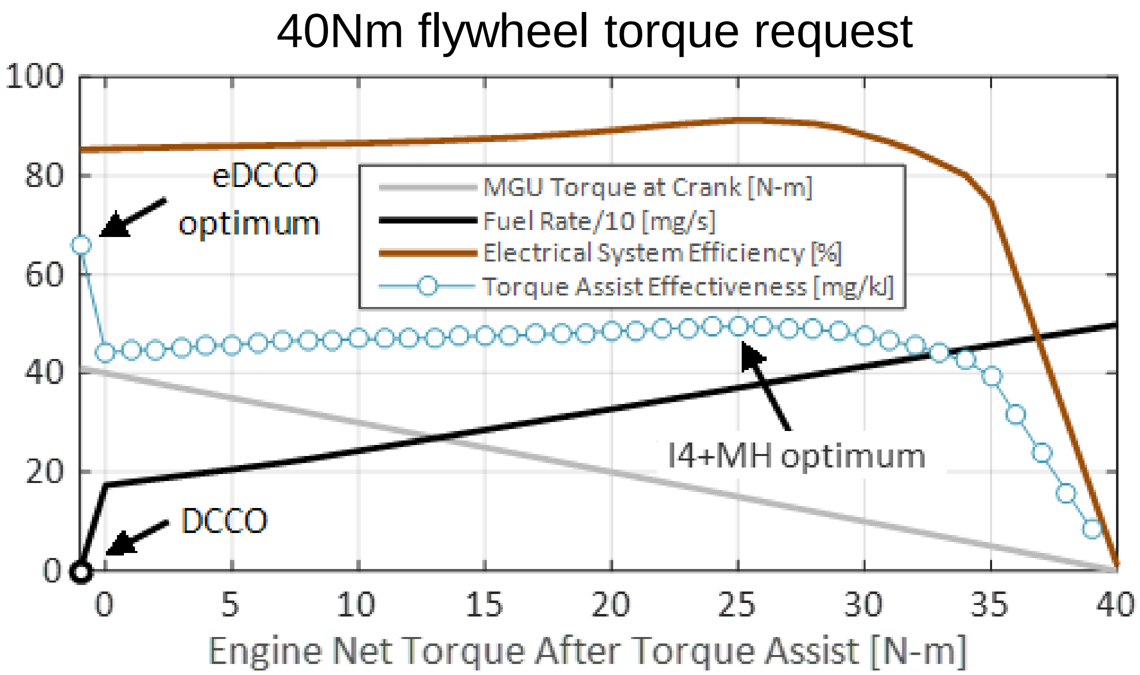
- Engine start in DCCO
  - Improved first combustion after spin-up
  - Eliminates pumping losses during cranking → reduced electrical energy required with better NVH
  - Eliminates air pumped into catalyst

- Reduced toxic emissions due to better catalyst management

- Reduced cold-start emissions due to better combustion after engine spin-up in deac

