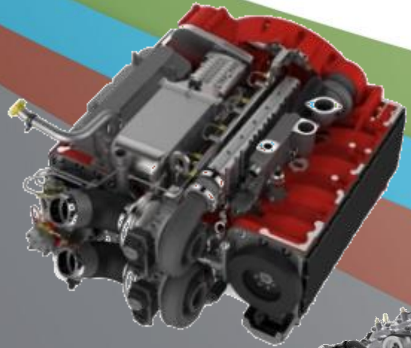
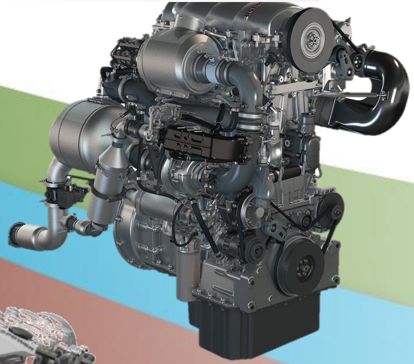




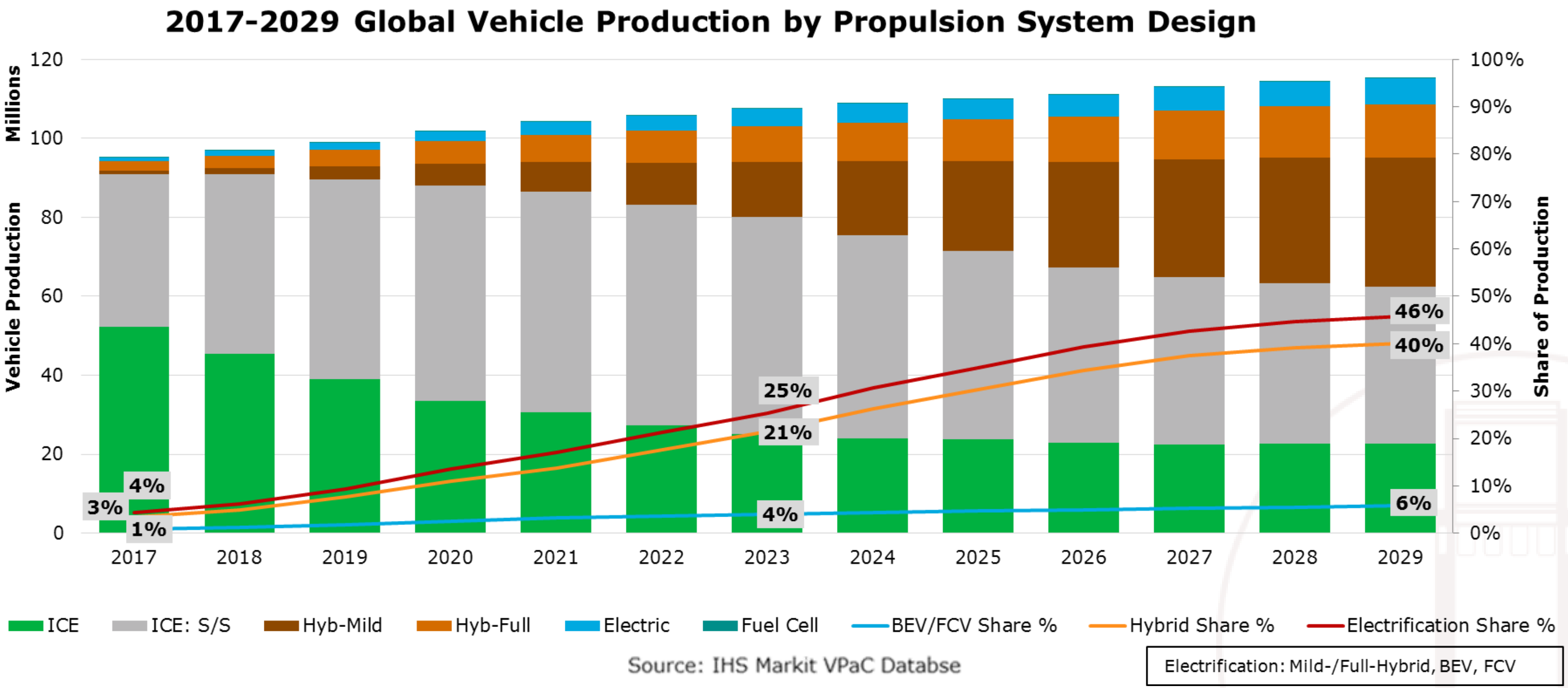
The Engine Imperative

Fabien Redon, EVP and CTO

Achates Power

achates POWER™ Fundamentally Better Engines®

Minimum 3 Billion More IC Engines Built by 2050



