Intelligent Integration of Electric Motors and Engines

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Outline

• Engine Research Center (ERC) overview
• Overview of DOE hybrid project
  – Typical off-highway powertrains and challenges
  – Electrification of air-handling
  – Electrification of torque actuation
• Summary
Engine Research Center Overview

- The Engine Research Center (ERC) was established in 1946 by Profs. Myers and Uyehara, who were joined by Prof. Borman in 1970.
- Over the 70 years of its existence, the ERC has pioneered:
  - in-cylinder measurements of gas temperature, composition and heat flux
  - the simulation of turbulent, multi-phase, reacting flows in reciprocating engines
  - high efficiency, low-emissions combustion strategies such as RCCI and HCCI
- Current ERC has 5 active faculty, 3 emeritus faculty, and ~50 graduate students, post-docs, and scientists
Engine Research Center Overview

- ERC Research Projects

- Fuel Injection and Sprays
- System Optimization
- Charge Preparation
- Low Emissions High Efficiency
- Exhaust Aftertreatment
- Controls
- Diagnostics
Overview of DOE Hybrid Project

- Recently started a new program with DOE focused on hybridization of off-highway vehicles
- Joint program between UW-ERC, WEMPEC, John Deere, and Purdue University

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<td>UW – Madison Engine Research Center</td>
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<td>Program Lead</td>
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Overview of Off-Highway Vehicle Powertrains

Baseline powertrain
- Turbo-charged diesel engine
- Hydraulic or mechanical transmission
- High pressure (>2000 bar) common-rail fuel system
- Suite of emissions control
  - Cooled exhaust gas recirculation (EGR) → in-cylinder NOx control
  - Selective catalytic reduction (SCR) → controls NOx in the exhaust
  - Diesel particulate filter (DPF) → captures soot in the exhaust
  - Hydrocarbon, carbon monoxide, and ammonia slip catalysts
Off-highway Vehicle Challenges

- Transient duty-cycle requires rapid torque response
  - Engine is often oversized to accommodate torque acceptance
  - Turbine is sized for transient response, resulting in increased back pressure at high flow conditions → decreased efficiency

- “Passive” control of air-handling results in upload soot “spikes” and download NOx “spikes”

- Periods of low-load operation require after-treatment thermal management (i.e., using fuel to keep the aftertreatment warm without performing work)

- Integration of electric motors and engines may mitigate these challenges while retaining the required energy density for operation in remote environments
Improved Air Handling through Electrification

• Electric supercharger
  – Located in parallel with existing turbocharger and used to provide additional air-flow to help spool turbo
  – Energy recovery is possible, but has substantial losses
  – System simulations show a substantial improvement in transient response
  – Efficiency improvement requires system architecture changes enabled by improved air control (e.g., downsizing)
Improved Air Handling through Electrification

- Electric turbocharger
  - High speed > 50,000 rev/min electric motor coupled to turbo-shaft
  - Natural operation in both powering and energy recovery modes
  - 48V and higher voltage systems are common
Soot Reduction using E-Turbo

- E-turbo’s improved control over airflow expected to reduce transient soot by avoiding operation at low AFR
- Assessed using one-dimensional fluid dynamics modeling over a load step from 50 to 400 N-m
- E-turbo uses exhaust air-fuel ratio feedback to minimize operation at low AFR (conducive to soot formation)
- Results show
  - 33% reduction in transient soot
  - Estimated 1.4% reduction in fuel consumption due to reduced DPF regeneration penalty
• Additional benefits are possible with full-hybridization due to transient nature of the drive cycle
  – Allow use of a smaller engine by peak shaving
  – Avoid low load operation where mechanical losses are high by valley shaving
Hybridization and Downsizing

- Baseline engine: 6.8 L Tier 4 final engine with a peak torque of 1057 N-m (BMEP = 19.5 bar)
- Peak load of downsized (4.5 L) engine constrained to 19.5 bar BMEP
- Non-road transient cycle (NRTC) simulated
  - Engine provides torque from 200 N-m to 700 N-m
  - Charging below 200 N-m
  - Motor provides torque above 700 N-m
  - NOx constant at 0.4 g/kW-hr
  - Battery SOC forced to return to initial value at the end of the cycle
- 4% reduction in fuel consumption at equal DEF consumption
Energy Recovery using E-Turbo

- E-turbo used in conjunction with hybridization allows recovered energy to be used as torque demand

- One-dimensional fluid dynamics model used to evaluate energy recovery using the e-turbo

- E-turbo was set to absorb power from the exhaust by targeting an air-fuel ratio 2 to 5 points below the steady-state air fuel ratio

- ~2.7% reduction in fuel consumption
Combined System Benefits

- System analysis shows pathway to > 10% increase in efficiency
Summary

• Substantial potential for improvement in off-highway vehicle efficiency through hybridization
• System analysis shows a pathway to >10% reduction in fuel consumption
  – Downsizing
  – Energy recovery
  – Reduced soot penalty
  – Reduced catalyst heating penalty
• Engine and in-vehicle demonstration planned
Questions???

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Reducing the Catalyst Heating Penalty

- SCR equipped engines have a fuel consumption penalty at low load conditions due to the requirement to keep the catalyst temperature above ~200° to 250° C to allow urea dosing.
- E-turbo can be used to control catalyst inlet temperature to keep the catalyst warm while minimizing the fuel consumption penalty.
- Application of e-turbo shows
  - 18% reduction in fuel consumption during catalyst heating or “stay warm” operation
  - Estimated reduction in NRTC fuel consumption of 2.7%