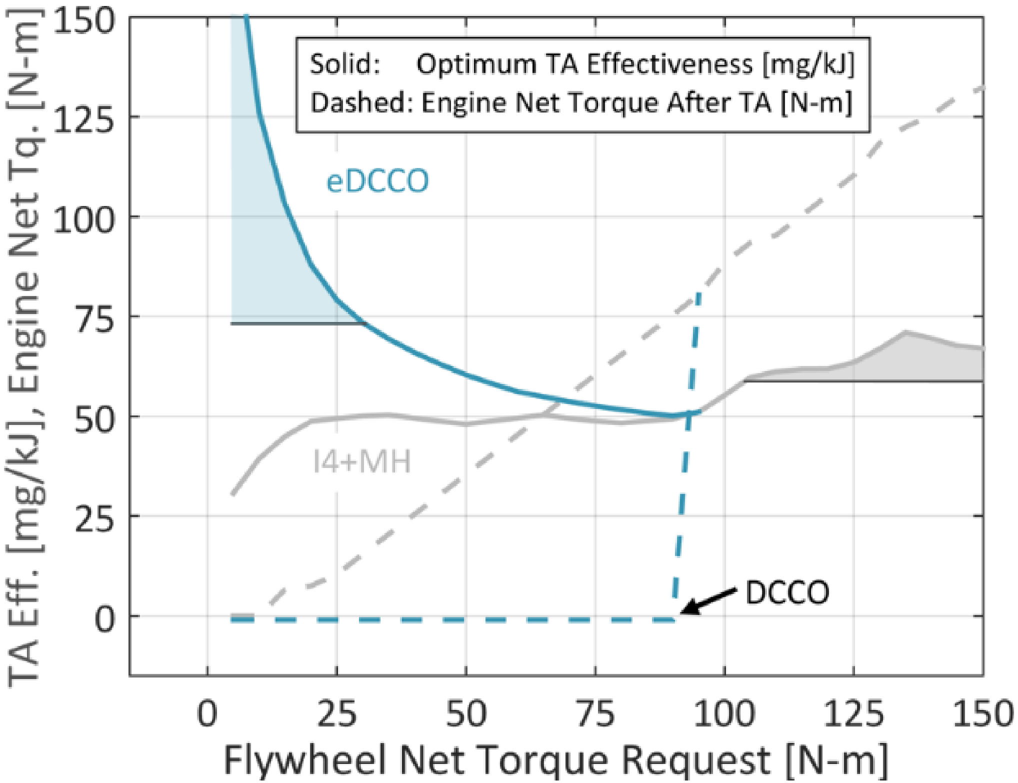
eDCCO Highly-Effective Use of Electrical Energy for Torque Assist

- Effectiveness of MGU torque assist quantified as fuel saved per unit electrical energy spent
- Most-effective torque assist with engine firing is near the maximum electrical system efficiency
- DCCO with electric driving is a higher-value use of battery energy than firing

