CORNING

Vehicle Powertrain CO_2 Emissions in Review

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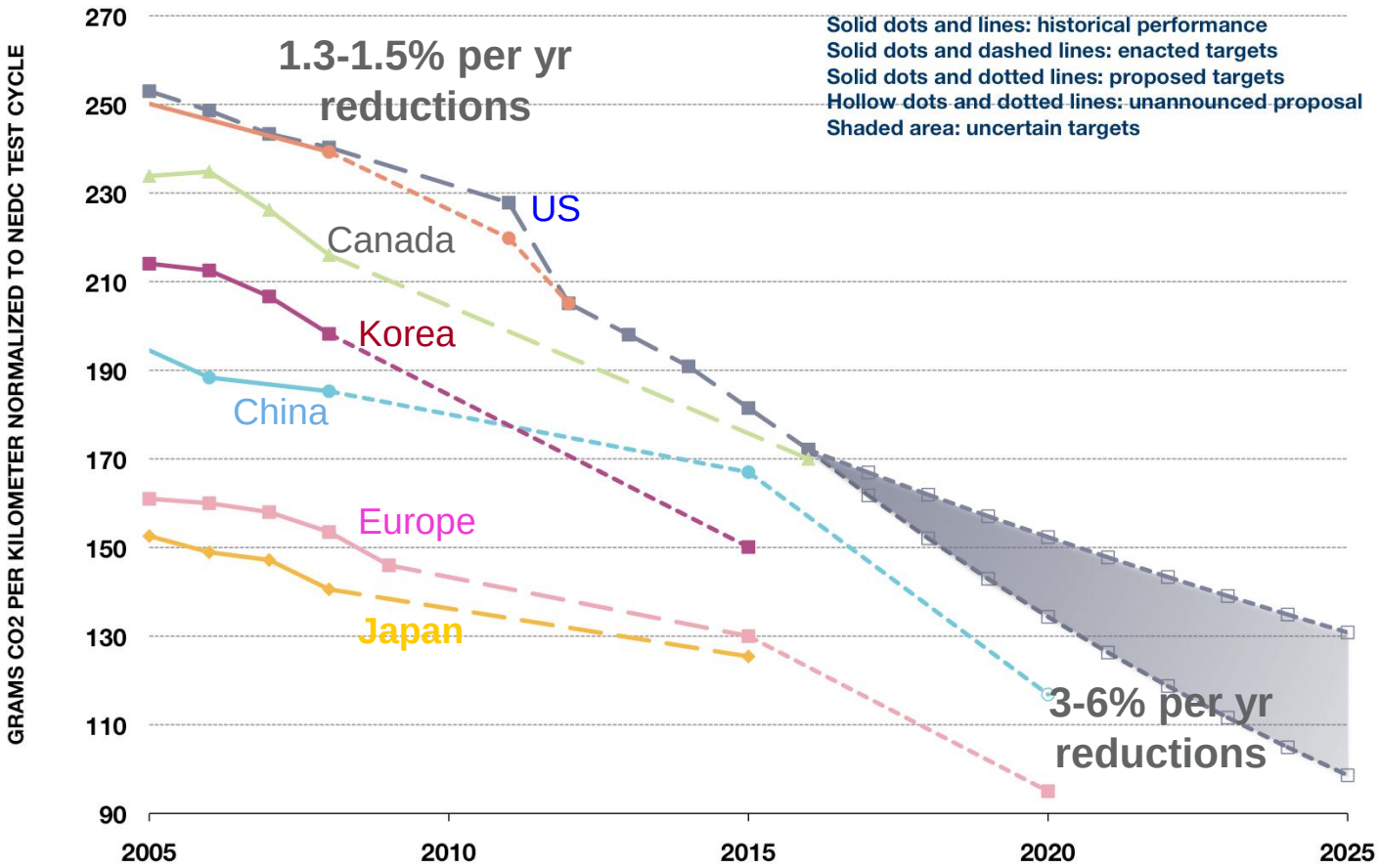
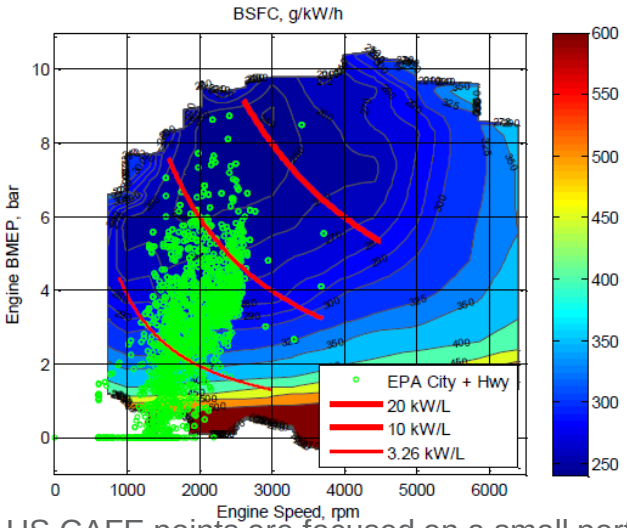
The US EPA (and CARB) are considering 5%/yr reduction in light-duty (LD) CO_2 emissions.

By 2025, 5%/yr brings near-parity with Europe of 2020.

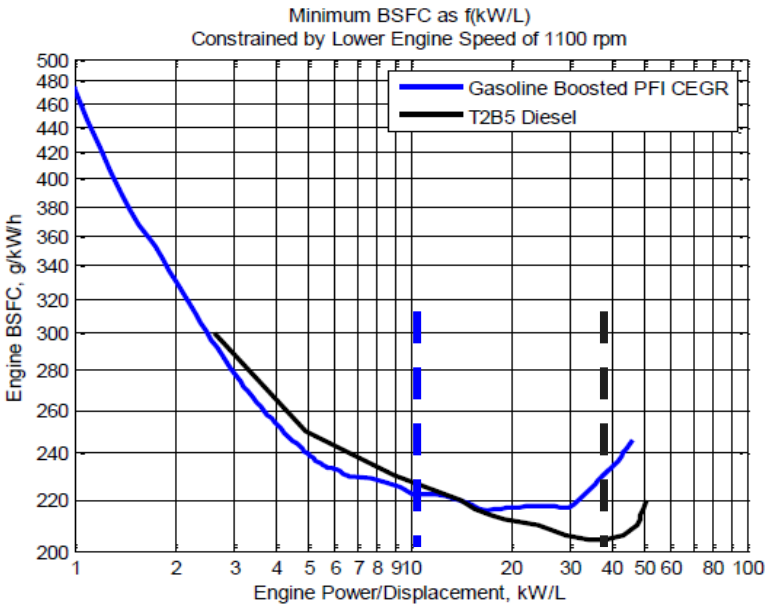


[1] Based on 3% annual fleet GHG emissions reduction between 2017 and 2025 in the September 30th NOI .
[2] Based on 6% annual fleet GHG emissions reduction between 2017 and 2025 in the September 30th NOI .
[3] China's target reflects gasoline fleet scenario. If including other fuel types, the target will be lower.

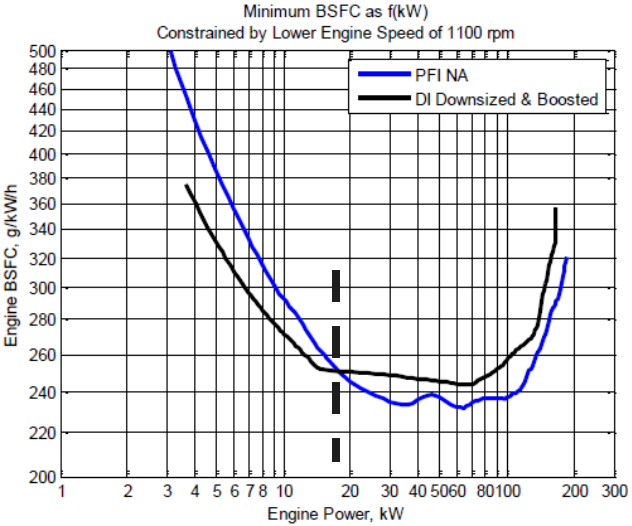
Options for reducing fuel consumption are evaluated using a specific power metric. Lean direct injection (DI), turbo-charged downsizing, and cylinder cut-off help in the low-load regimes. Cooled-EGR and diesel expand benefits to higher loads.



