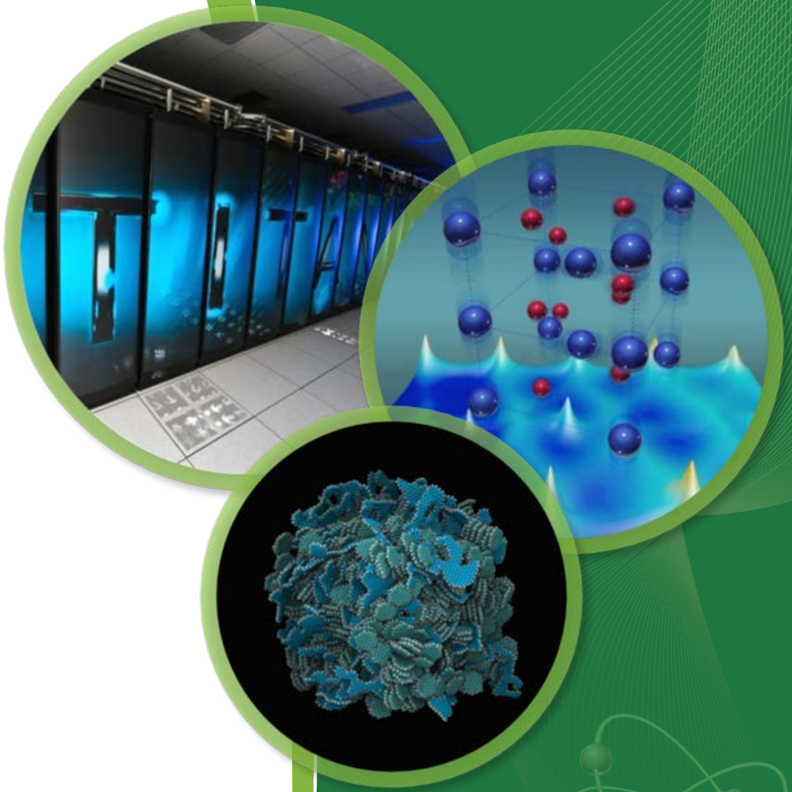
Internal Combustion Engines for Hybrid Electric Configurations

Jim Szybist, Robert Wagner and Scott Curran

National Transportation Research Center
Oak Ridge National Laboratory



ARPA-E High Efficiency Hybrid Vehicles Workshop
Southfield, MI
October 12, 2017

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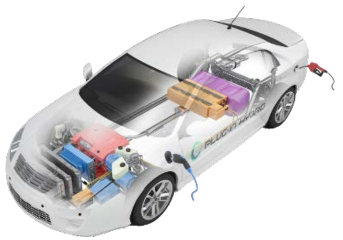
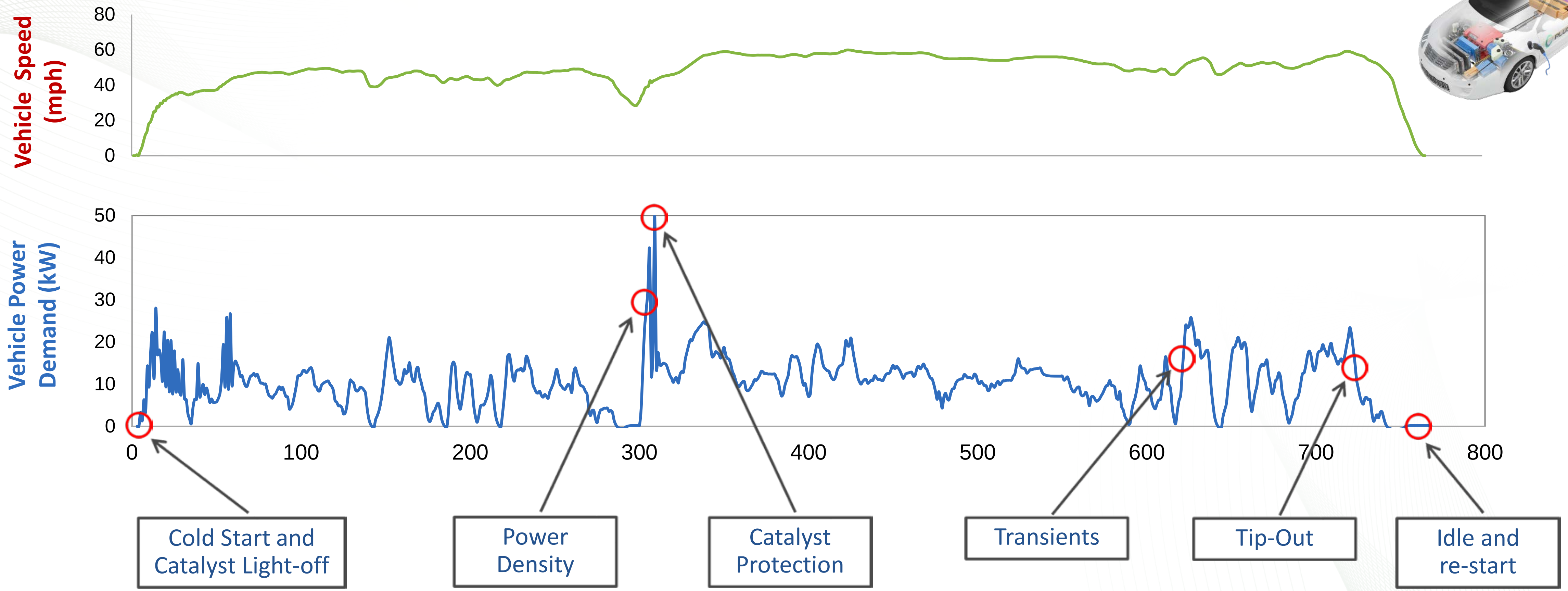
Hybridization of Light Duty Vehicles Changes Engine Requirements.

Presents Opportunities and Challenges





Hybrid configurations can change engine requirements and have potential to change powertrain configurations

ICE Hybridization Strategy will Dictate Engine Requirements.
OEMs make Decisions for Each Vehicle Platform, Portfolio will Likely Span Full Spectrum.

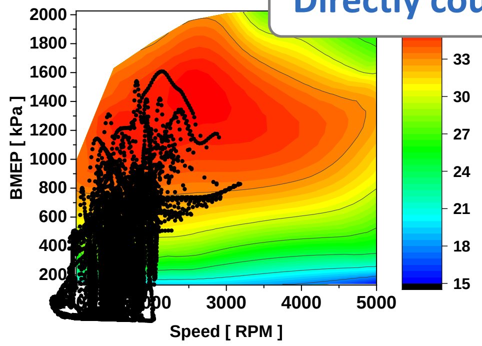
Electric Accessories and Stop-Start Technology:
No Change to Engine Requirements

Degree of electrification

0%

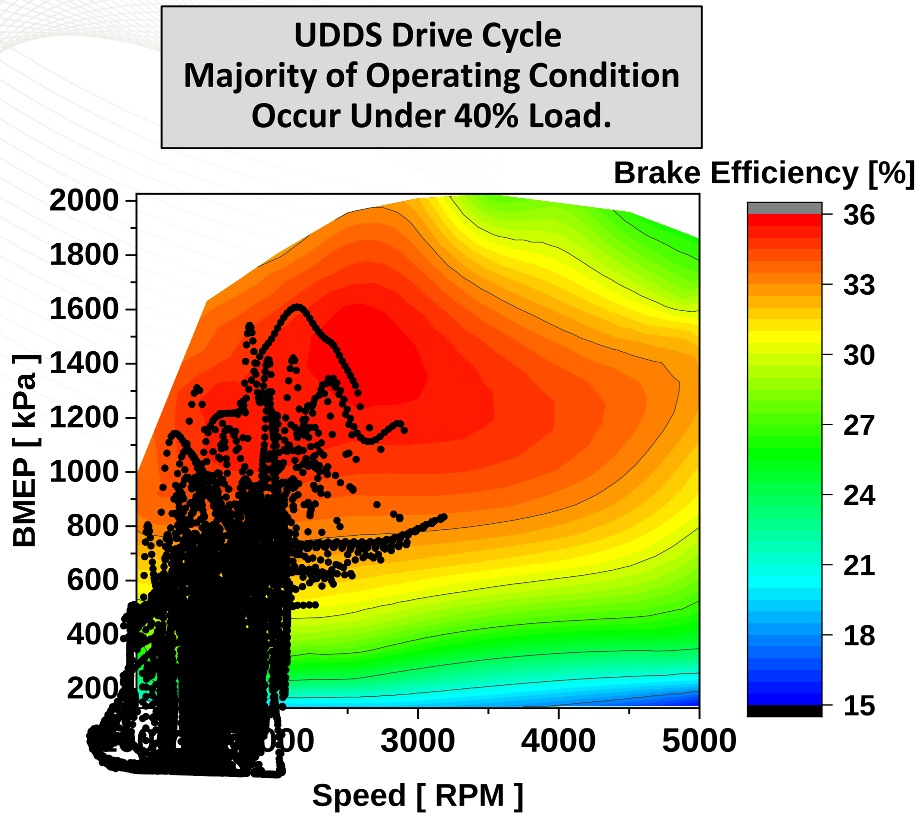
100%

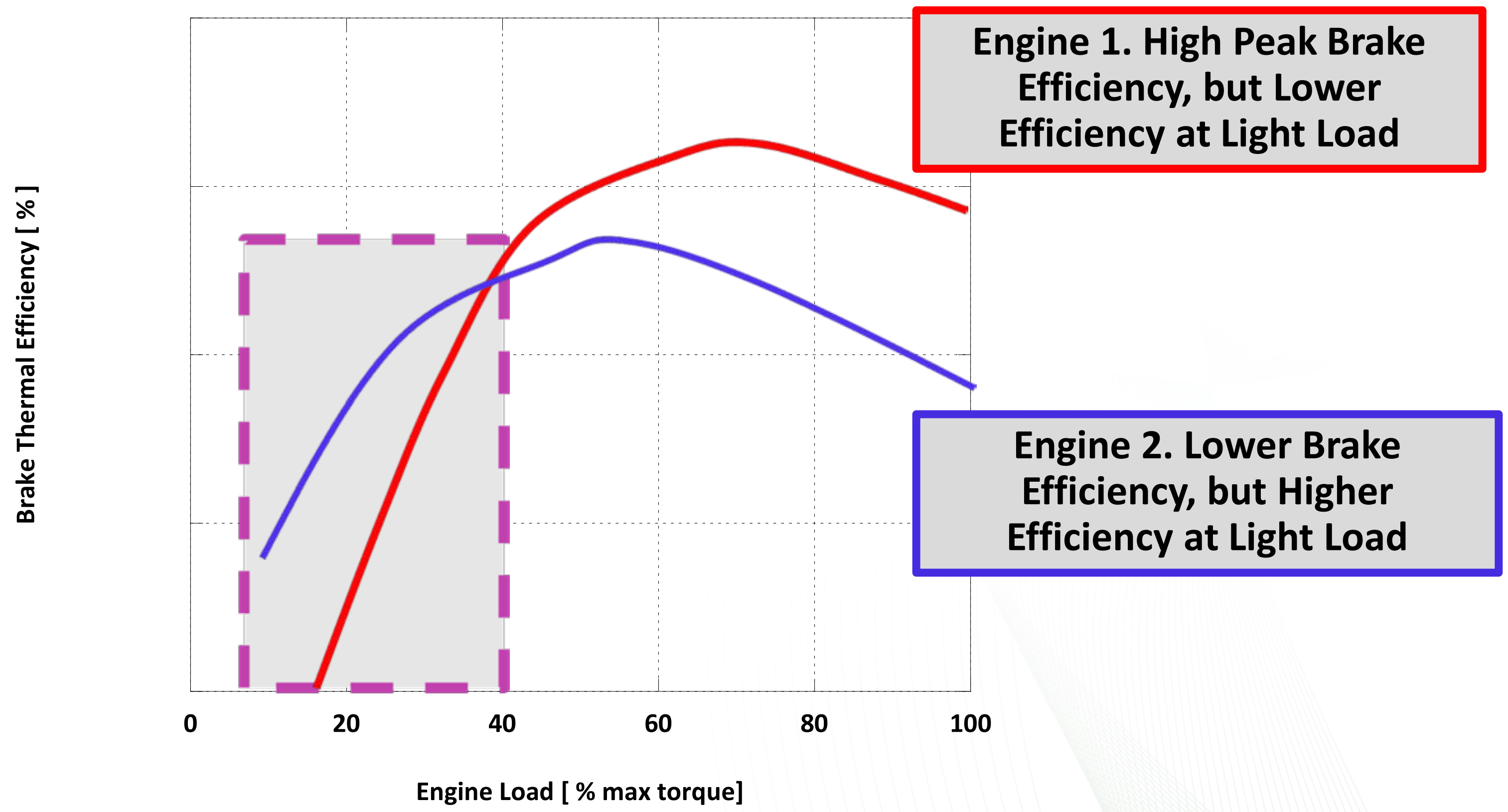
Directly coupled



For Conventional Vehicle or Low Degree of Hybridization, Engine is Required to Follow Load Demand of Vehicle