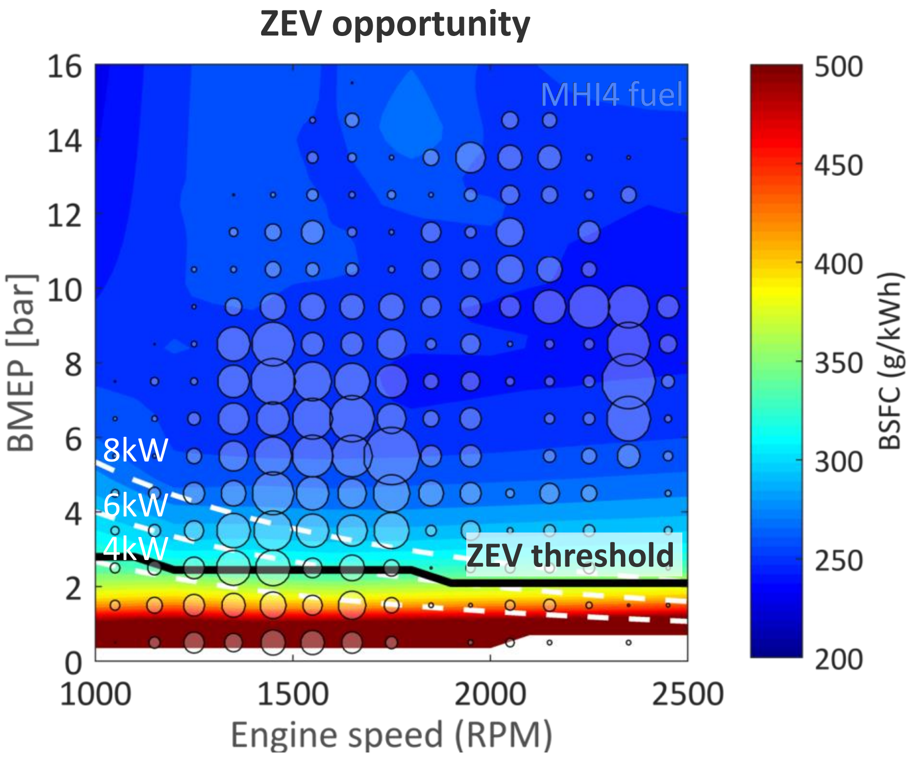


eDCCO Highly-Effective Use of Electrical Energy

- Below 95Nm flywheel torque request, ZEV driving has better TA effectiveness than firing the engine, especially at the lowest loads
- To limit the use of TA, a threshold of effectiveness is chosen, here 73 mg/kJ produces battery state of charge at the end of a drive cycle matching that at the beginning
- For I4+MH operation above 95Nm, TA improves engine efficiency only at the highest flywheel torque requests. A threshold of 60 mg/kJ maintains SoC
- The lower threshold indicates less opportunity to use battery energy in a highly-effective way



ZEV operation to replace low load ICE operation



- ZEV operation occurs at low torque where ICE operates inefficiently
- Operation spans a range of 4-8kW and 25Nm MGU tq
  - Depending on system efficiency and available battery energy

Test Vehicle

Base Vehicle	2016 Volkswagen Jetta SEL
Test Weight	1588 kg
Engine	EA888 1.8L gasoline turbocharged direct injection
Valvetrain	4 valves per cylinder, full-authority deactivation, operated in ganged mode
Transmission	6-speed automatic with torque converter clutch *
Gear Ratios	4.459, 2.508, 1.556, 1.142, 0.851, 0.672
Final Drive Ratio	3.23
Driven Wheels	Front
Tires	225/45 R17

***** Torque converter clutch operated fully locked (no slip) in gears 3+ to emulate target vehicle application***

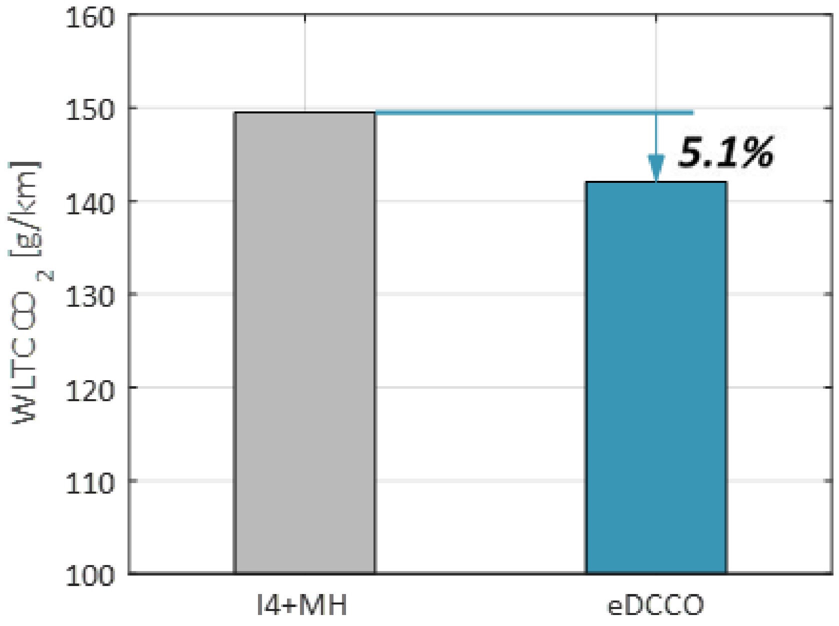
Electrification

MGU	Borg-Warner 12kW rated power permanent magnet synchronous
Inverter	Tula 550A power stage
Battery	A123 8Ah 48V lithium iron phosphate
P0 Pulley Ratio	2.137
FEAD Tensioner	Litens bidirectional