US CAFE points are focused on a small portion of the engine map. FC at 3 to 10 kW/liter specific power may be a good metric for evaluation of FE technologies.



cEGR extends FC benefit to somewhat higher loads. Diesel is a high load FC reduction strategy.



Downsizing via DI and boost is a low-load FC strategy. High BSFC at high power levels. Downspeeding similar.

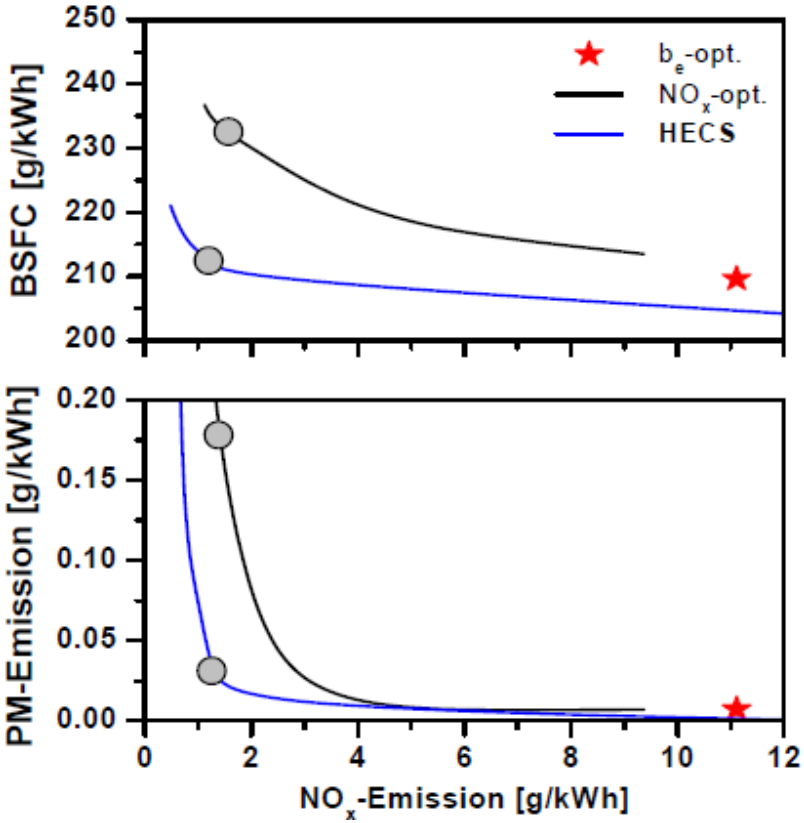
Chrysler, SAE FE Panel 4/10

Second-generation optimized (light-duty diesel) LDD engine has 44% thermal efficiency (BTE) - same as earlier low-FC calibration) and lower NOx than the earlier low-NOx calibration. Opt EGR, air handling, combustion.

Specification *HECS* II

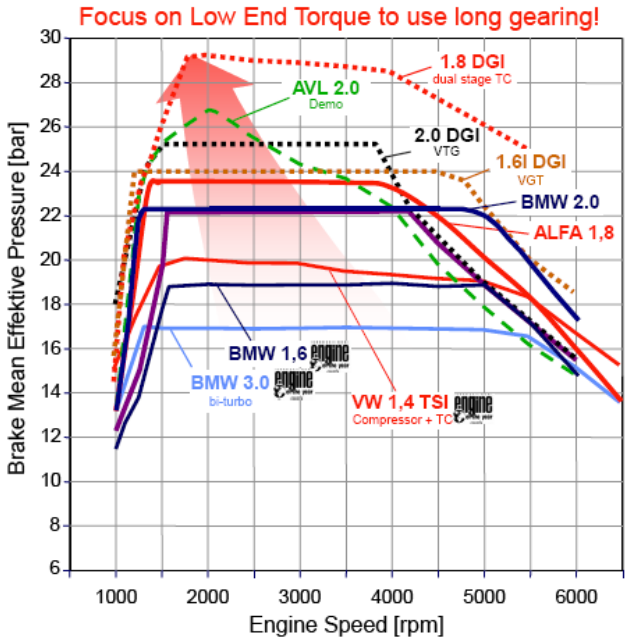
- 1.6l 4-Cyl. Diesel Engine
- 80 kW/l spec. Power (200 bar PFP)
- Euro 6 w/o DeNOx (<1700 kg)
- ~120g/km CO_2 (1590 kg)
- 2-stage boosting system
- High and Low Pressure EGR
- Advanced Cooling Concept
- Split&intelligent cooling engine
- 2000 bar Piezo FIE
- Optimized Bowl with CR 15:1
- Variable Swirl Concept (VVL)
- Exhaust Cam Phaser
- Model based Air path control
- Closed loop combustion control
- Start & Stop

Red items are new relative to HECS1

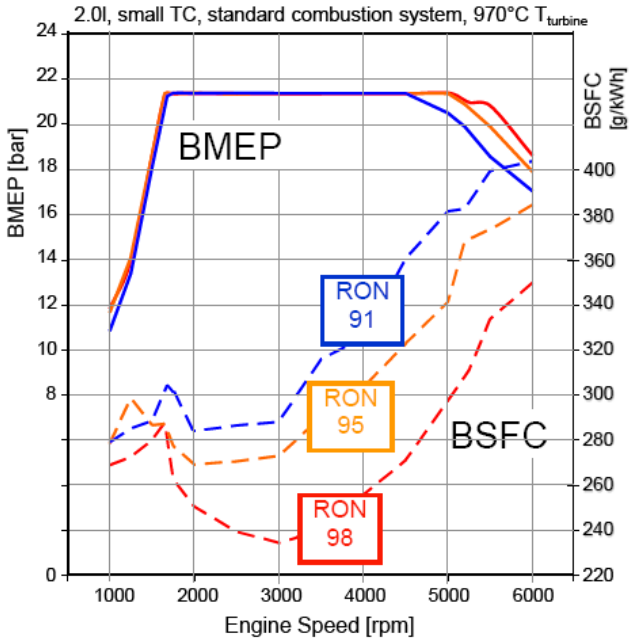


FEV, DEER Conf, 9/10

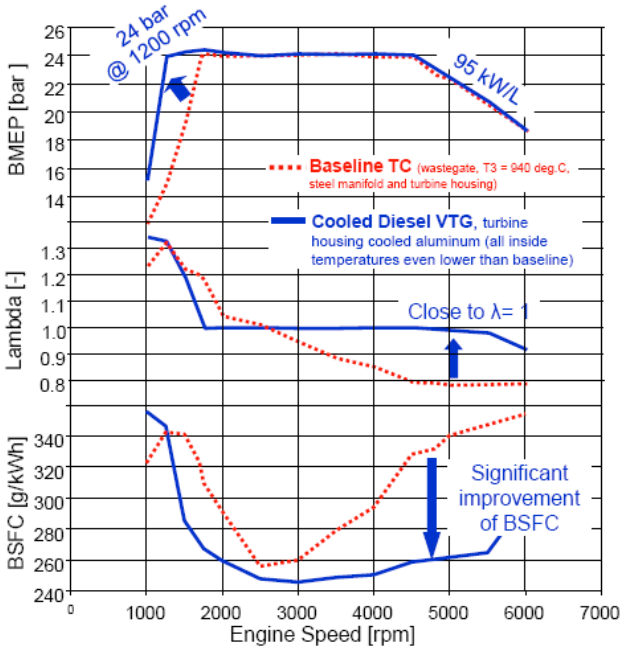
Turbocharged GDI BMEP is being downsized ~40% from advanced engines of today. Low octane fuel is potential challenge.