Part-Load Efficiency is of Primary Importance





Since light duty vehicle drive cycles are primarily at light engine loads, Engine 2 will likely lead to higher fuel economy despite lower peak efficiency

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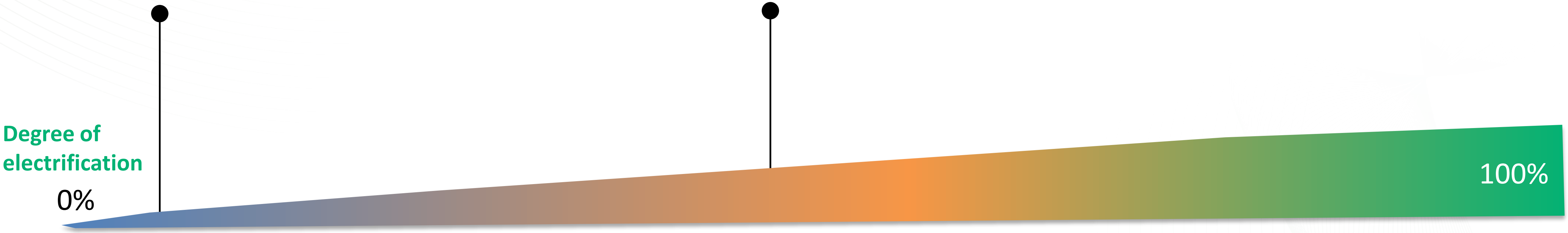
Electric Accessories and Stop-Start Technology:
No Change to Engine Requirements

Partially electrified drivetrain.

Less capable engine acceptable for acceleration and load tracking.

Engine still required to meet peak vehicle power.



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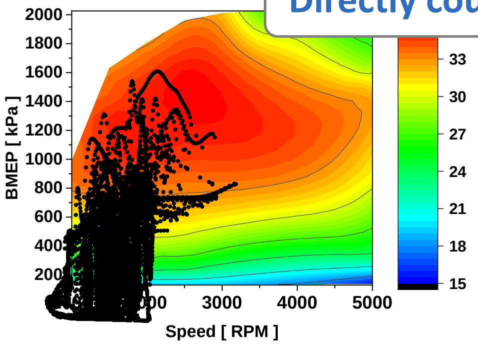
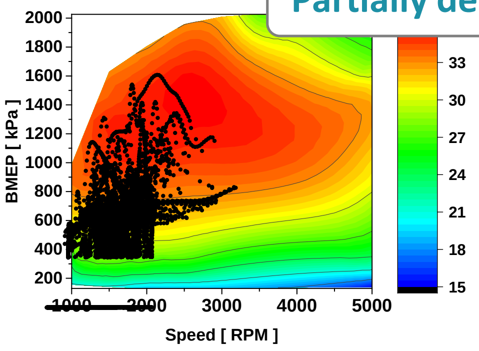
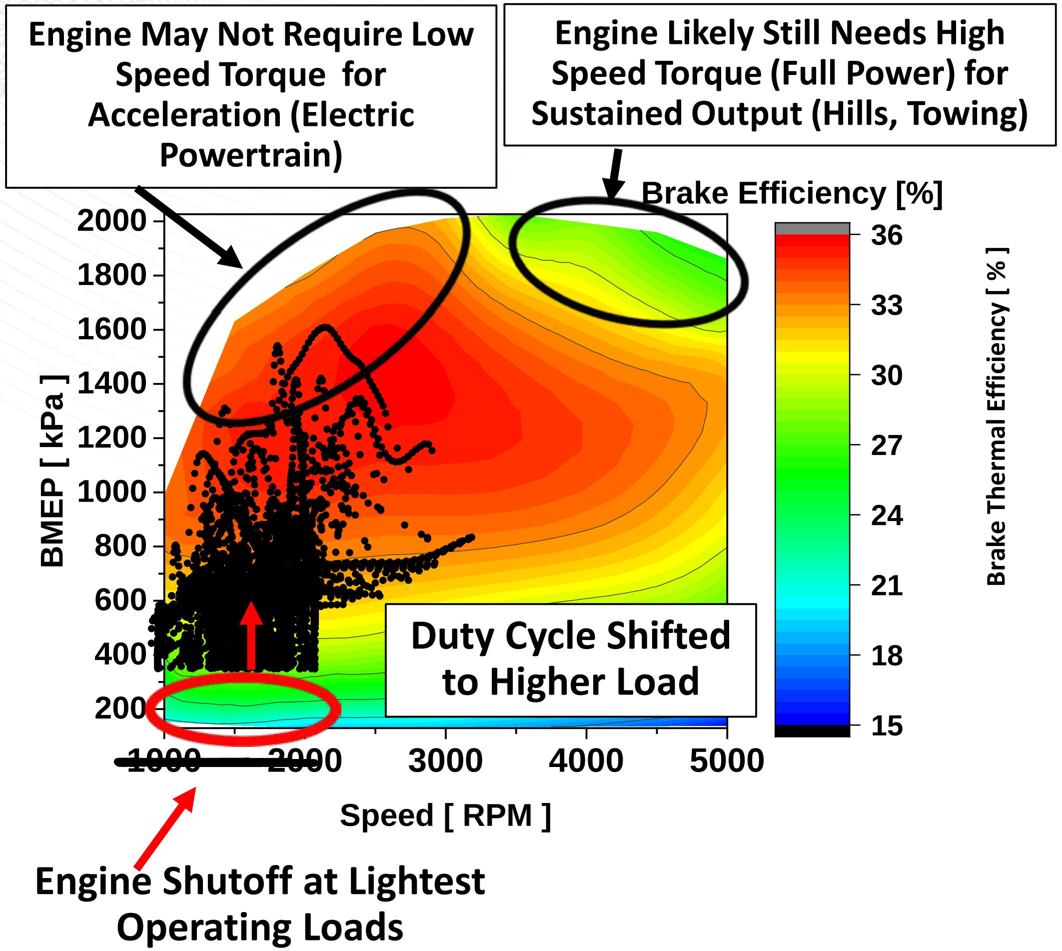


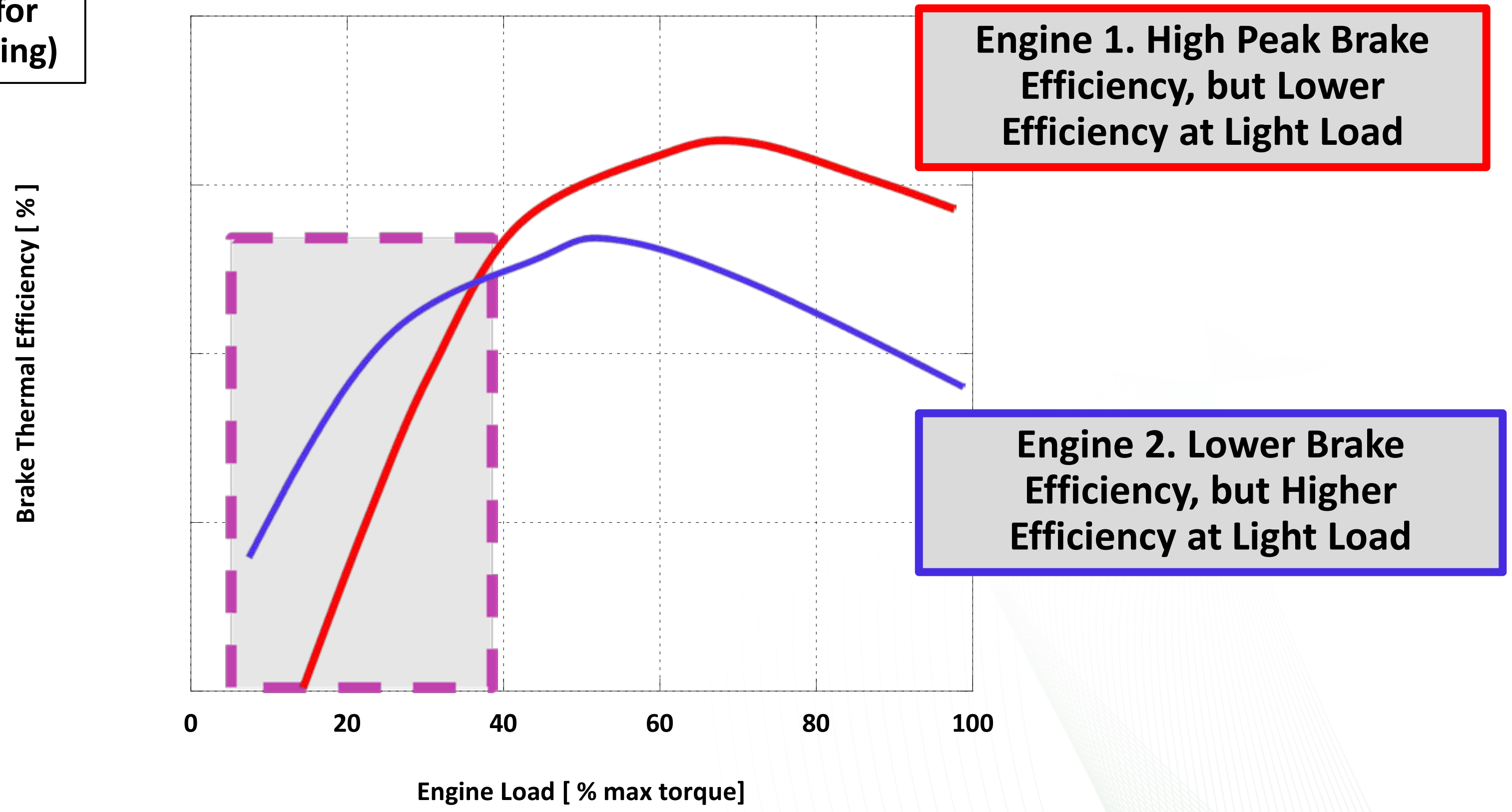
Partially decoupled



For Higher Degree of Hybridization, Engine Shutoff at Lightest Loads and Operating Points Shifted to Higher Load Conditions

Peak Engine Efficiency Increases in Importance





Shifting engine duty cycle toward higher loads reduces the importance of light load efficiency. Best engine for hybrid application is determined on a case-by-case basis.

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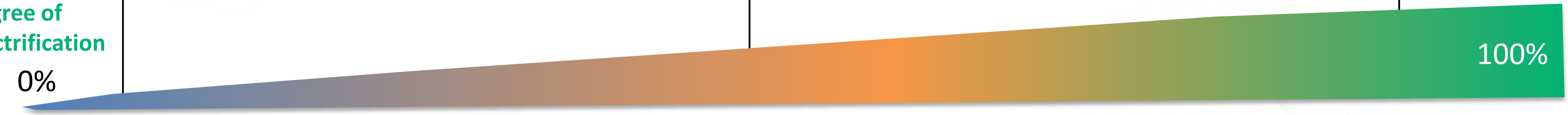
Fully Electric Drivetrain, engine operates only to charge batteries.

Engine required to meet average vehicle power. Load following not required.