- 40Nm MGU torque limit imposed

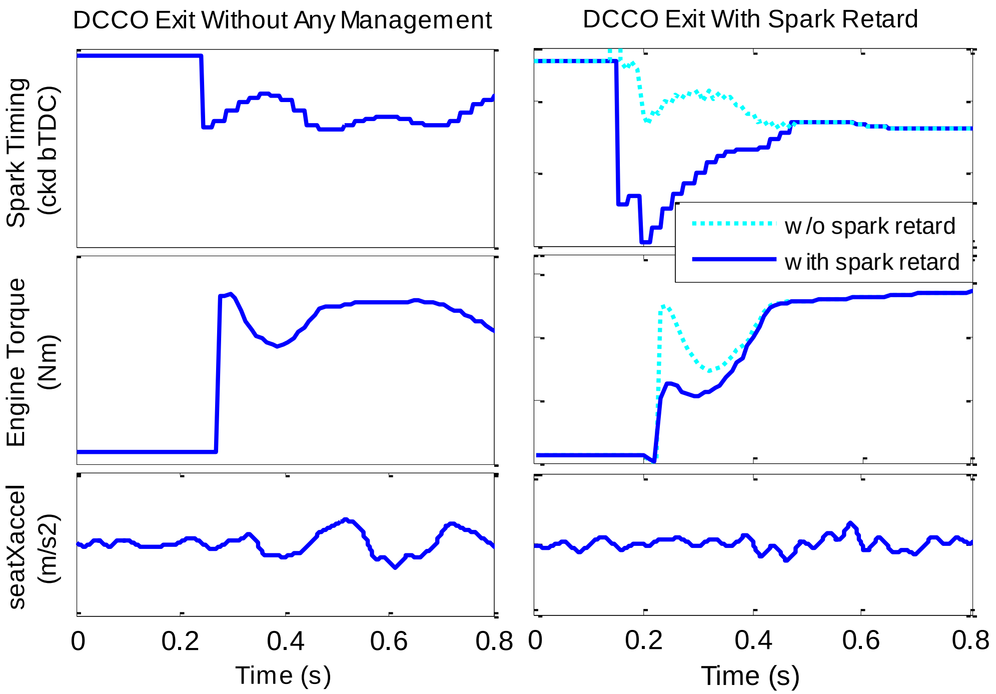
Projected CO2 Reduction

- With electric driving in DCCO strategy, no need for catalyst oxygen purge, and MGU managed DCCO exits, CO2 reduction of 5.1% is predicted over I4 mild-hybrid baseline