Low speed torque is improving. Affects gearing. Std today with 1-stage boost is 21-23 bar. VCR allows higher load (43 bar), but 30-35 bar is opt.



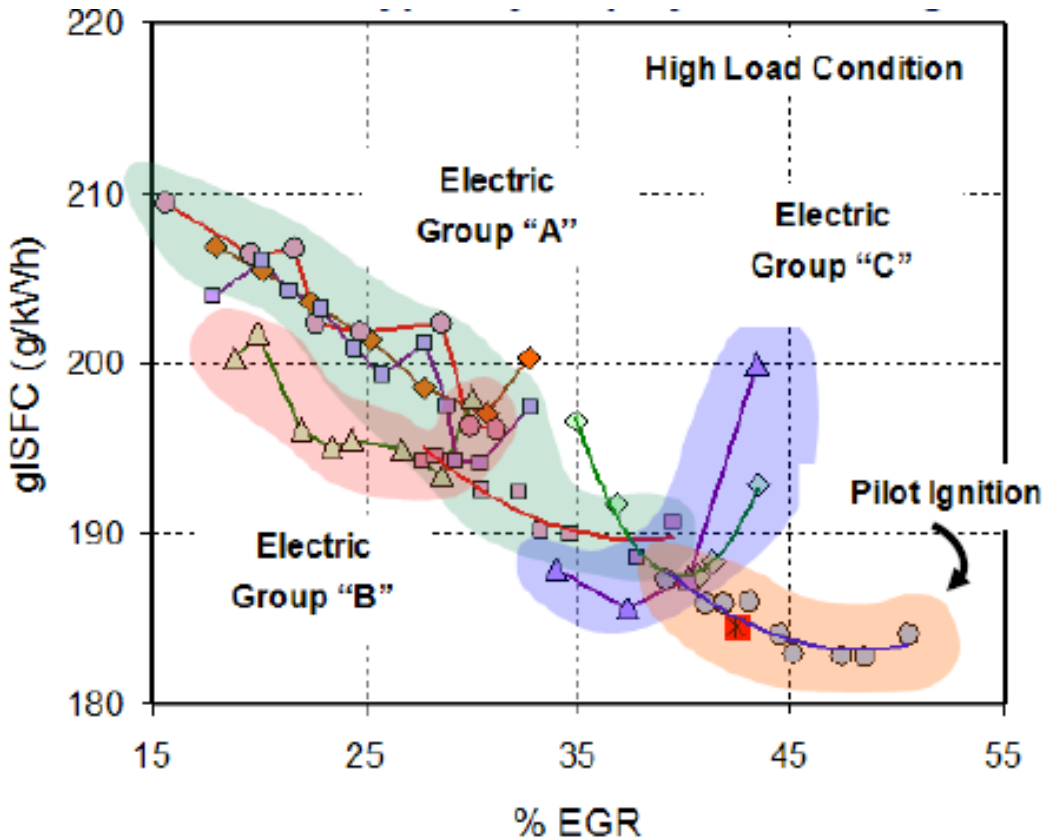
Low RON fuel requ more enrichment at HL. Managing for low RON fuel is challenge



TC cooling is one approach, enabling low cost turbo components that also give good response.

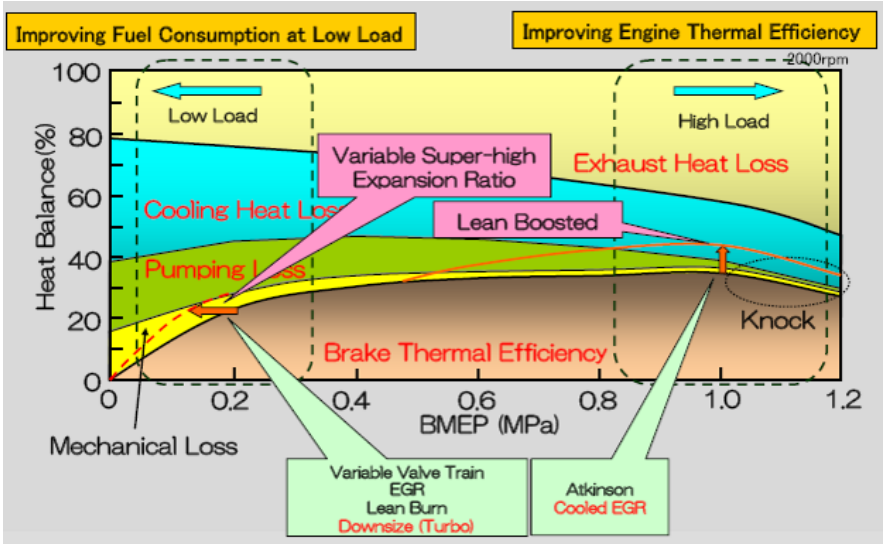
AVL, CTI Conf 5/11

At high exhaust gas recirculation (EGR) levels strong ignition systems are needed to get stable and efficient combustion.

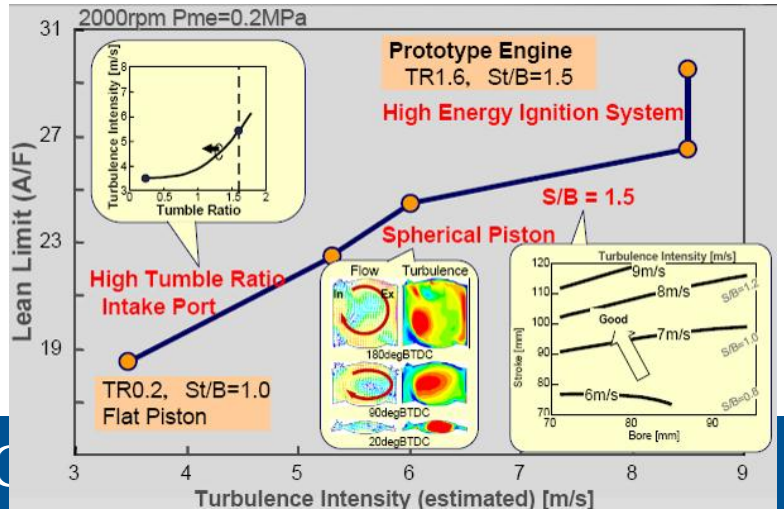


SwRI, SAE panel 4-10

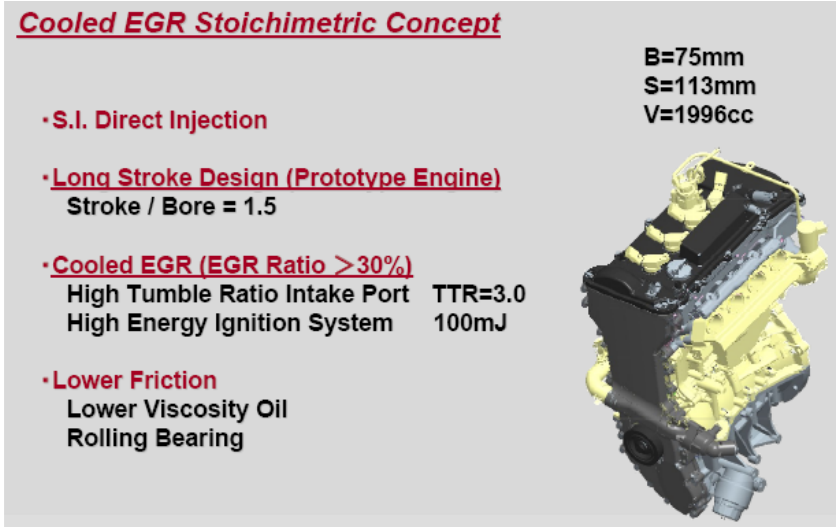
Toyota shows lean+EGR gasoline engine concept for 2020. Long stroke, low surface/volume, ~T2B5 engine NOx