Degree of electrification



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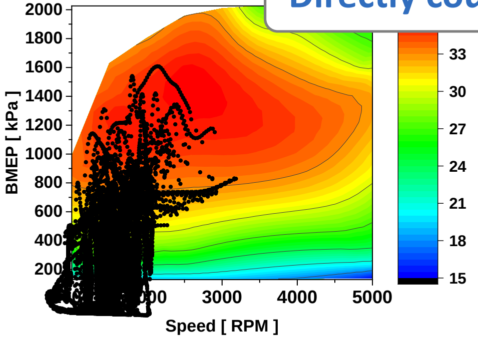
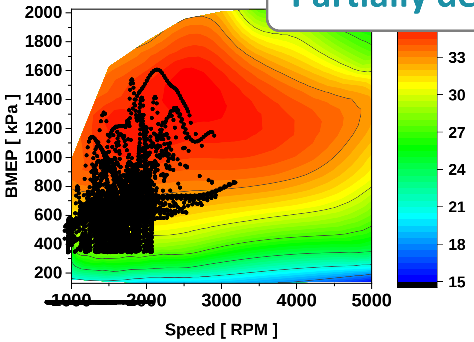
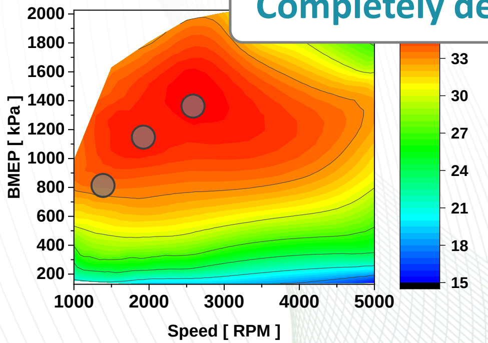


Partially decoupled



Completely decoupled



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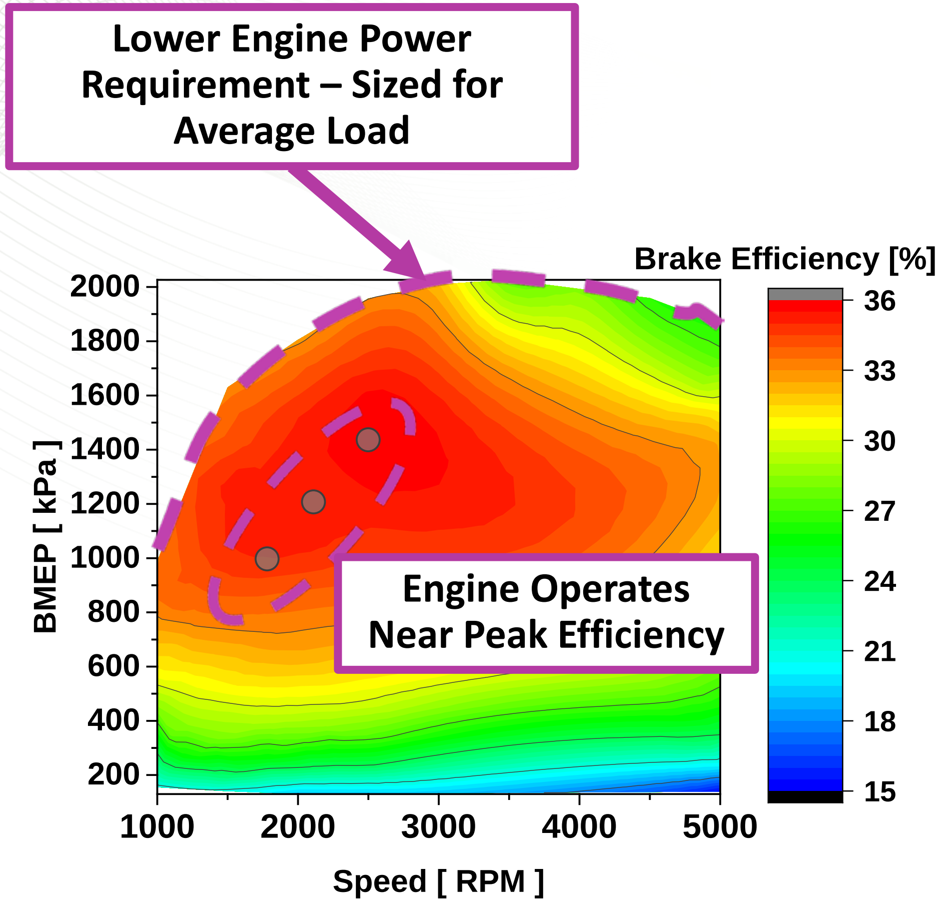
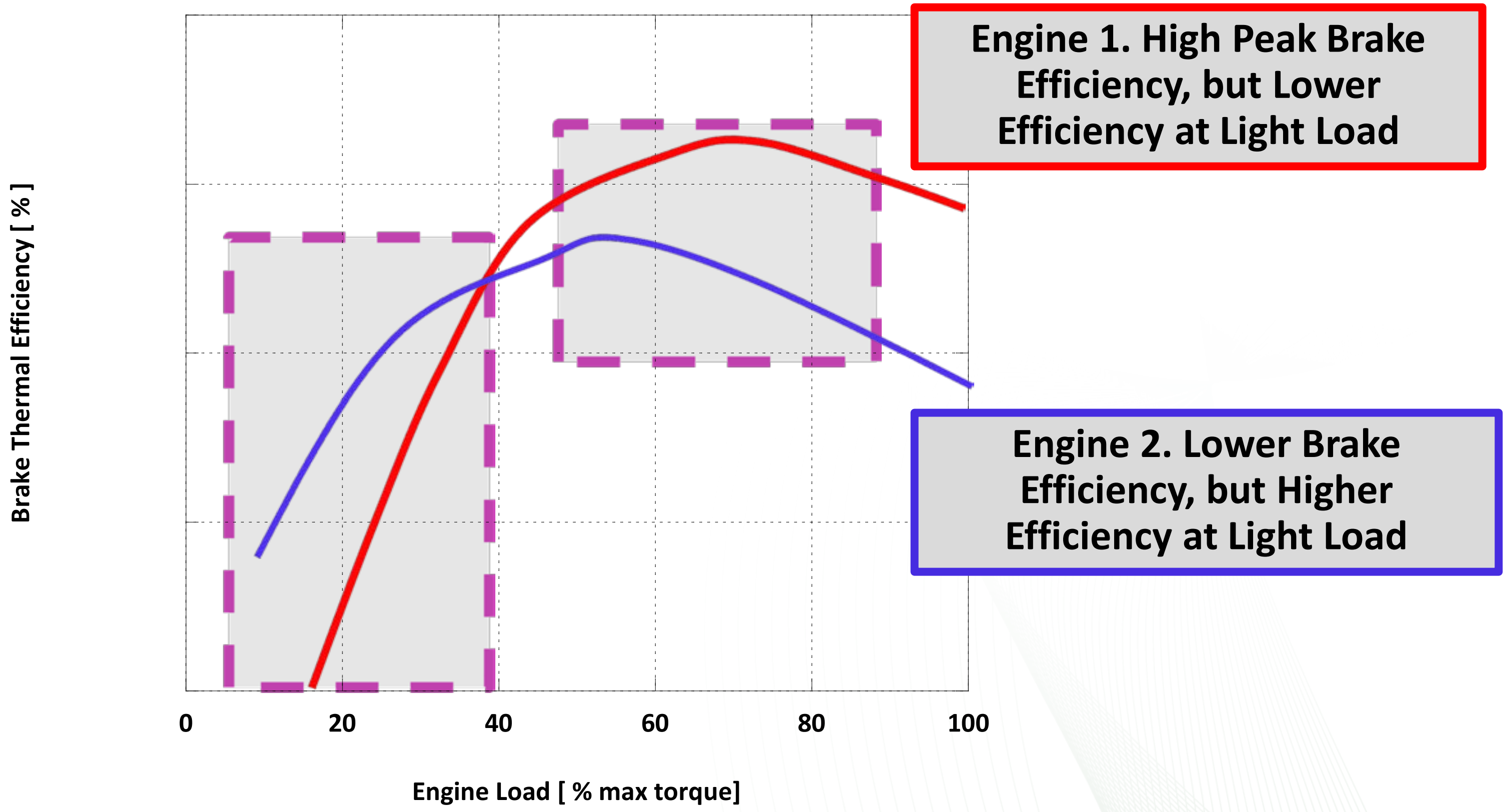
For Decoupled Hybrid, Engine Meets Average Power and Does Not Follow Vehicle Load

Engine Operates Near Peak Efficiency while Charging Batteries, Otherwise Shut Off





Peak efficiency is of primary importance with decoupled powertrain.
Engine 1 will result in superior vehicle efficiency.

Light Duty Engine Technology Options for Hybrid Electric Vehicles

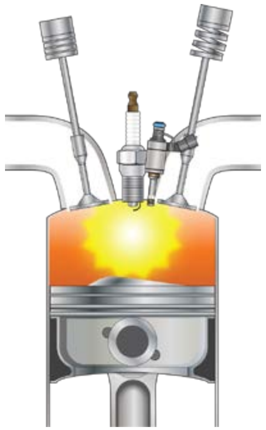
Stoichiometric SI

Benefits:

- *Mature emissions controls*
- *Low cost engine and emission control components*
- *Consumer acceptance (97% of LD energy consumption)*

Challenges:

- *Low efficiency?????*



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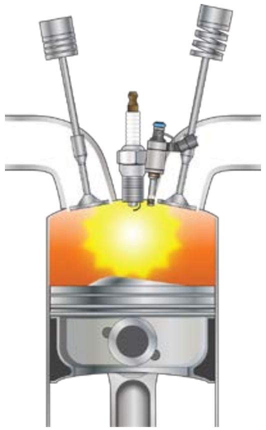

Diesel

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Challenges:

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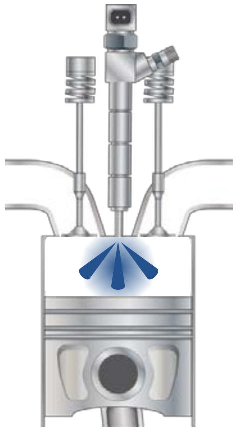

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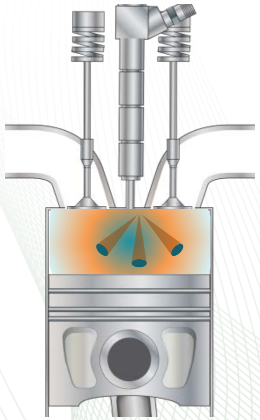

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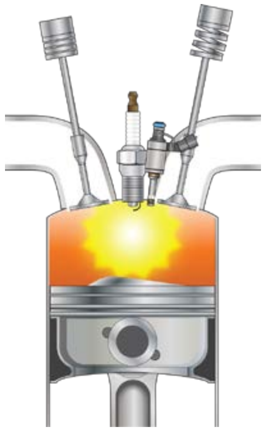

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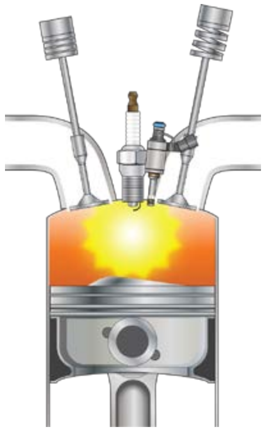

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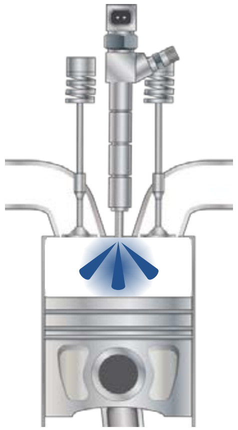