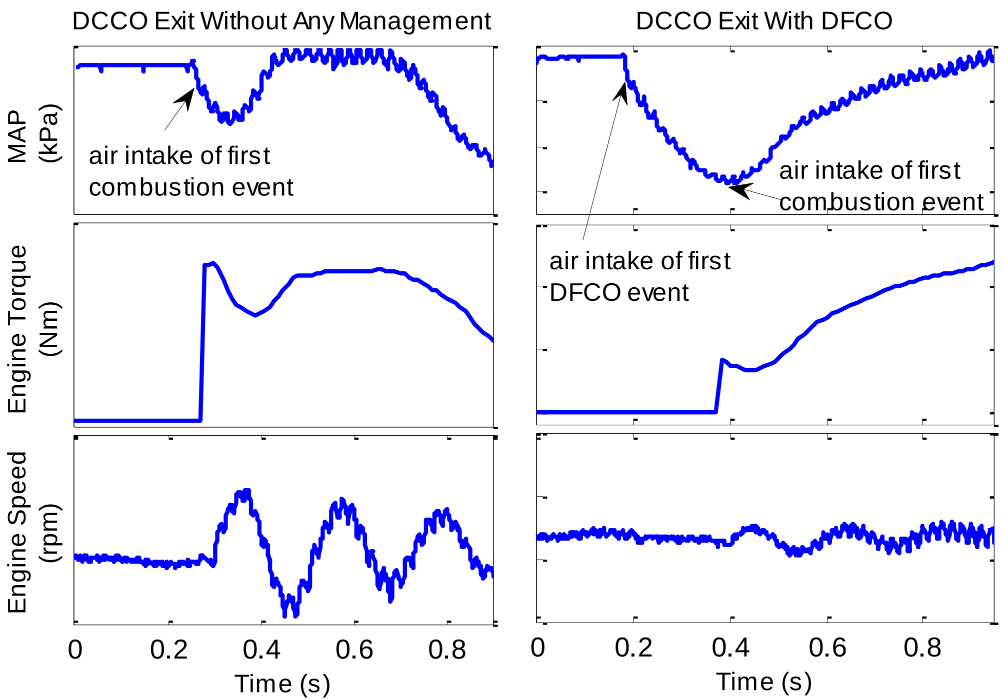
DCCO Transitions – Introduction

- Locked torque converter clutch introduces additional challenges for NVH
- Refiring of all cylinders at end of DCCO, at atmospheric manifold pressure, results in jarring engine torque not mediated by slipping TCC



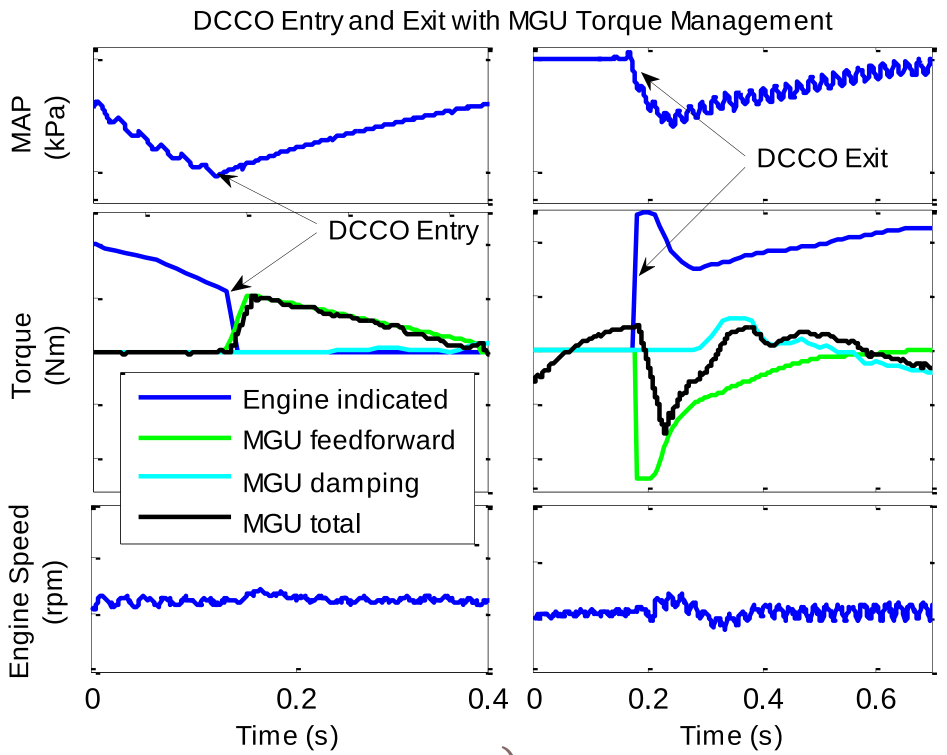
DCCO Exit Management – DFCO Managed

- Brief DFCO period at the end of DCCO reduces manifold pressure and combustion torque on refiring