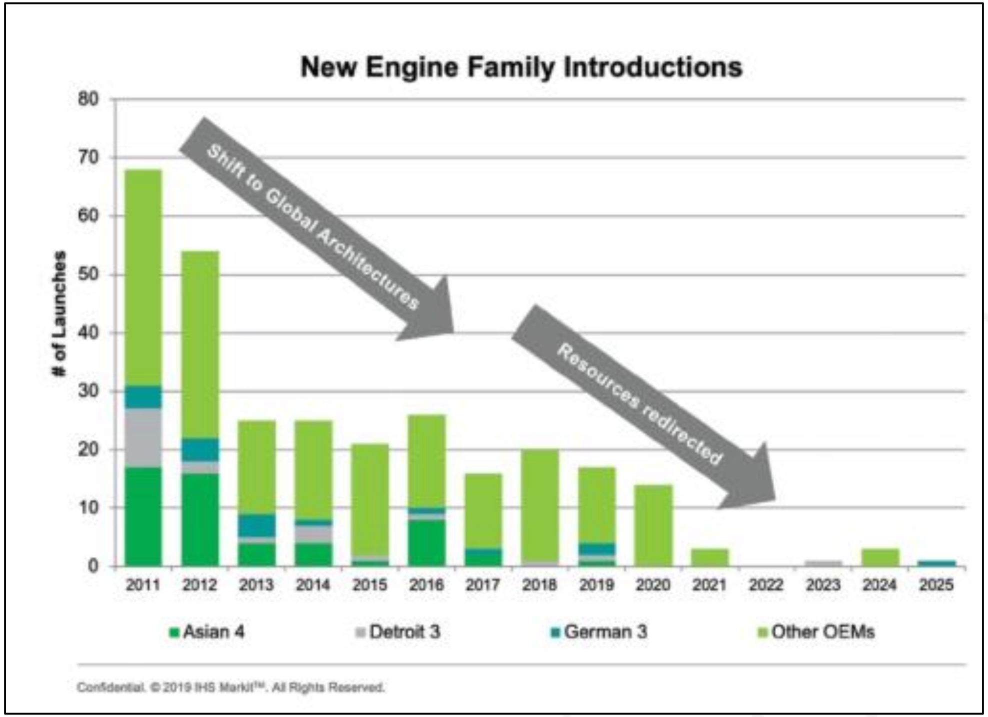
Even with more rapid EV deployment – assume 80% by 2050 – 3 billion more internal combustion vehicles will be sold by 2050 globally

- *If EV sales do not grow as projected, even more engines will be sold → better engines are essential for sustainable global transportation needs*