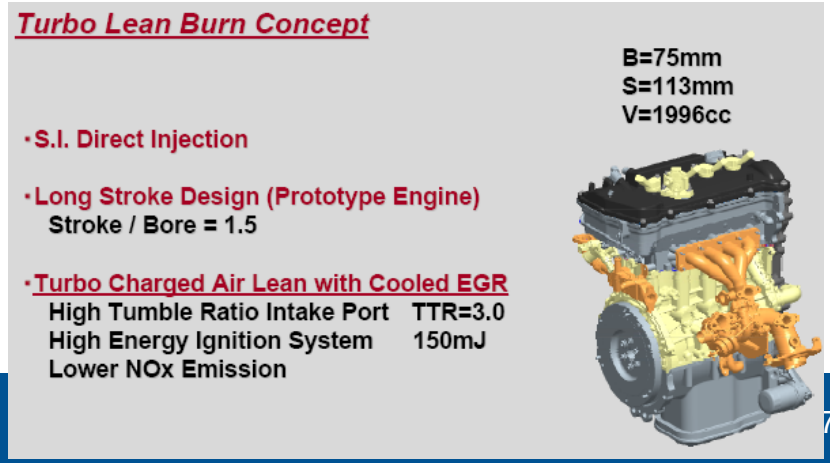
At low load, long stroke, VVT, EGR+lean, boosted downsized. High-load: more EGR+lean.



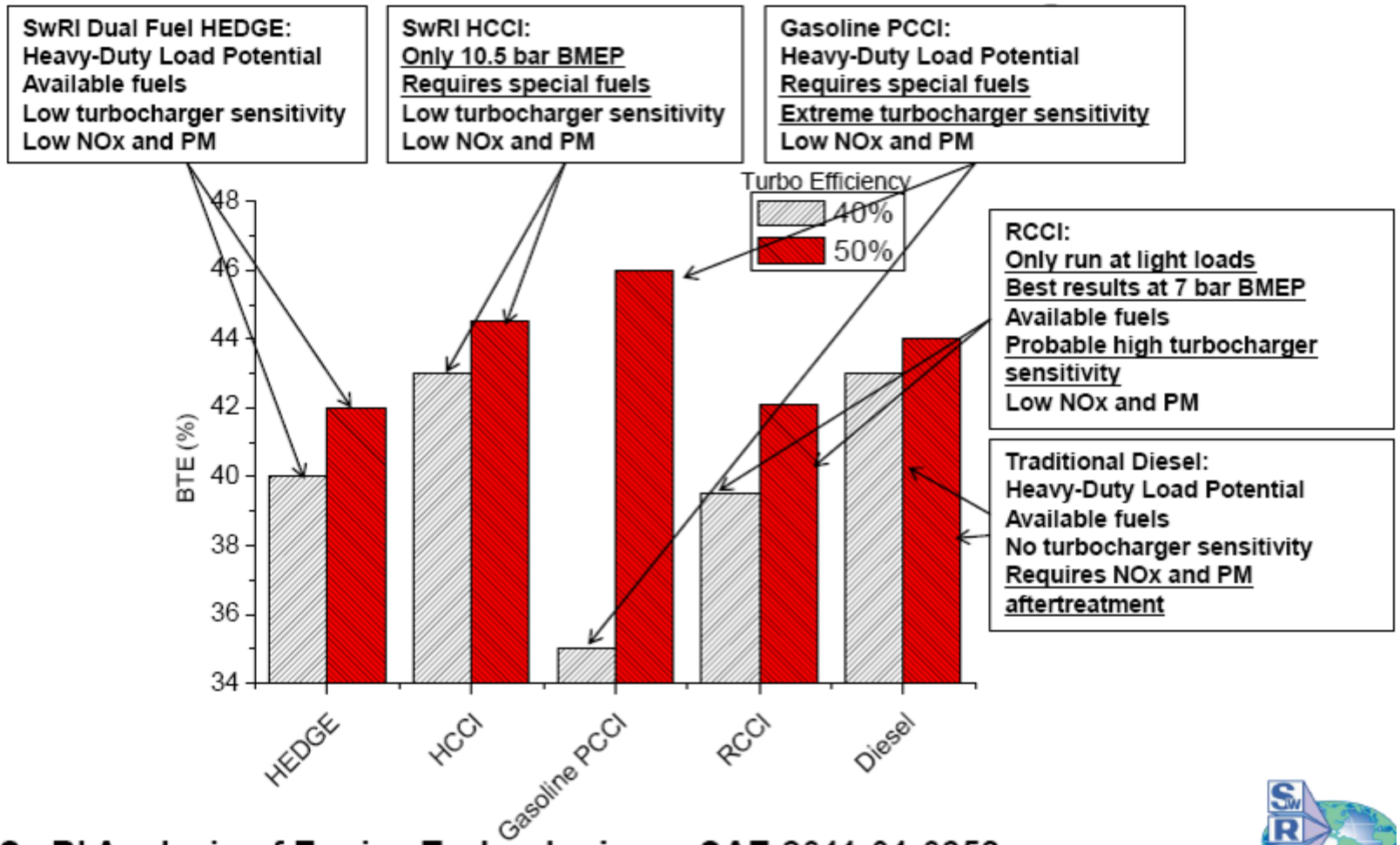
Next generation Prius engine concepts.



Later Prius engine concepts.

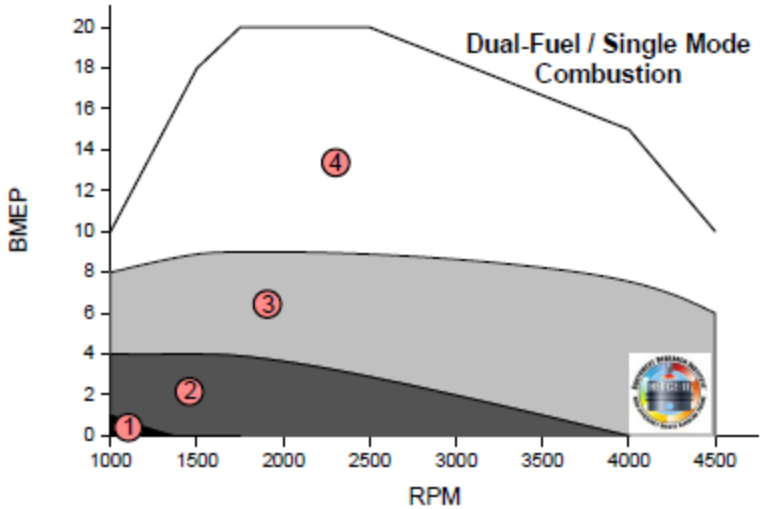


Critical assessment of emerging LD engine technologies is provided. Boost is very important consideration. Emerging PCCI and RCCI interesting, but have trade-offs. HEDGE and diesel are most-robust.



SwRI Analysis of Engine Technologies - SAE 2011-01-0358

Future combustion systems might take advantage of dual fuels and multiple combustion modes.