DCCO Exit and Entry – MGU Managed

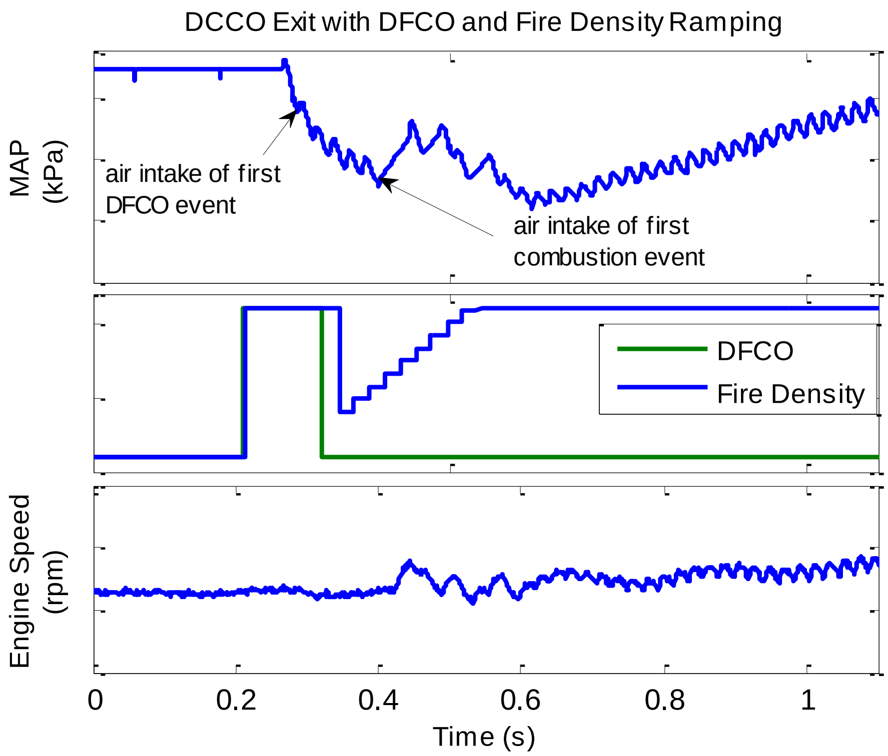
- Absorb excess torque on refiring using the MGU, energy captured in battery
- A combination of feedforward and feedback damping strategies shown effective



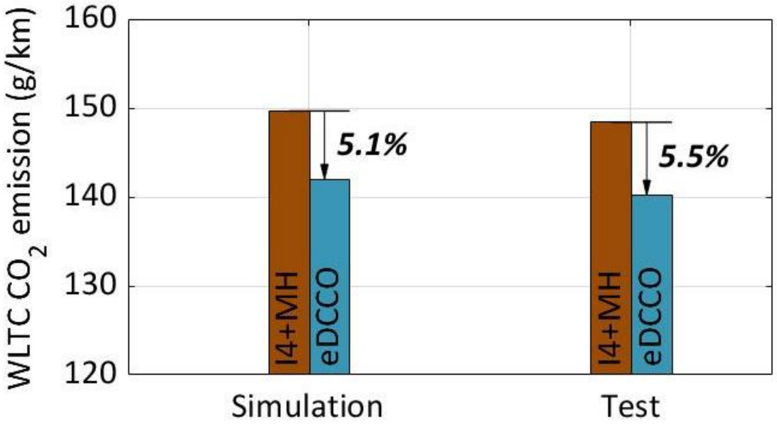
$$T_{MGU} = T_{feedforward}(T_{engine}, T_{desired}) + T_{damping}(N_{engine})$$