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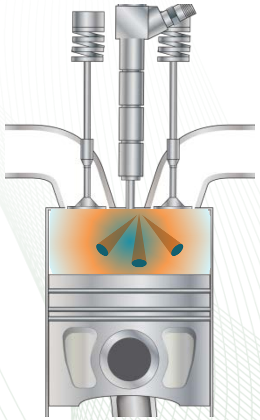
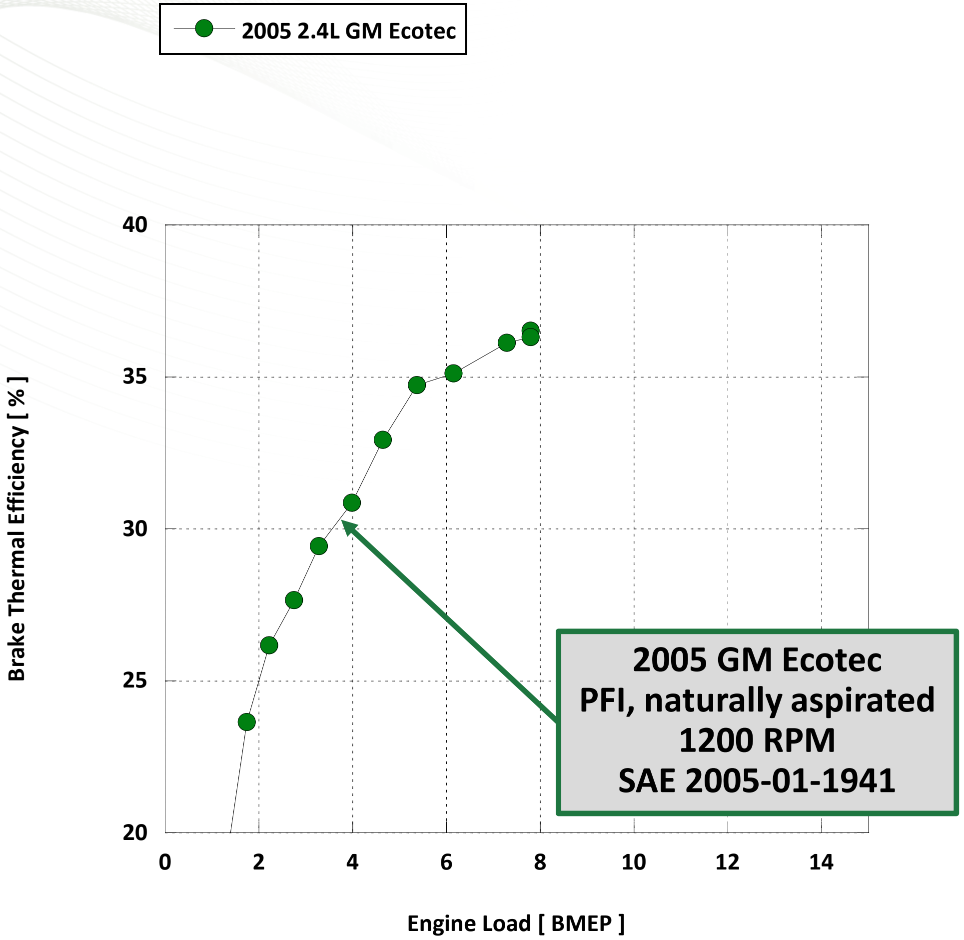


Significant Part-Load Efficiency Increases Realized over Last 10-15 Years



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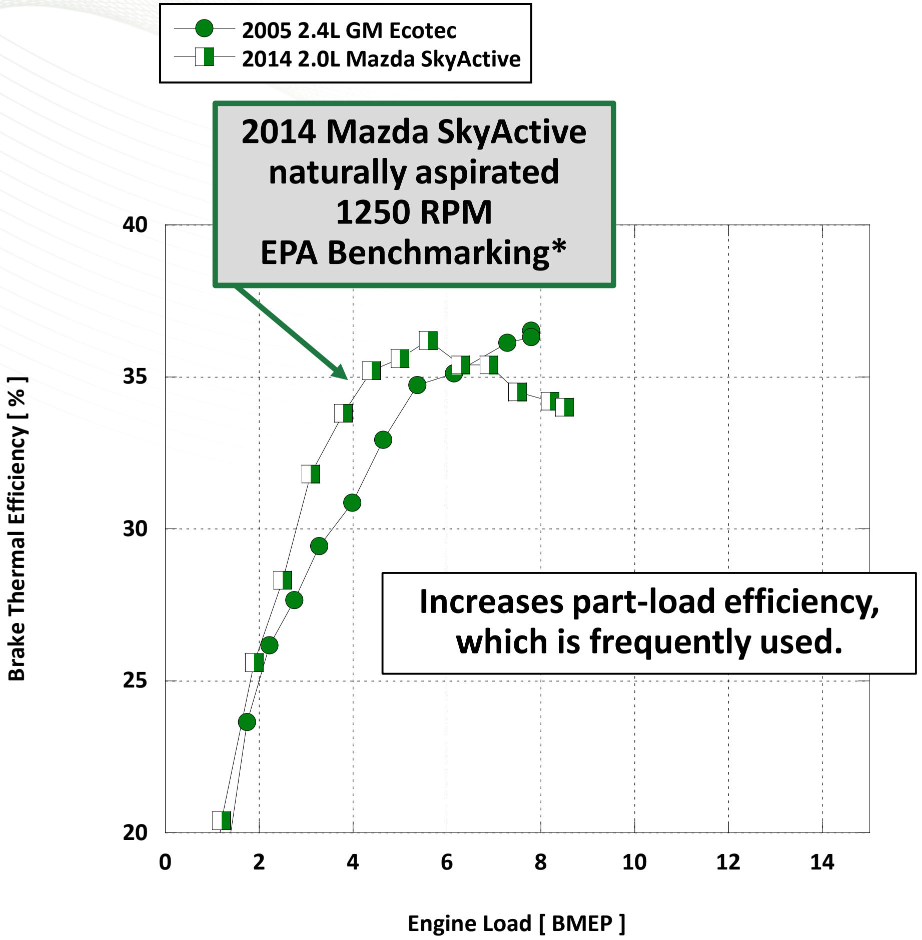
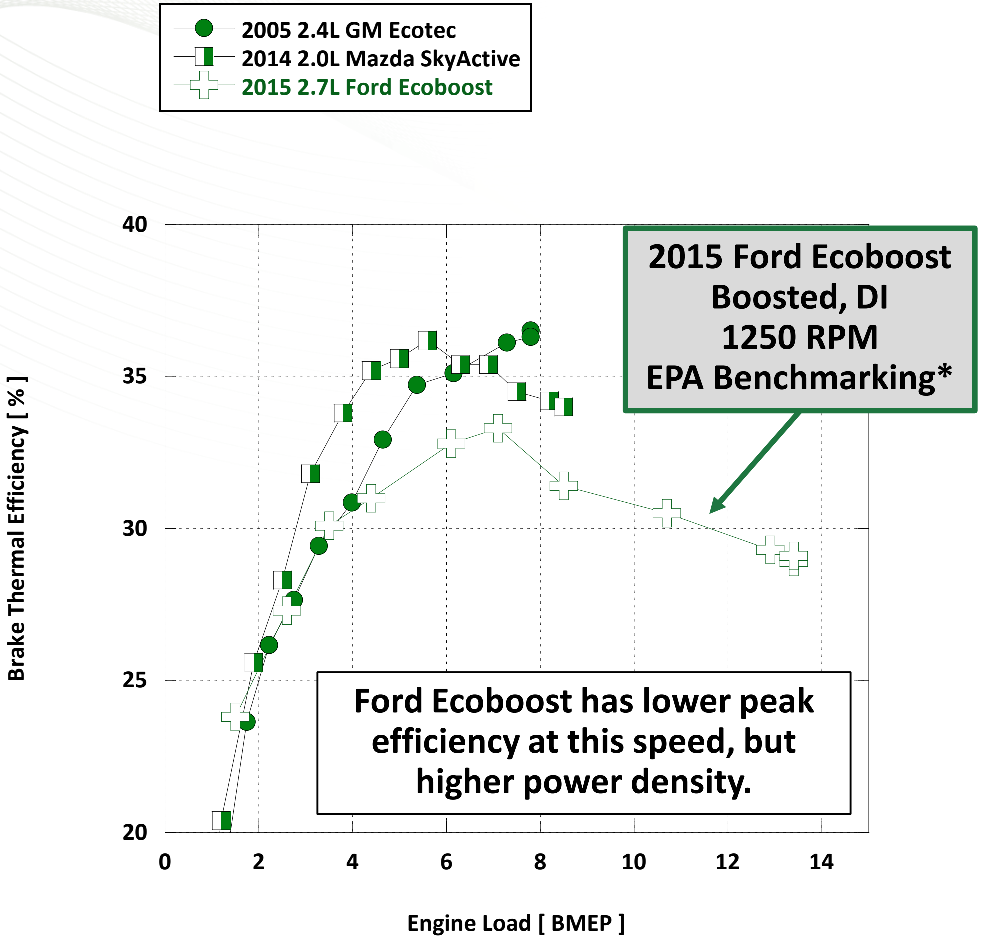


* https://www.epa.gov/vehicle-and-fuel-emissions-testing/test-data-light-duty-greenhouse-gas-ghg-technology#test-data

Significant Light-Load Efficiency Increases Realized over Last 10-15 Years
High Degree of Hybridization May Benefit More from High Peak Efficiency

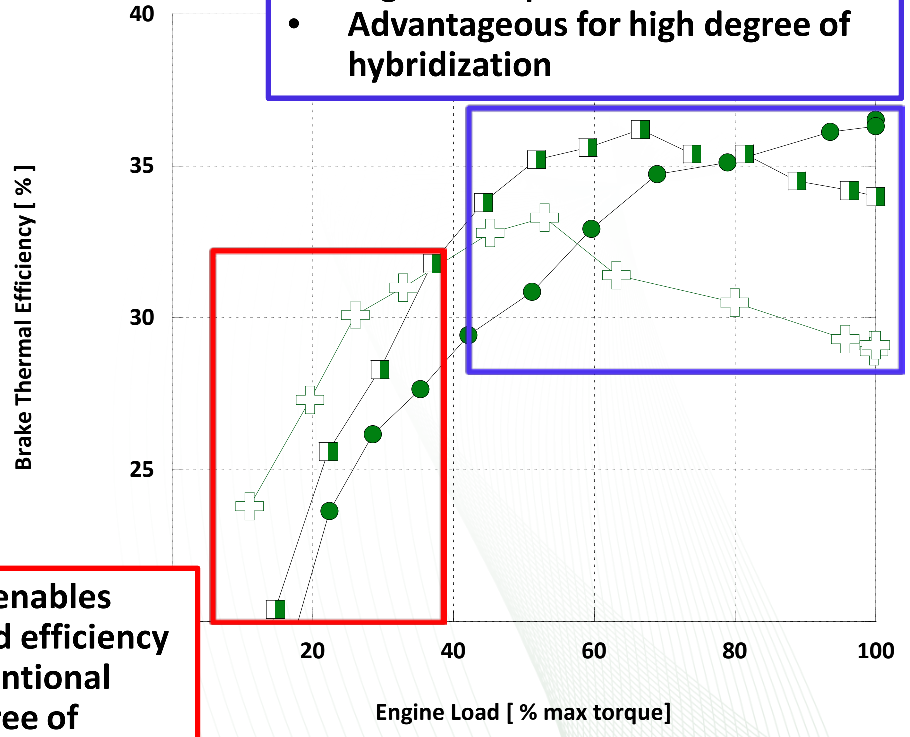


Higher power density enables downsizing.

Normalize all engines to same torque.

Higher peak efficiency realized with naturally-aspirated engines

- Less knock-limited
- Higher compression ratio
- Advantageous for high degree of hybridization



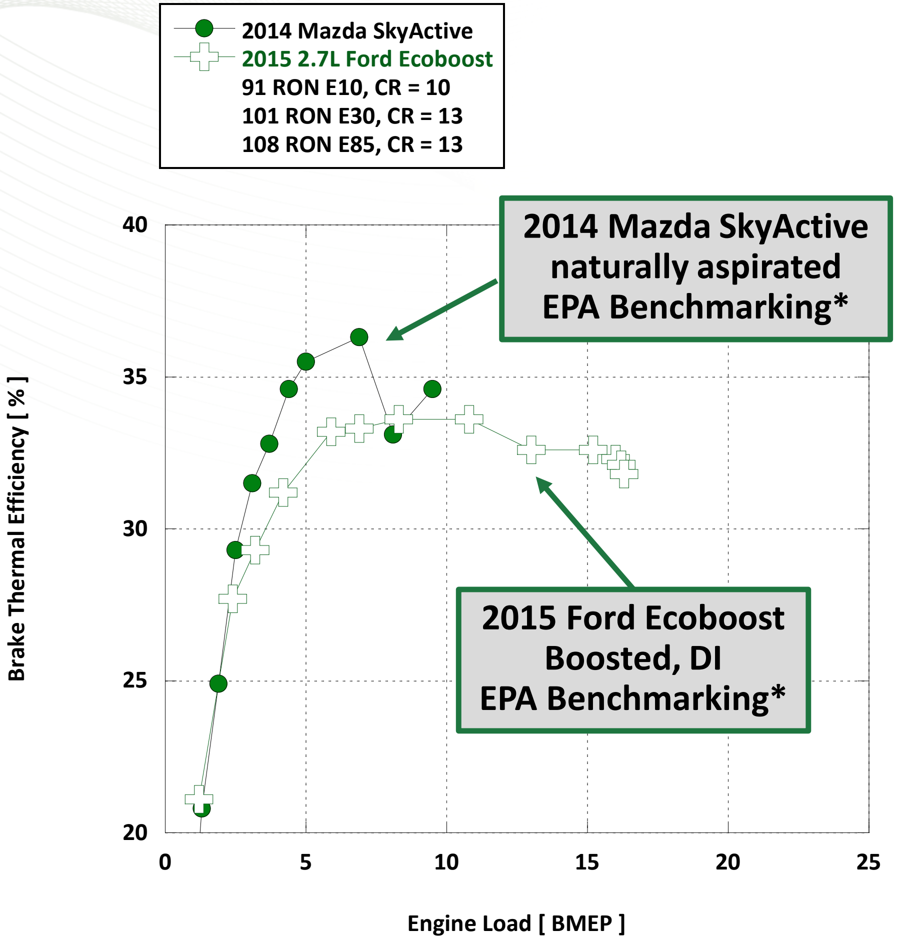
Higher power density enables improvements in light-load efficiency

- Advantageous in conventional powertrain or low degree of hybridization

* https://www.epa.gov/vehicle-and-fuel-emissions-testing/test-data-light-duty-greenhouse-gas-ghg-technology#test-data

Switching to more Knock-Resistant Fuel can Enable Large Efficiency Increase Across Entire Load Range with Modest Changes to SI Engine Technology

All data at 1500 rpm.