Combustion Zones

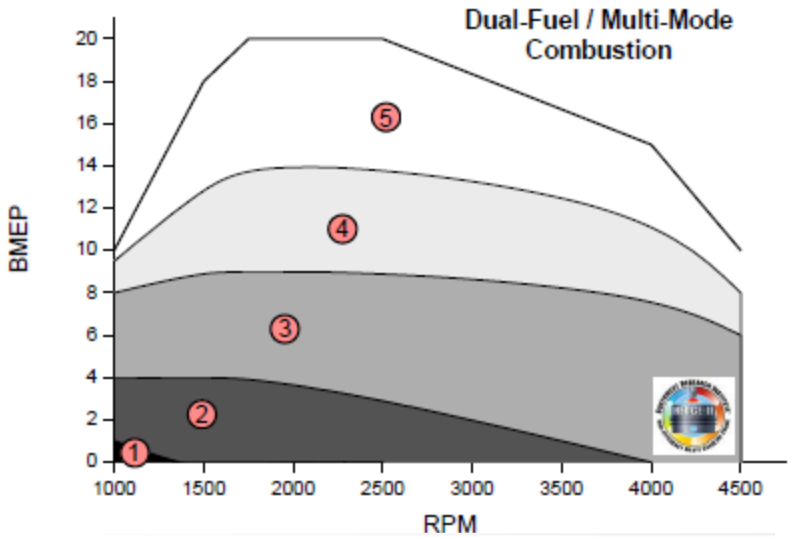
1: λ=1 Spark ignition, light EGR
2: λ=1 Spark ignition, high EGR
3: λ=1 Spark and pilot ignition, high EGR
4: λ=1 Pilot ignition,high EGR

Engine Hardware

- Base EU5 Diesel engine with lower CR
- Rematched turbocharger
- Add spark plug in place of glow plug
- Add gasoline port fuel injection system
- Replace HPL EGR system with LPL EGR

Aftertreatment

- TWC



Combustion Zones

1: λ=1 SI gasoline, light EGR
2: λ=1 SI gasoline, high EGR
3: λ=1 Gasoline w/Diesel pilot ignition, high EGR
4: λ≥1 Diesel combustion w/gasoline support, moderate EGR
5: λ≥1 Diesel combustion only, light EGR

Engine Hardware

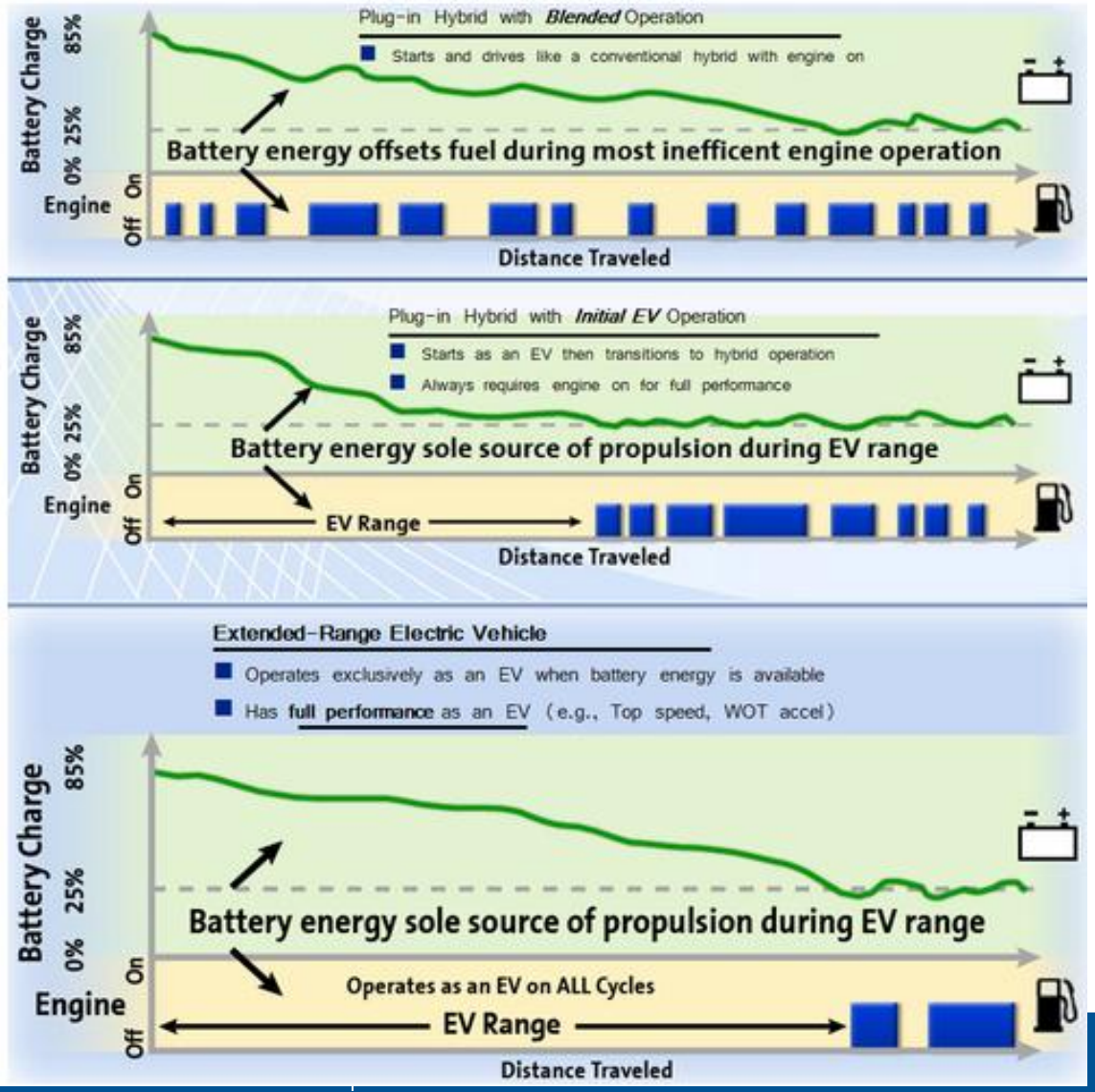
- Base EU5 Diesel engine
- Base Diesel turbocharger
- Add spark plug in place of glow plug
- Add gasoline port fuel injection system
- Potentially add LPL EGR system

Aftertreatment

- DPF
- DOC
- LNT / TWC

SwRI, SAE panel 4-10

Plug-in HEV concepts emerge and vary according to strategy. Low cost battery vs. maximum grid utilization



•Always uses blended operation for maximum total energy efficiency.

• Operations like an HEV, but early range uses more electricity

• Moderate all-electric range, after which it becomes an HEV.

• Battery power might not be sufficient for full power.

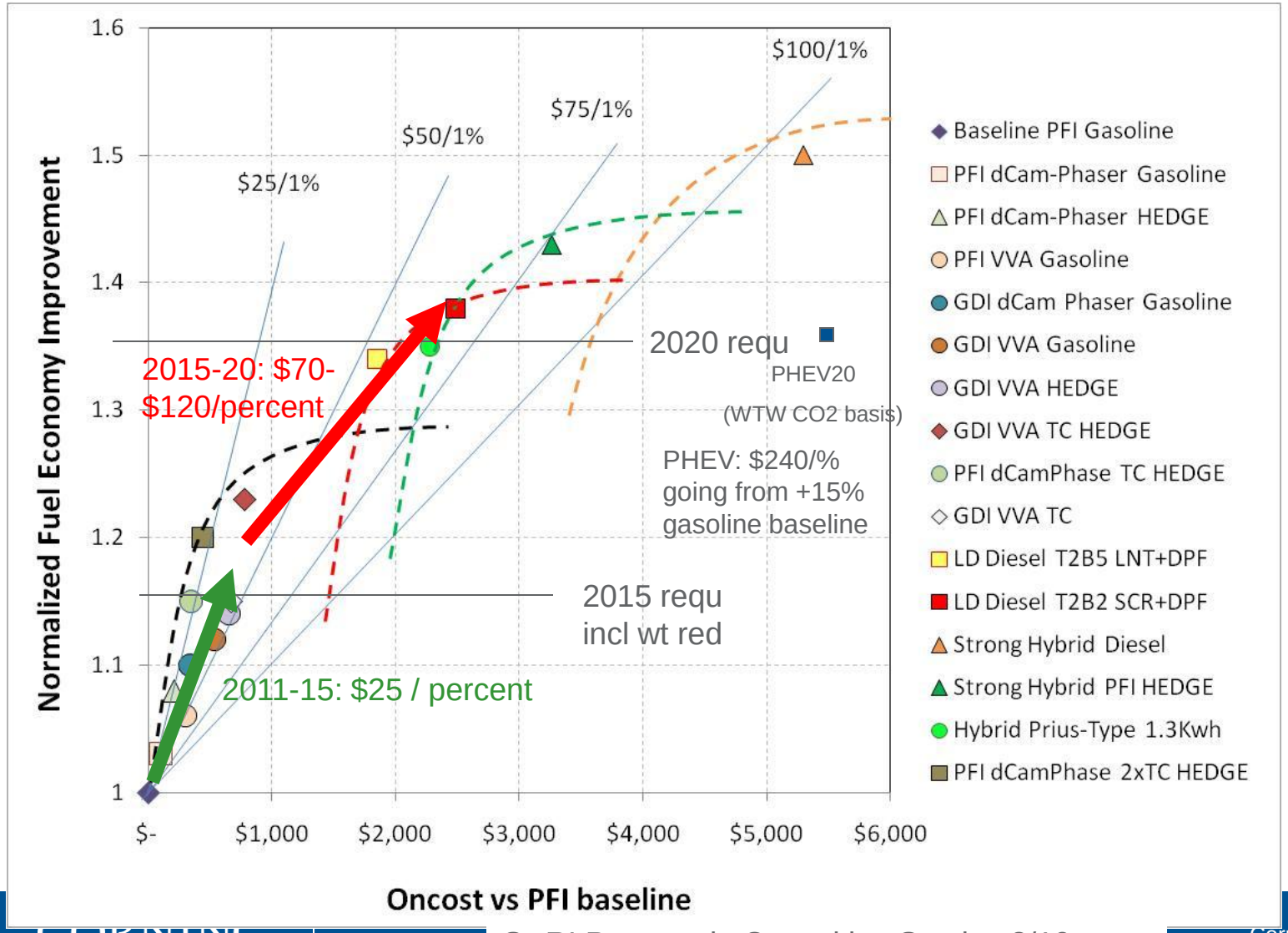
• Extended all-electric range with full power from the battery.