DCCO Exit and Entry – DFCO + FD Managed

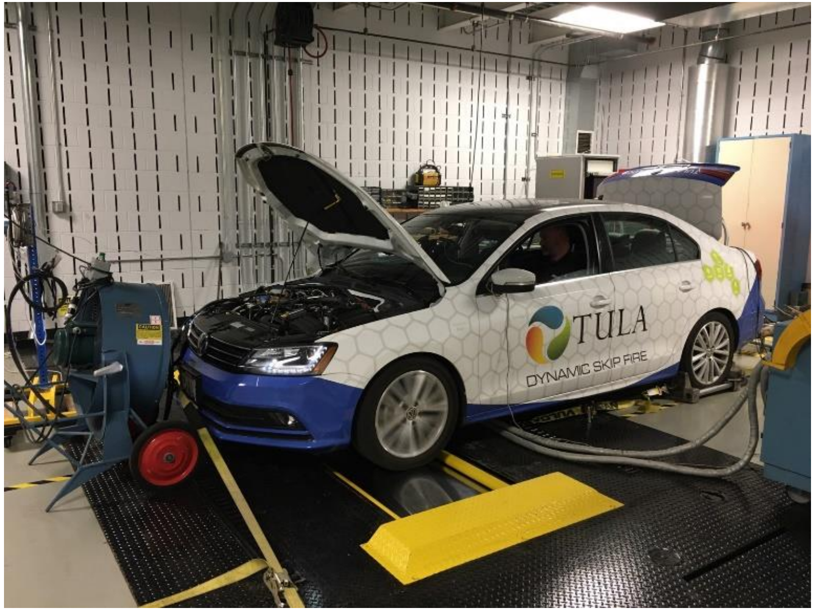
- Under certain operating conditions such as low speeds, a ganged deactivation mechanism may still be capable of skip-firing
- This allows possibility of FD managed exits, and combination strategies



Drive Cycle Results

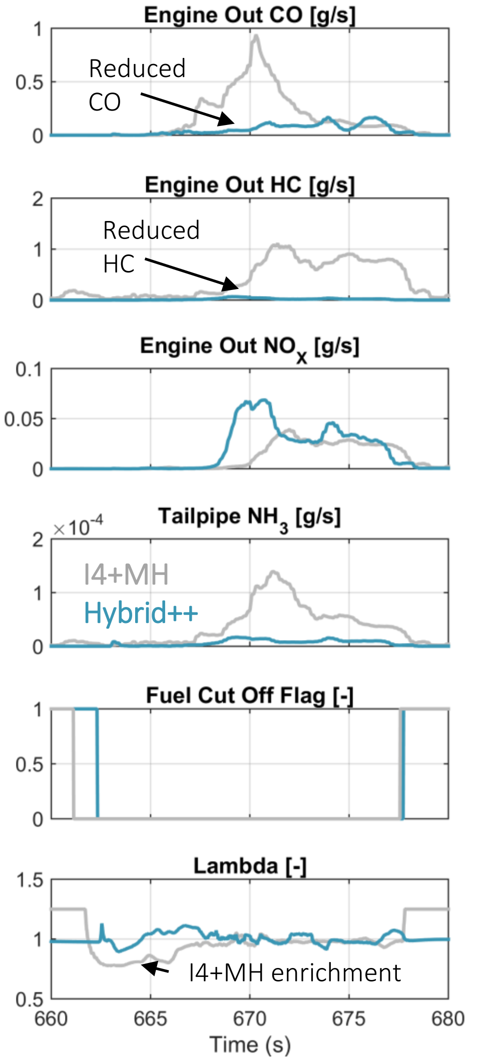


	I4+MH	eDCCO
Fuel Cut-off Time [s]	186	**374**
Catalyst O2 purge fuel [% of drive cycle fuel]	1.0	**0**
Electrical Regen Energy [MJ]	1.37	**1.51**
TA Effectiveness [mg/kJ]	61	**90**
Electrical TA Energy [MJ]	0.63	0.63
Battery SoC Change [%]	0	+6