Declining Industry Investments in ICE

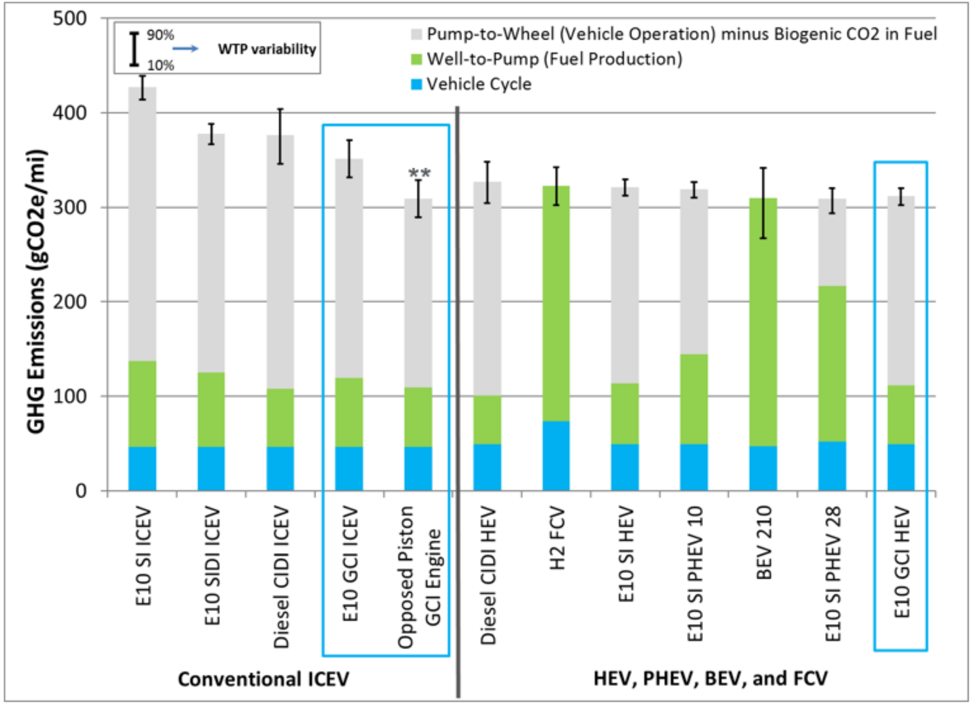
Unprecedented industry optionality is starving IC Engine development

- Alternative funding sources needed to offset capital shift
- Better ICE engines will be needed
- Time to double up and get ready to support vehicle manufacturers when their focus shifts back



Automotive Engineering Magazine, April 2019

Cradle-to-Grave CO2: ICE based vehicles are competitive



- Pump-to-Wheel* (Vehicle operation)
- Well-to-Pump (Fuel Production)
- Vehicle Cycle

Assumptions:
- *Vehicle technologies are mixed*
- *Most data from 2015 GREET Model- for US only*
- *Gasoline Compression Ignition results created based on a joint study by ANL and Aramco*

ARGONNE'S GREET
TAKING LIFE CYCLE ANALYSIS TO THE NEXT LEVEL

→ **Entire lifecycle of transportation energy needs to be considered.**
→ **Aramco is working with ANL on LCA and fleet modeling for U.S. and Chinese markets.**

*minus biogenic CO_2 in Fuels

** Based on Achates Power 50% better fuel efficiency data relative to gasoline engines

Argonne NATIONAL LABORATORY aramco

Achates Power, Inc.

Who we are

Develop enabling technologies for low CO_2 and low emissions Opposed-Piston Engines

Achates Power, Inc.

How we do it

Partner with strategic industry members to co-develop engine solutions – not manufacture ourselves

Joint Development
Achates Power + Customer

Why we do it

Provide economic value to the customer while accelerating positive impact on the environment