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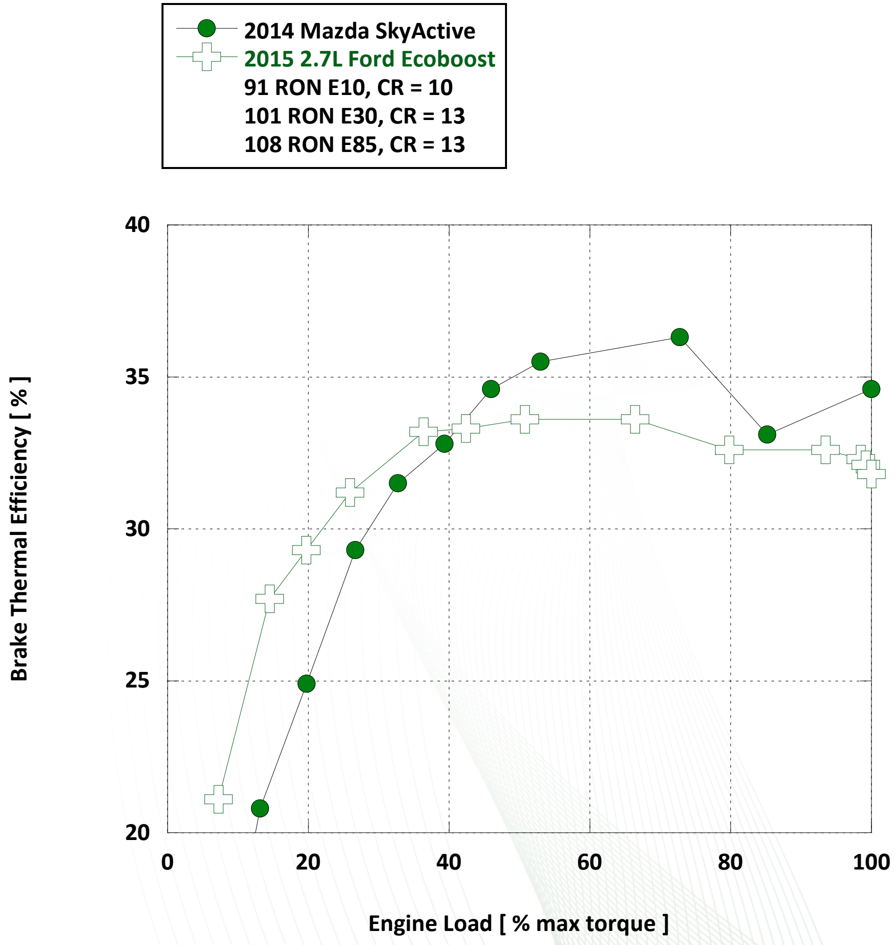

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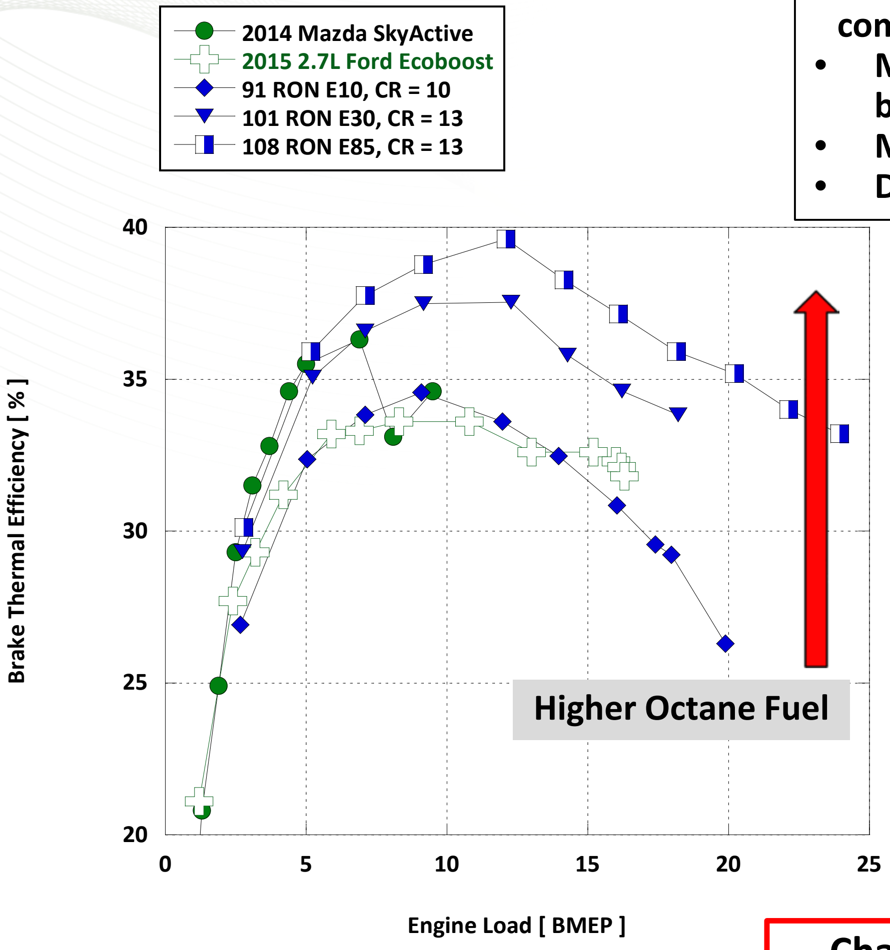
Switching to more Knock-Resistant Fuel can Enable Large Efficiency Increase Across Entire Load Range with Modest Changes to SI Engine Technology

All data at 1500 rpm.

Using a higher octane number fuel with higher compression ratio enables large increase in BTE.
- More significant BTE increase than difference between 2005 and 2014 engine
- More significant BTE increase than downsizing
- Data from SAE 2014-01-1228



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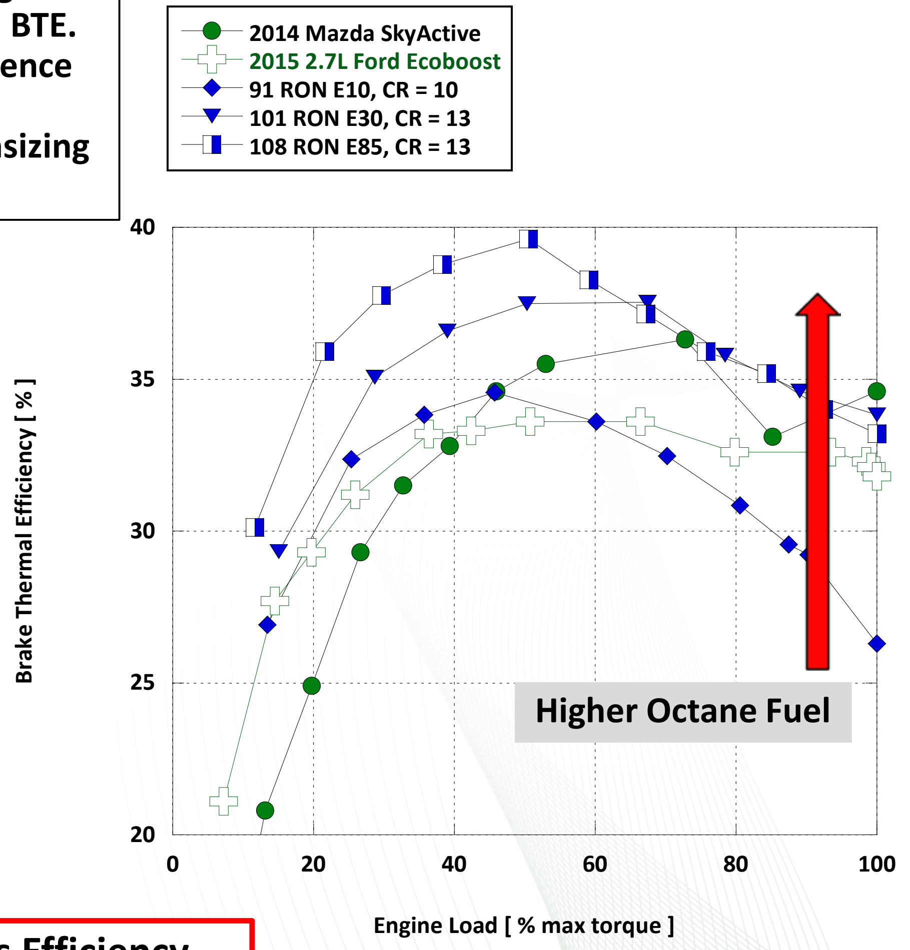

Changing to High Octane Fuel Provides Efficiency Benefit Across Entire Load Range.
- Beneficial for conventional powertrains
- Beneficial for high degree of electrification

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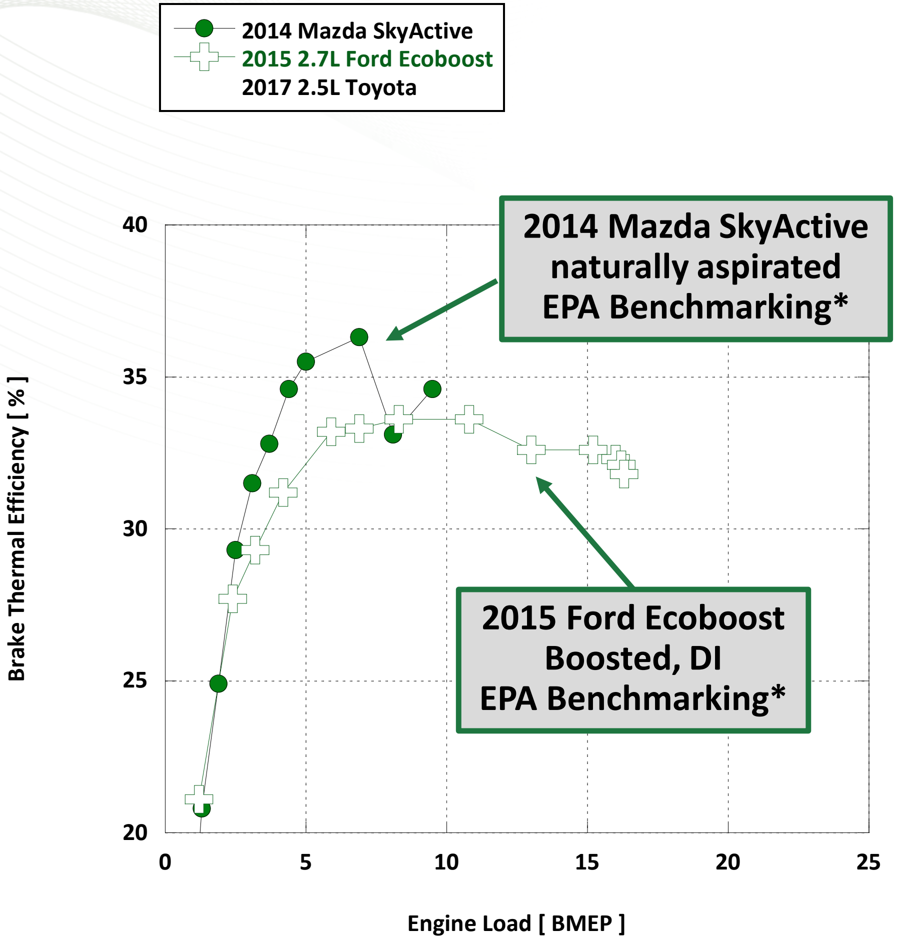
Long Stroke Design Coupled with High EGR Dilution and Overexpansion Enable Higher Peak Efficiency. Low Power Density Creates Part-Load Disadvantage.