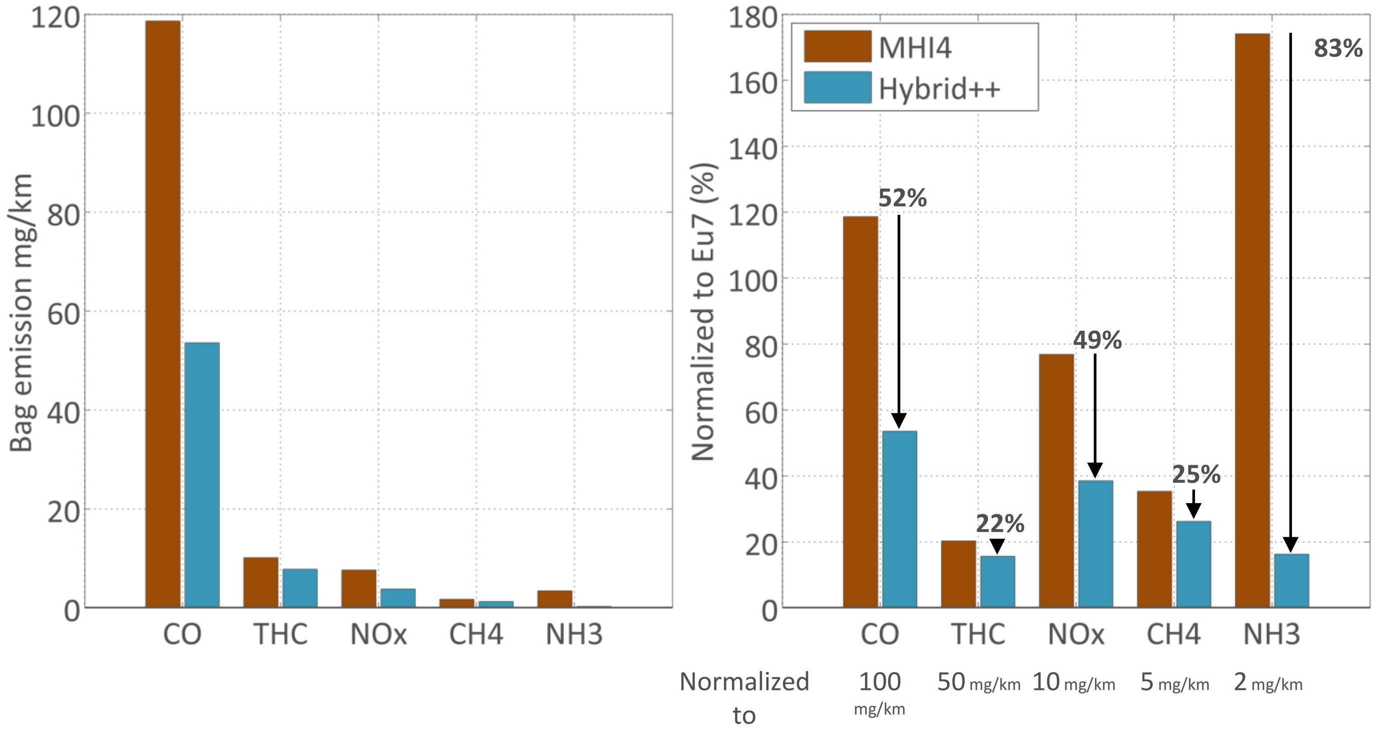


Catalyst Oxygen Management

- During DCCO, no oxygen is introduced into the exhaust aftertreatment system
- On refiring the engine, significant catalyst management challenges are avoided
  - ➢ No enriched air-fuel mixture to deoxygenate the catalyst
  - ➢ Engine out CO and HC avoided, limiting reactants for NH_3 production
  - ➢ Also inhibits NH_3 production by maintaining higher catalyst temperature by eliminating of air pumping



Significant Toxic Emissions Reduction



- WLTC CO and NOx reduced by 50% with respect to mild-hybrid I4 operation
- HC and CH4 reduced by 20 – 25%
- NH3 reduced by 80%
- Test vehicle achieved strictest proposed targets for Euro7 with margin
- Further reductions in emissions expected with implementation of deac in cold start and stop-start

Conclusions and outlook

- eDCCO can be mechanized with grouped deactivation valvetrain to minimize cost
- Controls and calibration well understood
- Favorable CO_2 and NVH results on 4-cylinder platform
- Favorable toxic emissions results, and further potential exists
- Estimated value proposition for 4-cyl at \$35/%CO_2 and 3-cyl at \$25/%CO_2, against MH baseline
- High-value target applications of 3/4-cyl, P0/P1 48V mild hybrid

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