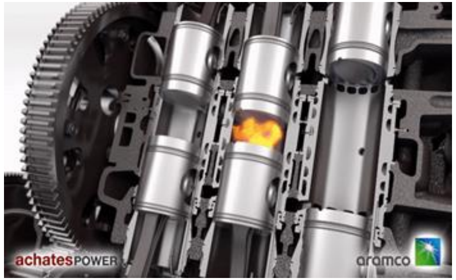
Customer

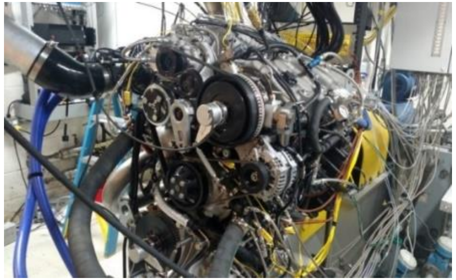
Enabling Technology Development

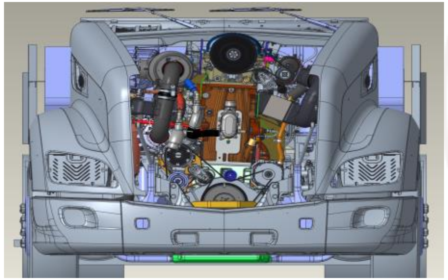
Power Train Integration and System Validation