• series HEV takes over after EV range

• Largest battery but most energy off the grid

GM SAE 2008-01-0458

Fuel economy improvements get increasingly more expensive, with diminishing step-by-step returns to the consumer. There is a gap in plug-in cost vs. the benefit relative to more conventional technologies.



As efficiency improves, incremental costs go up, but fuel savings decrease.

- First step: $500 OEM cost saves $340/yr
- 2020 step, OEM cost of $1400 to $2900 saves ~$280/yr.

Heavy-duty (HD) engine CO_2 proposal calls for 3% reductions in both 2014 and 2017 for line haul.

3-5% reductions for vocational in 2014; 2-4% in 2017.

GVWR CLASS	FUEL	MODEL YEARS	CO_2 REDUCTION FROM REFERENCE CASE
HHD (8a-8b)	Diesel	2014-2016	3%
		2017+	6%
MHD (6-7) and LHD 4-5	Diesel	2014-2016	5%
		2017+	9%
	Gasoline	2016+	5%
LHD 2b-3	Gasoline	2016+	5%
	Diesel	2016+	9%

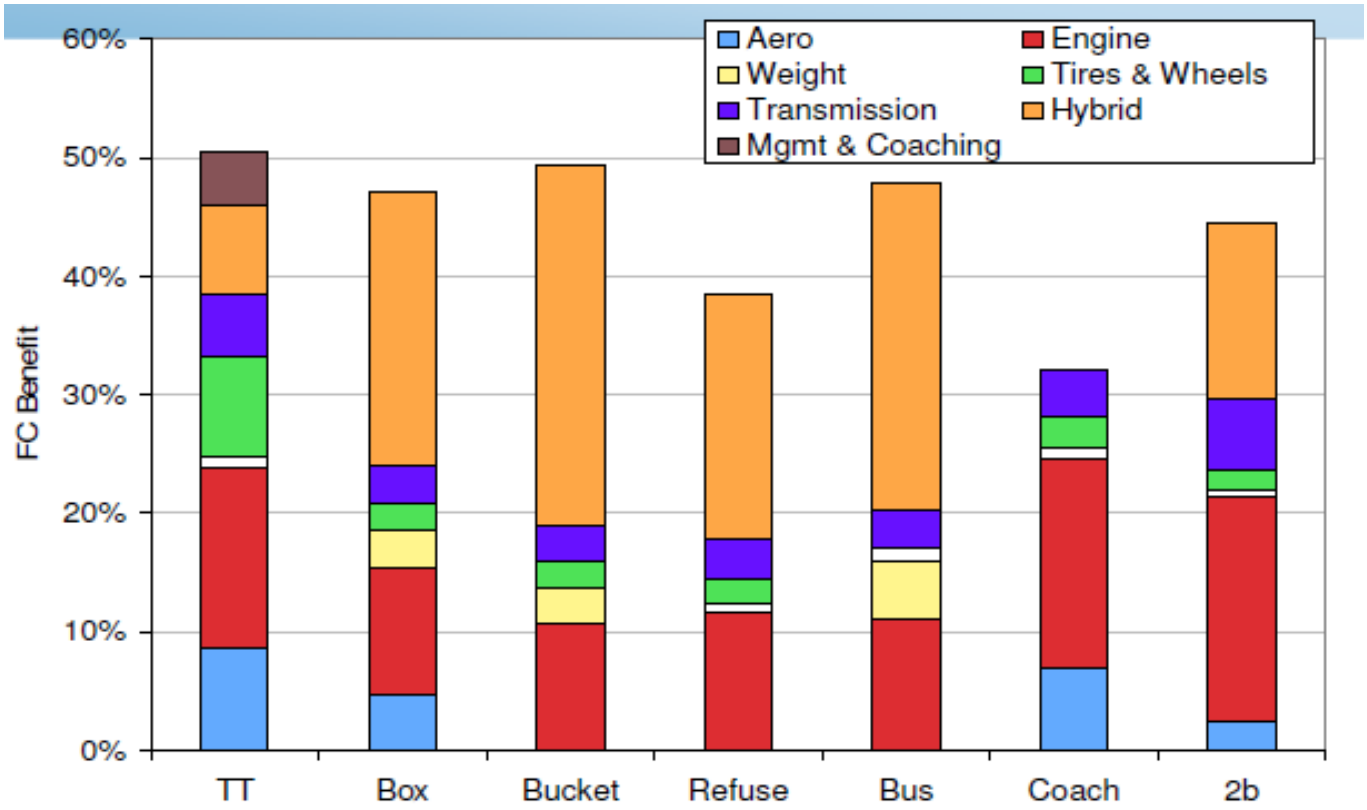
General: Proposed engine CO_2 standards relative to the 2010 industry average. Heavy-HD: 3% drop in 2014 then additional 3% in 2017. Medium-HD and Light-HD: 5% drop 2014, then additional 4% in 2017.

Total Vehicle Reductions

Line Haul:	20%
Vocational	7-10%
Small trucks	12-17%

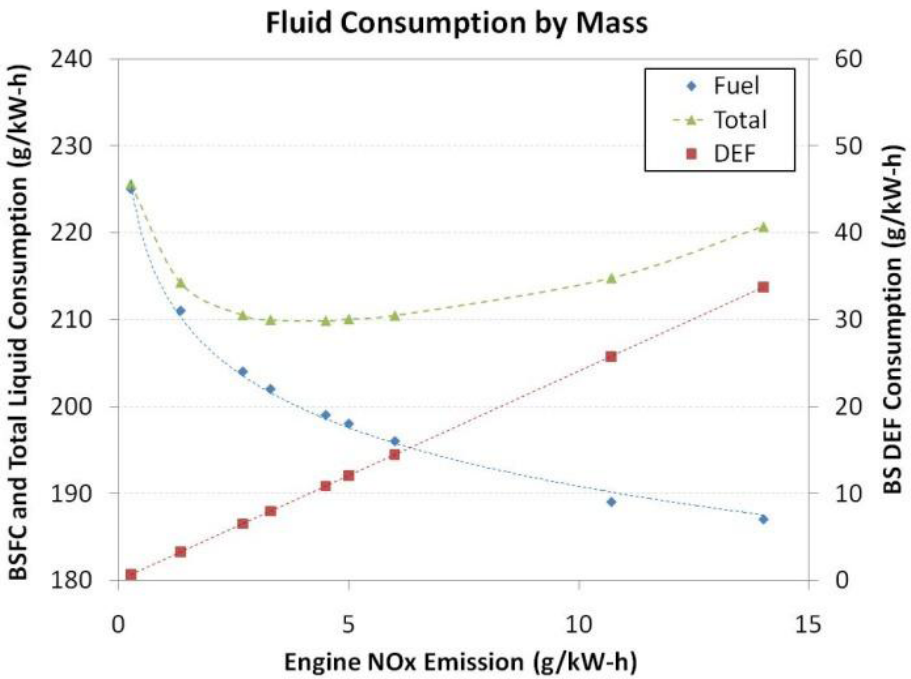
There are numerous opportunities for fuel savings on commercial trucks.