All data at 1500 rpm.



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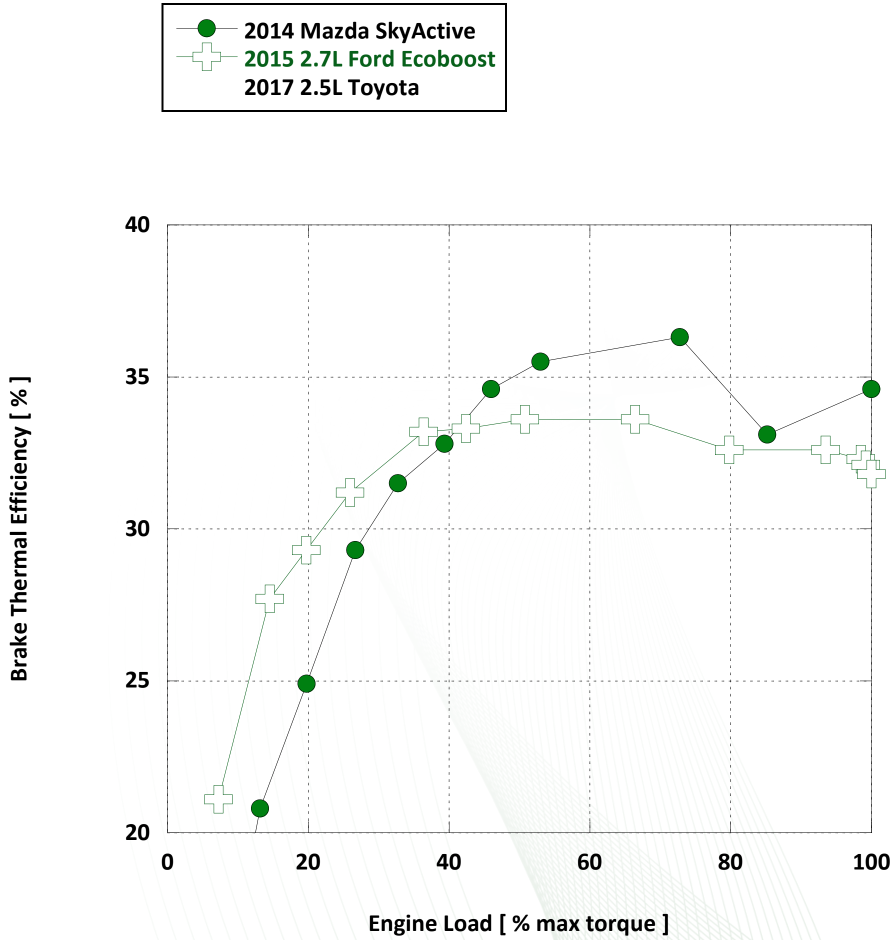

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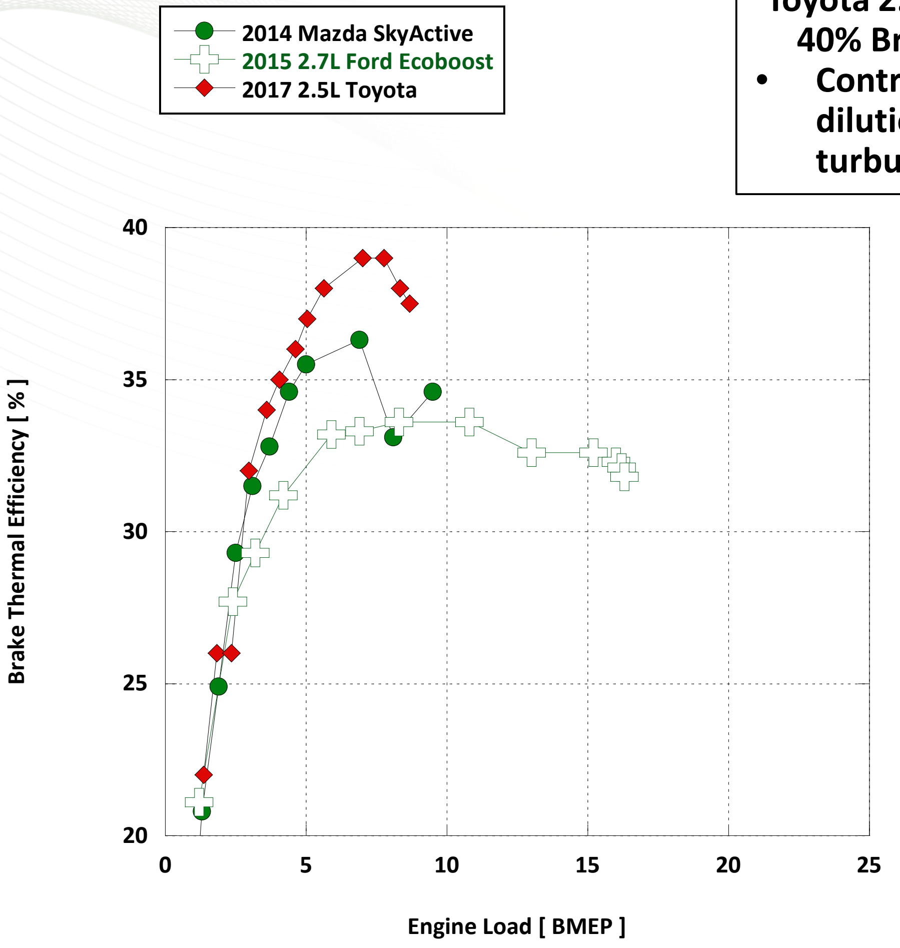
Toyota 2.5L Naturally Aspirated Engine Achieves Peak 40% Brake Thermal Efficiency (SAE 2017-01-1021)

- **Contributing technologies include high EGR dilution, high stroke-to-bore = 1.18, high turbulence combustion chamber, and more**



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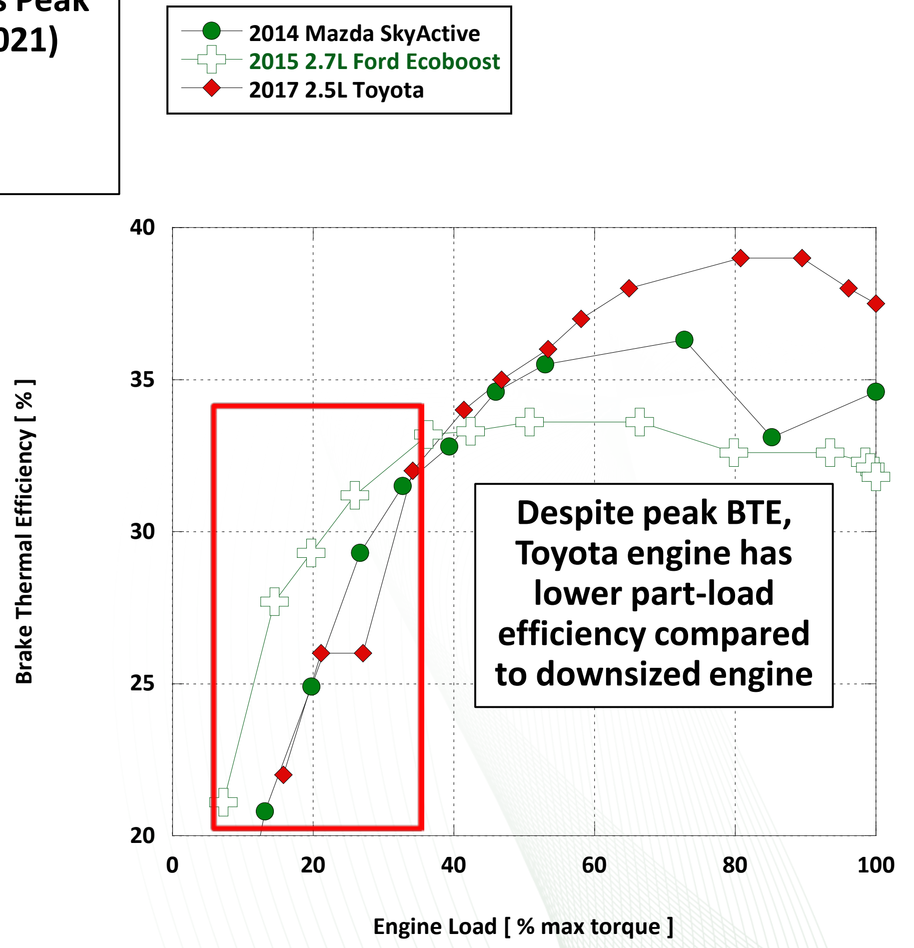

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Other High Efficiency Stoichiometric SI Engine Technology Under Development

- Honda projects 45% brake thermal efficiency with a naturally aspirated engine configuration (SAE 2015-01-1263)
  - Stroke-to-bore ratio = 1.5
  - EGR > 30%
  - High mechanical compression ratio (17:1) with over-expansion cycle
  - Low power density engine
- D-EGR from SWRI uses partial-oxidation reforming to produce hydrogen and extend EGR dilution limit (SAE 2016-01-0712)
  - Demonstrated 42% brake thermal efficiency in prototype engine
  - Nominal EGR rate fixed at 25%, high compression ratio (13.5:1)
  - Stroke-to-bore ratio = 1.22

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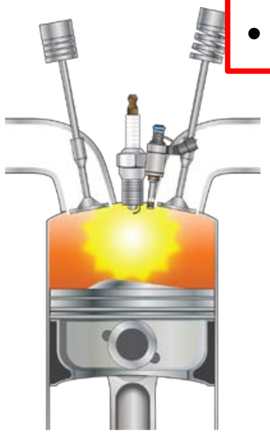

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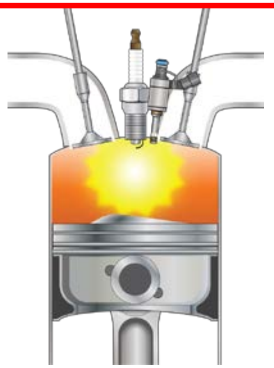
Lean SI Not Discussed Specifically Here

- **Can produce substantial efficiency benefit at light load**
- **Engines typically switch to stoichiometric for full-load for power density, little effect on peak efficiency**
- **Lean NOx emission control is primary barrier**



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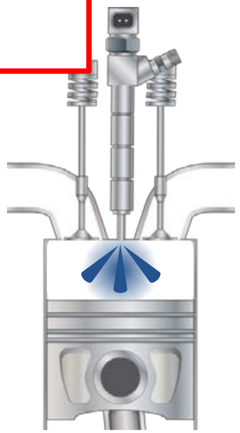

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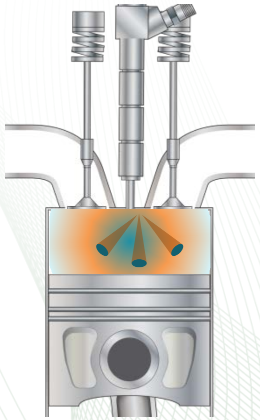

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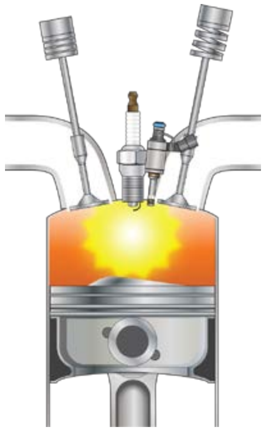

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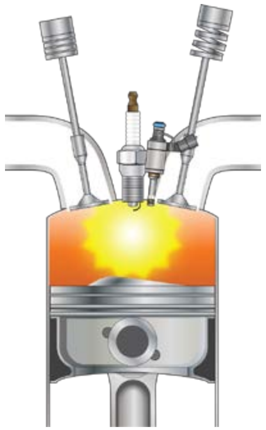

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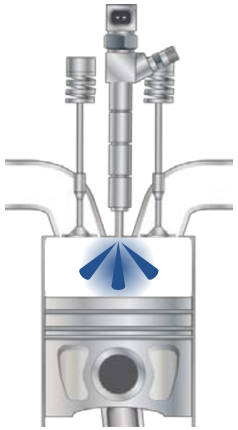

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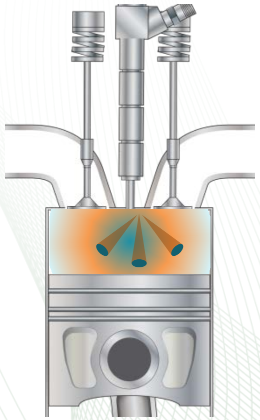