Vehicle Integration

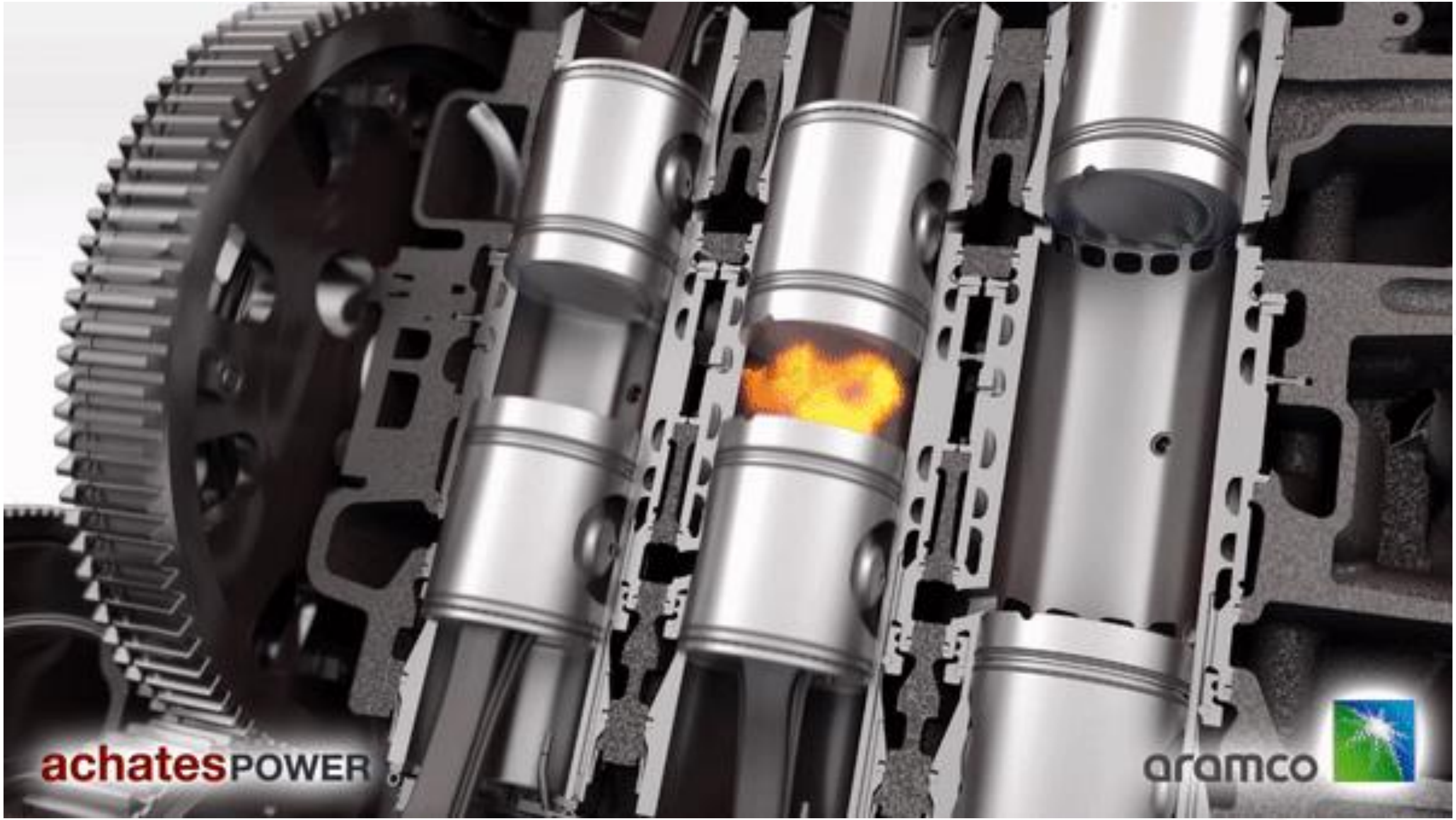
Business Integration





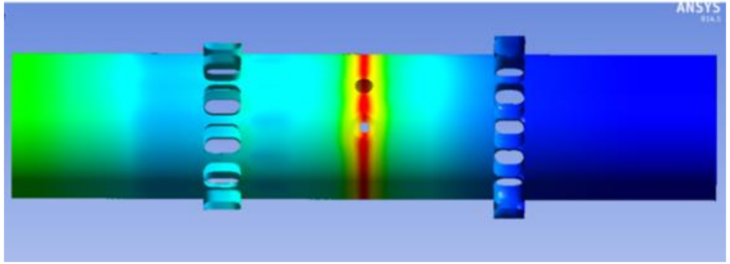


Achates Power Opposed-Piston Engines

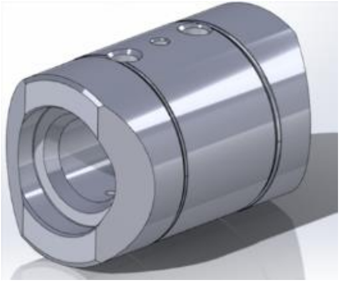


OP Engine Technical Challenges - Addressed