Engine improvements dominate line haul, coaches, and small delivery trucks. HEV dominates larger utility trucks and transit buses.

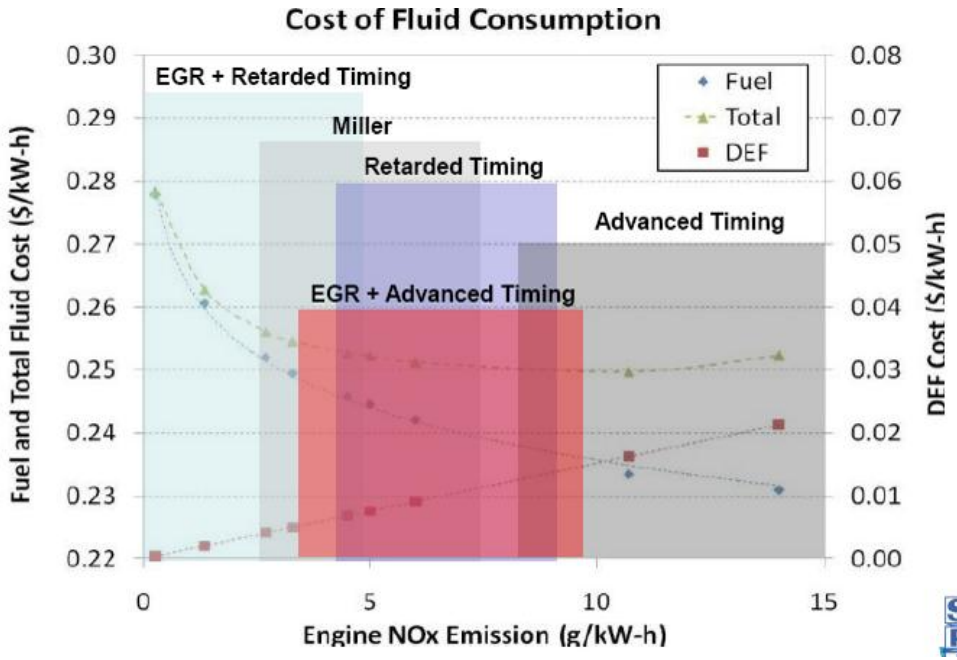


Fuel savings of 30-50% can be achieved on representative truck applications. Engine benefits dominate, and then comes HEV. Note: Non-TT (tractor trailer) applications represent ~60% of new HD vehicles.

As the spread between diesel emissions fluid (DEF) and fuel increases, engine strategies will move to higher NOx calibrations.



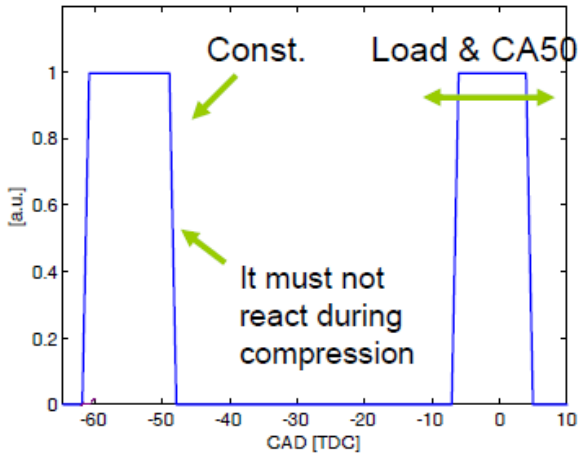
On a mass basis, 2.5 to 5 g/kW-hr NOx is the optimum calibration. Note the significant slope of the BSFC vs. NOx curve at higher NOx levels. DEF consumption 1.1% DEF per g/kW-hr NOx



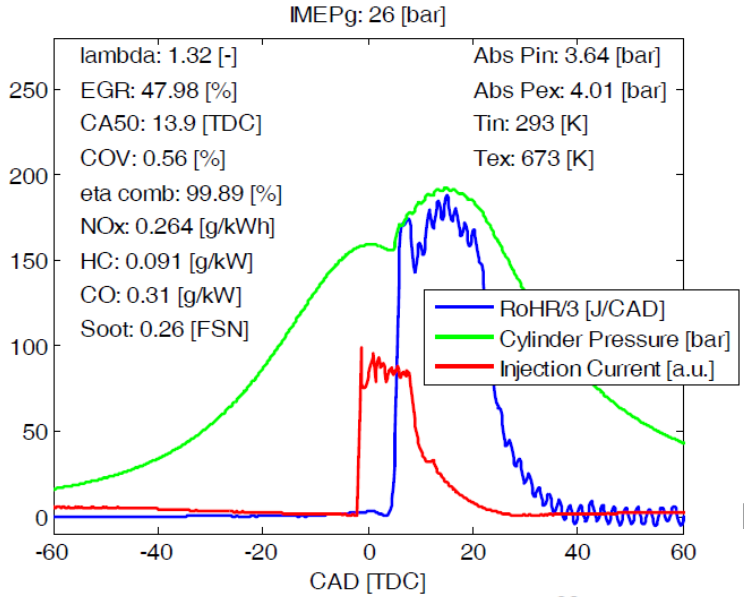
Economics will help drive choices of HD engine technology. Diesel fuel: $3.89, DEF: $2.59

SwRI, Emissions 2011, 6/11

HD Partially Pre-Mix Combustion (PPC) with gasoline is showing 50% BTE and low emissions.

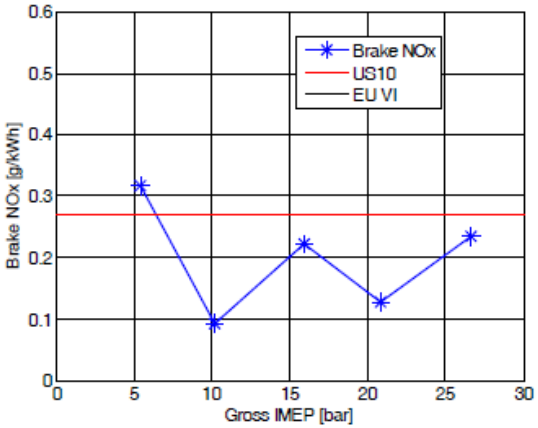


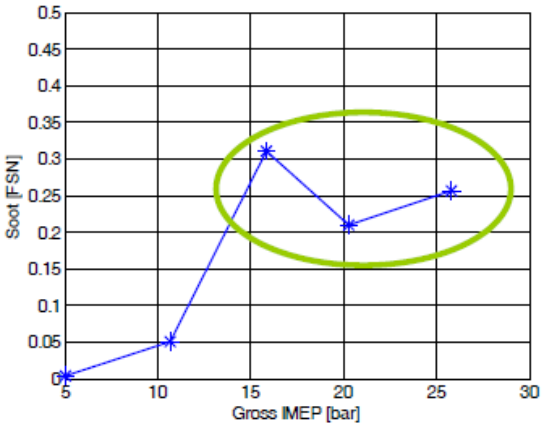
Two-stage injection for HD PPC. First one depends on octane and EGR.