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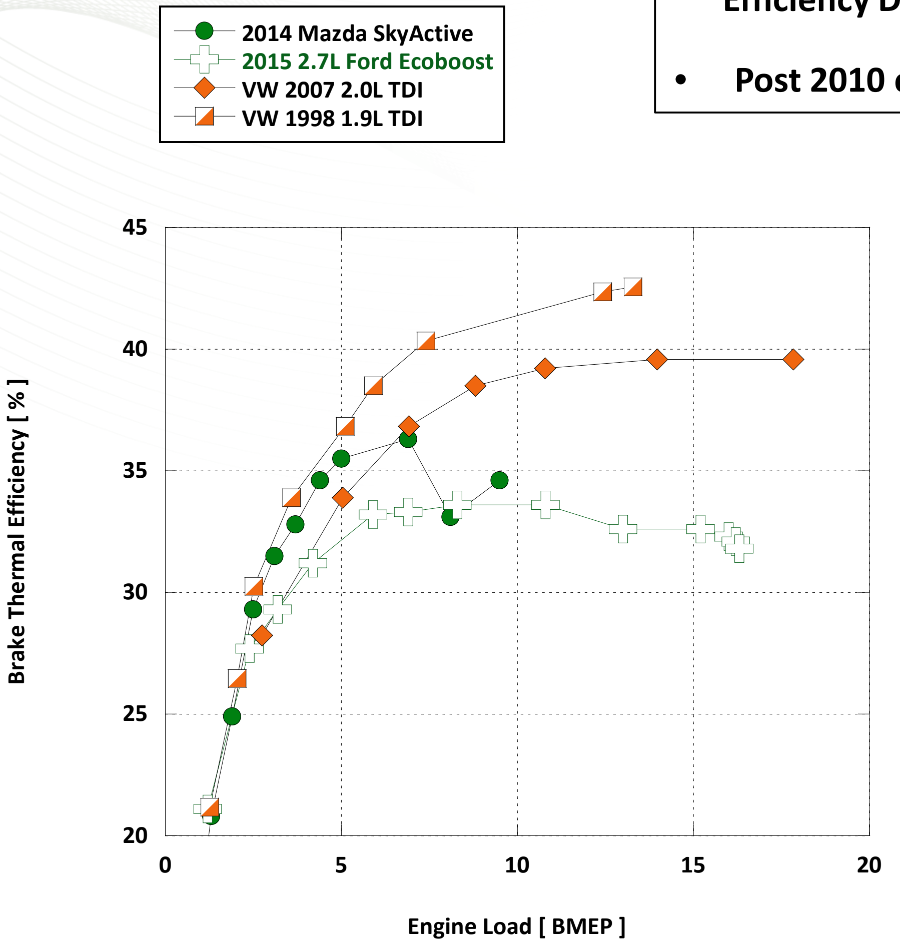
Significant Efficiency Benefits can be Realized with Diesel Over Entire Load Range.
Beneficial for Conventional Powertrain and High Degree of Hybridization.

All data at 1500 rpm.

Efficiency Decrease from 1998 to 2007 Attributable to Emission Control Calibration

- **Post 2010 calibrations are higher efficiency than 2007**



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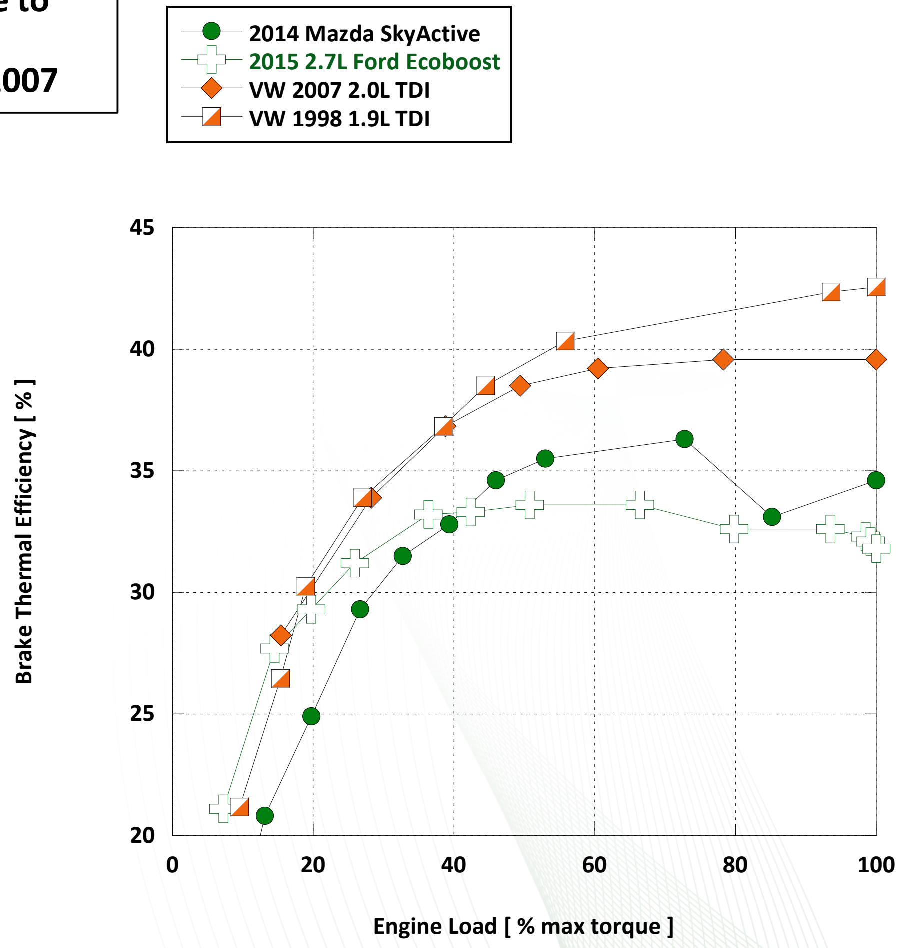

- **1998 data from SAE 981950**
- **2007 data from Internationales Wiener Motorensymposium 2008**

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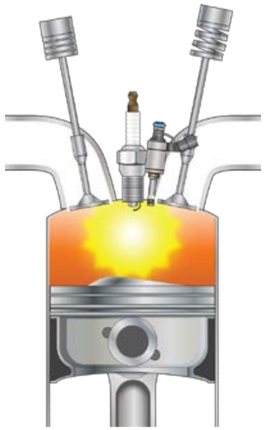

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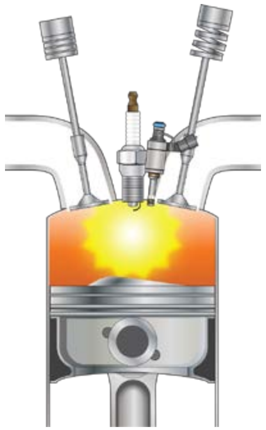

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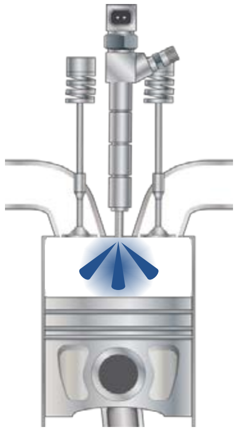
- *Higher cost for engine and emission controls*
- *Consumer acceptance (low conventional diesel penetration)*



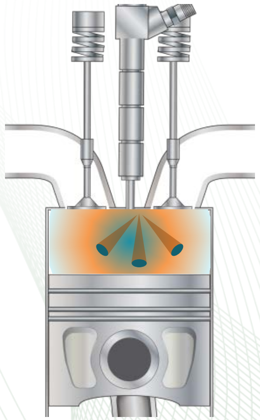
Advanced Compression Ignition (ACI)

Benefits:

- *Potential for high efficiency*

Challenges:

- *Emission control technology undefined*
- *Engine and emission control technology costs*
- *Consumer acceptance for new technology*



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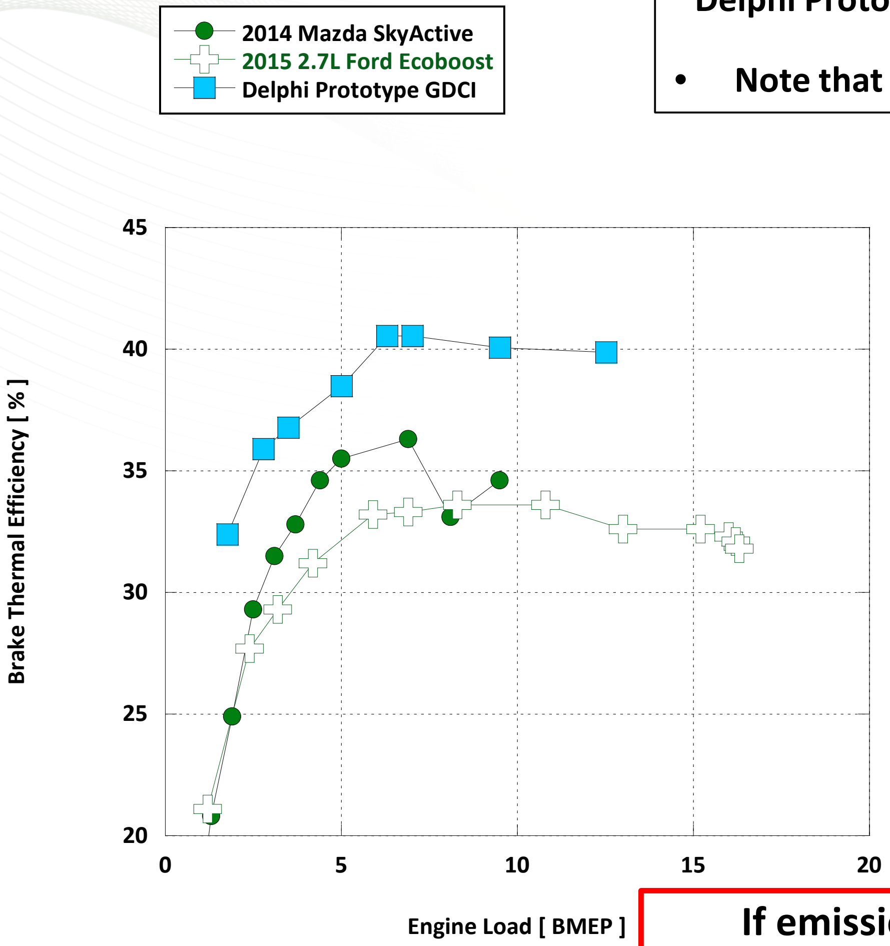
ACI Strategy Offers Largest Improvement in Light Load Efficiency of All Strategies.
Peak Efficiency Comparable to Diesel and Emerging Stoichiometric SI Technology.

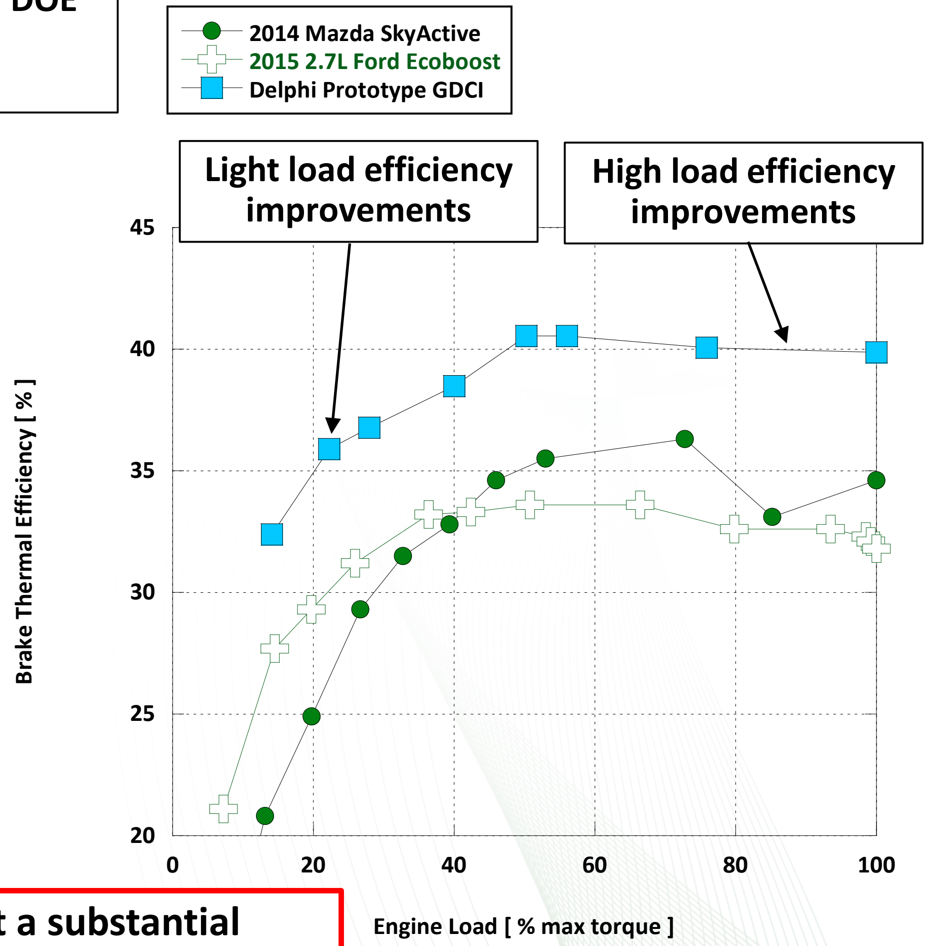
All data at 1500 rpm.