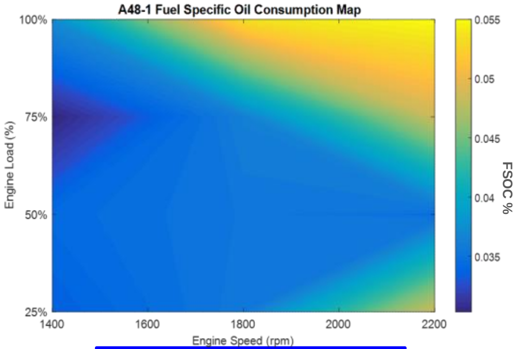
Piston Thermal Management



Cylinder Thermal Management

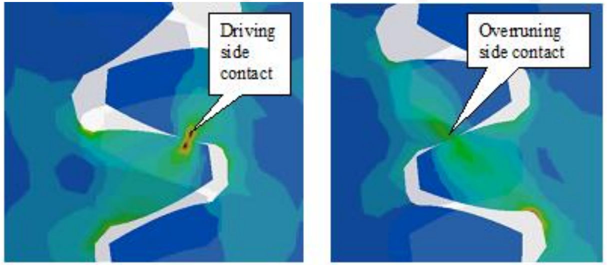


Wrist Pin Lubrication



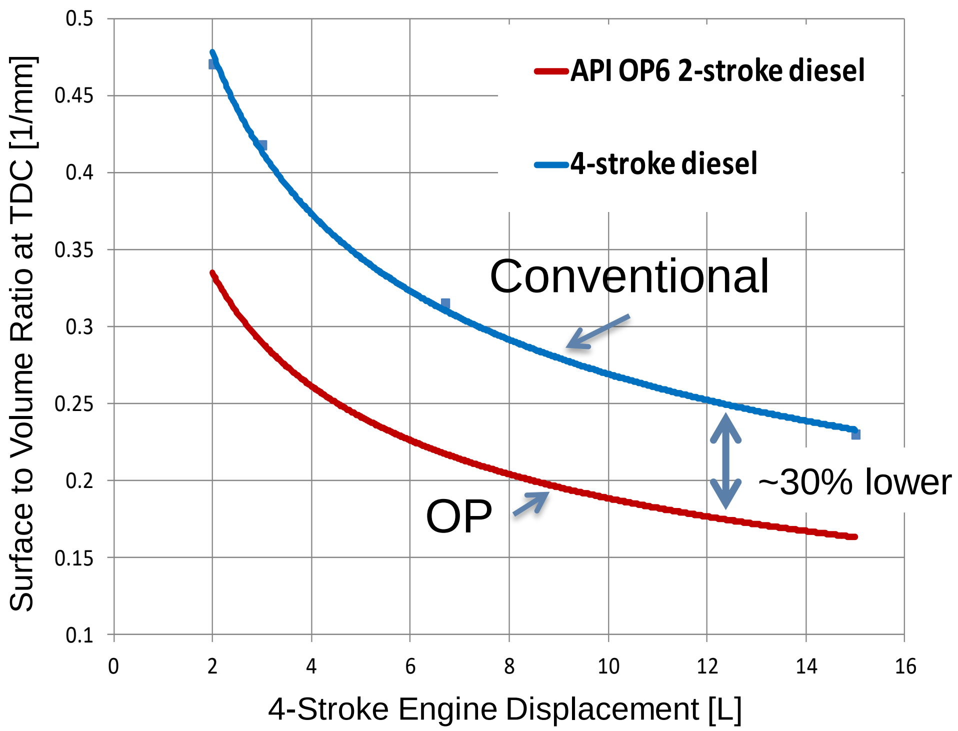