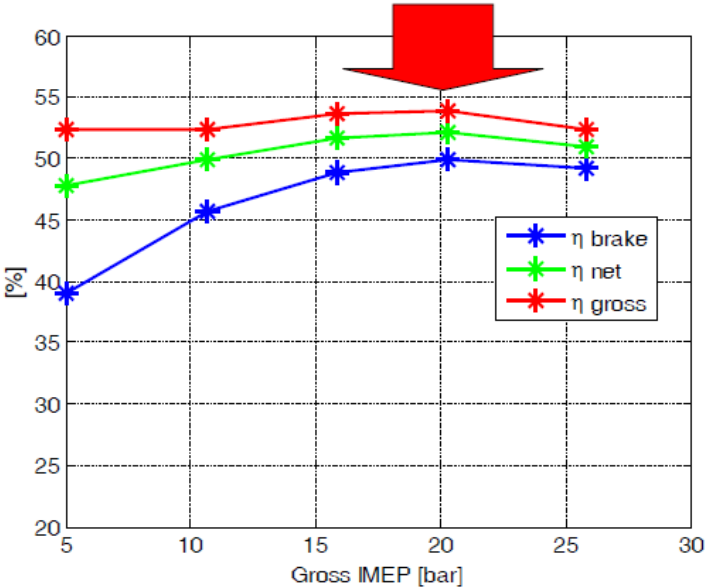


- Scania D13 engine but only one cylinder is used.
- Low-Octane gasoline, but it "is from a refinery stream".

Lund Univ., DEER Conf 9/10







Engine-out emissions are quite low. CO and HC less than US2010 at IMEP>15 bar

HD HEVs are seeing about 20-30% FC savings, use Li-ion batteries, and have a parallel architecture

Truck Manufacturer	GVW / Usage	HEV Type	Energy Storage	System Configuration	Claimed FC Improvement
Daimler (Atego BlueTec)	12.0 Tonne (Distribution)	Parallel (P2)	Li-ion Batteries	Engine downsized to 4 cylinder 44kW electrical machines +60kg weight increase (total vehicle)	20%
MAN (TGL 12.220)	12.0 Tonne (Distribution)	Parallel (P2)	Li-ion Batteries	Engine downsized to 4.6L 4 cylinder 2 and 6kWh battery options 60kW electrical machine (425Nm) +100kg weight (reduced payload)	15%
DAF (LF 45)	7.5 Tonne (Distribution)	Parallel (P2)	Li-ion Batteries	Engine downsized to 4.5L 4 cylinder 44kW electrical machine (420Nm) 2km full EV range (fully charged)	30%
Kenworth (T270 / T370)	11.5/15.0 Tonne (Distribution)	Parallel (P1)	Li-ion Batteries	Paccar PX-6 engine with ISG Eaton 6-spd ultrashift transmission 340volt Li-ion battery pack 44kW electrical macine +200kg weight (50kg battery)	20%
Peterbilt (330)	12.0 Tonne (Distribution)	Parallel (P1)	Li-ion Batteries		30%
Hino (Ranger)	13.0 Tonne (Distribution)	Parallel (P1)	NiMH Batteries	Hino J05D engine 4.7L 36kW electrical machine (350Nm) 288volt NiMH battery pack	20%

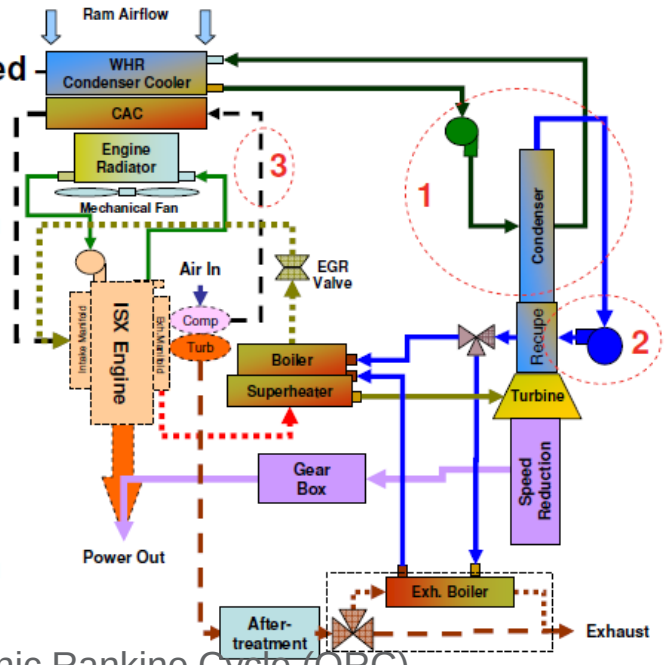
Source: OEM websites and public information

Ricardo, 2010

Second generation waste heat recovery system shown.

Improvements gain 1.4% FC impact, on top of 6.2% for generation 1.

1. **Replaced water-cooled condenser for air-cooled** – gained 0.2%
2. **Replaced 2-stage, centrifugal pumps with single-stage positive-displacement pump** – gained 0.6%
3. **Added Charge Air heat recovery** – gained 0.6%
4. **5% reduction in power transfer parasitics with MORC**

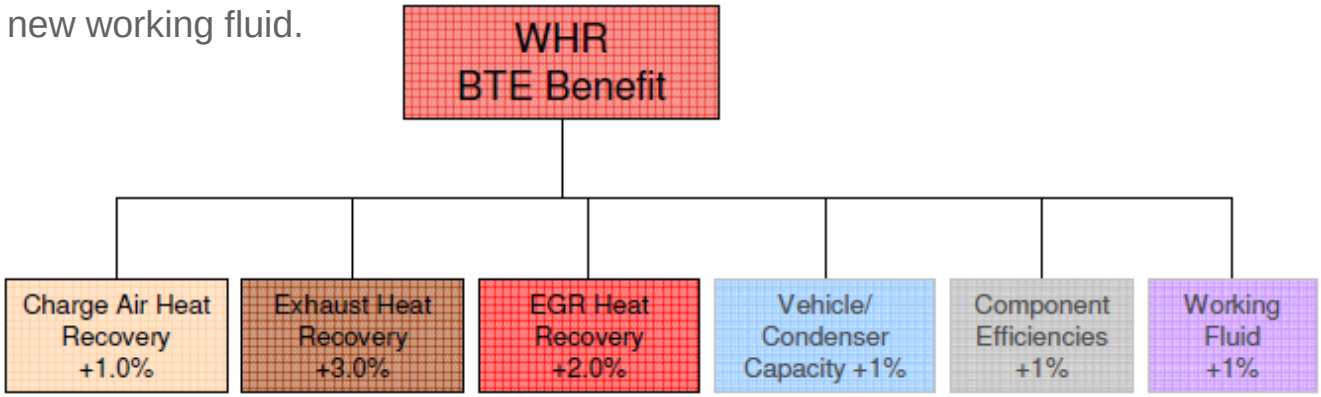


Second generation Organic Rankine Cycle (ORC) improvements include the condenser, pumps, added heat source, lower parasitic losses, and new working fluid.

Future Directions

- System Architecture and Controls
- Turbine Expander
- Expander to Engine Geartrain
- Heat Exchangers – on and off engine
- Feedpump and instrumentation
- Fluid Development (low GWP alternatives)
- Vehicle Packaging
- Cost Focus

Cummins, Emissions 2010 Conf, 6/10



Potential benefit of 9% energy from WHR. 6.2% realized in generation 1.

Summary

- Criteria pollutant tailpipe standards are tightening again
- CO_2 mandates are in place for LD and HD vehicles
  - Onset of another major regulatory-driven technology evolution
- CO2 emission improvements depend on the test cycle in which the vehicle is run
- Light-duty diesel approaches are focusing on downsizing, and high NOx calibrations for FC reductions
- Gasoline engines are showing significant advances in both downsizing and in the use of cooled EGR.
- HDD engine technologies are addressing engine-out NOx and FC