Delphi Prototype GDCI Gen 3 Engine Data from 2017 DOE Annual Merit Review
- Note that technology is not emissions compliant



Higher power density enables downsizing.

Normalize all engines to same torque.



If emission targets can be achieved without a substantial efficiency penalty…
- ACI has significant potential for conventional powertrain
- Is the benefit for decoupled ACI engines (range extenders) enough considering lack of peak efficiency benefit?

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What Engine Technology will Auto Makers Incorporate Into Hybrids? It Depends.

Degree of Hybridization

- Determines what is being asked of the engine (power, torque, transients)
- Determines importance of light-load efficiency vs. peak efficiency
  - Light-load efficiency for low degree of hybridization
  - Peak efficiency for range extender application

Emissions

- Mature emission controls for stoichiometric SI
- Established emission controls for diesel, but higher level of scrutiny after "diesel-gate"
- ACI engines will require lean emission controls similar to diesel, but lower exhaust temperature represents challenge

Different Engine Technologies Provide Different Benefits

- ACI provides the highest efficiency at light operating loads
- Diesel currently provides the highest efficiency at higher engine loads
- Peak efficiency of emerging SI technologies is competitive (> 40% BTE)

Cost

- SI engines are the lowest cost option
- Diesel engines have higher cost (Higher cylinder pressure, complex, fuel injection equipment, emission controls)
- ACI engines are likely to have higher cost relative to SI (similar cylinder pressure and emission controls to diesel, additional engine sensors and controls required)

Thank you for your attention

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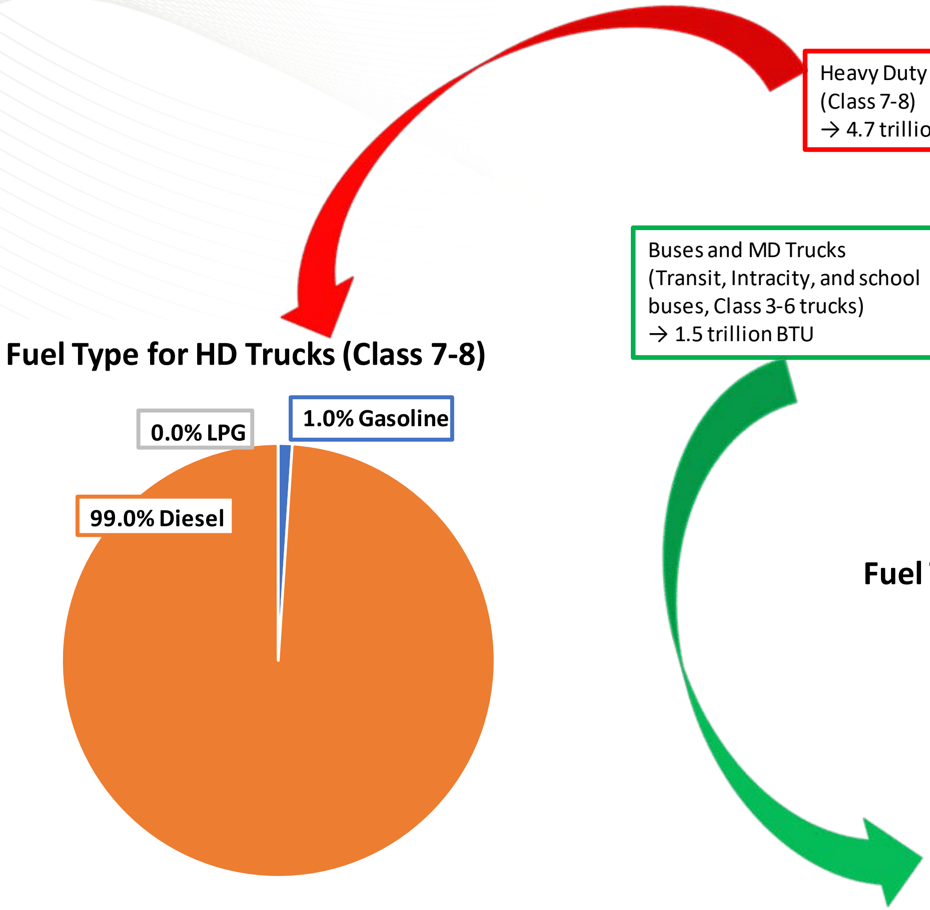
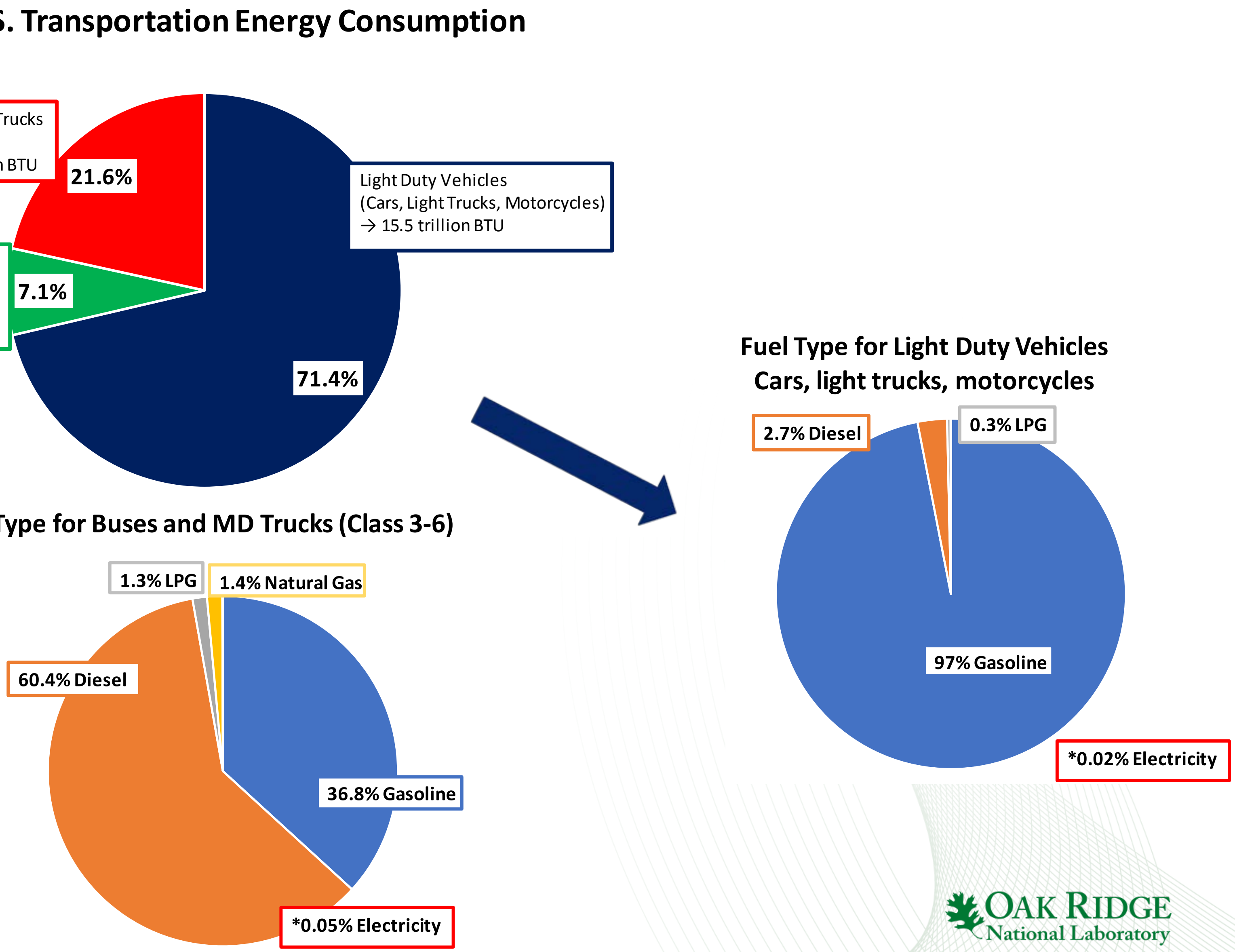
Backup Slides

Light Duty Transportation Accounts for 71% of On-Highway Energy Consumption and is Dominated by Gasoline in the U.S.





Data From: S. C. Davis, S. W. Diegel, R. G. Boundry, *Transportation Energy Data Book* (ORNL-6992, Oak Ridge National Laboratory, Oak Ridge, Tennessee, ed. 35, 2016).

ICE Hybridization Strategy with will Dictate Engine Requirements.
OEMs make Decisions for Each Vehicle Platform, Portfolio will Likely Span Full Spectrum.

Electric Accessories and Stop-Start Technology:
No Change to Engine Requirements

Partially electrified drivetrain.

Less capable engine acceptable for acceleration and load tracking.

Engine still required to meet peak vehicle power.

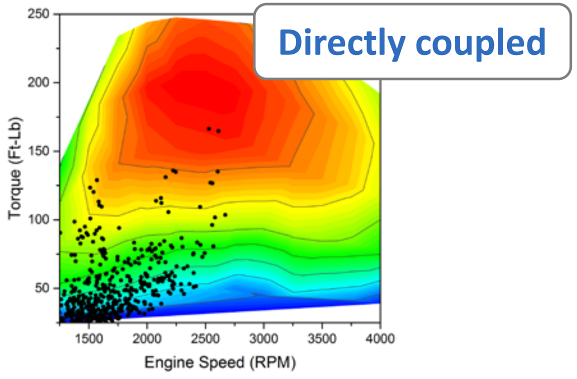
Fully Electric Drivetrain, engine operates only to charge batteries.

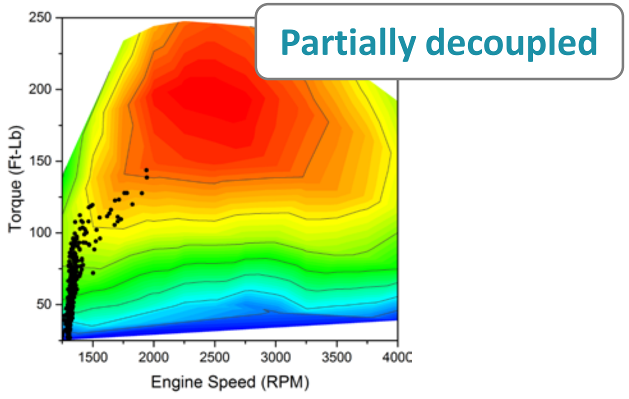
Engine required to meet average vehicle power. Load following not required.

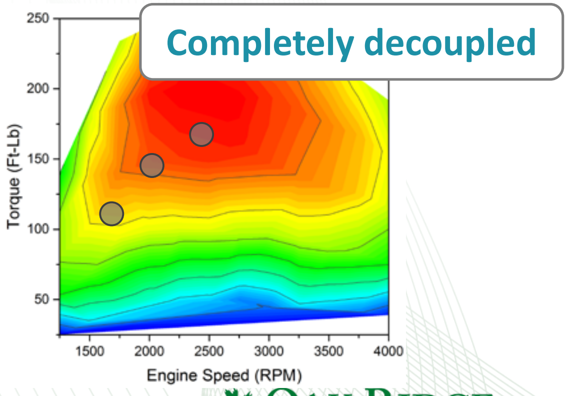
Degree of electrification

0%

100%







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