Oil Consumption

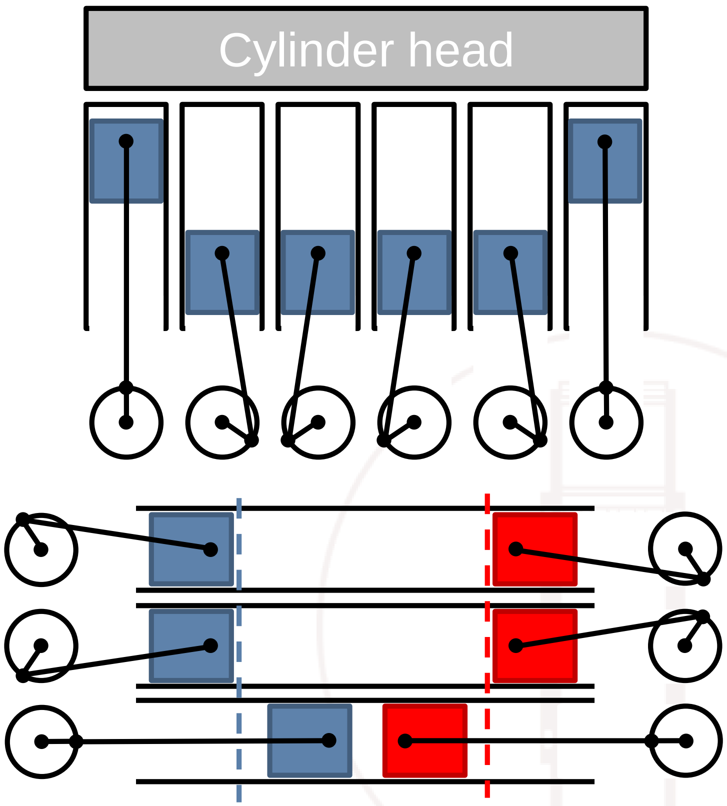
Ring Durability



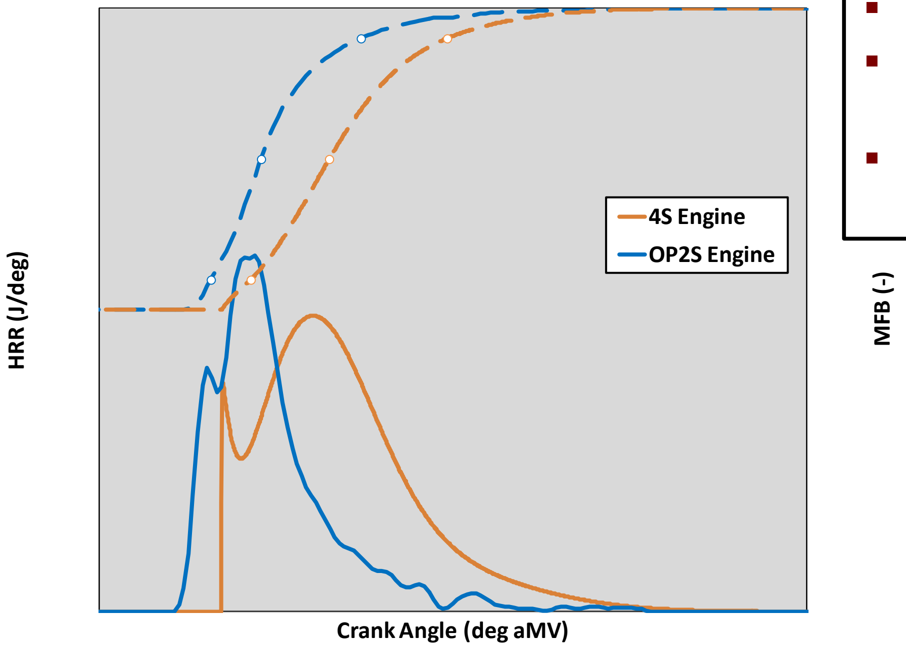
Geartrain Rattle Management

Reduced Heat Losses

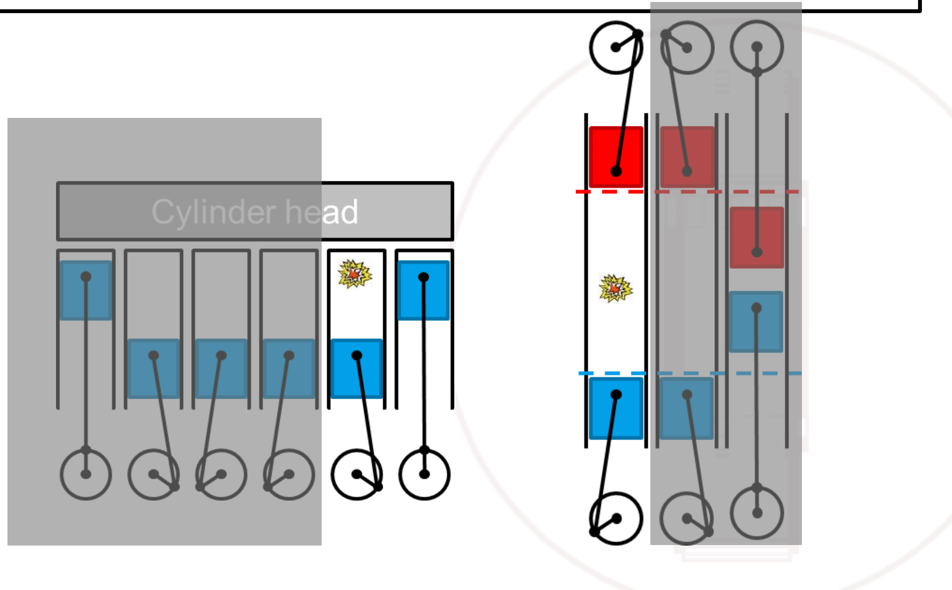




Earlier & Faster Combustion

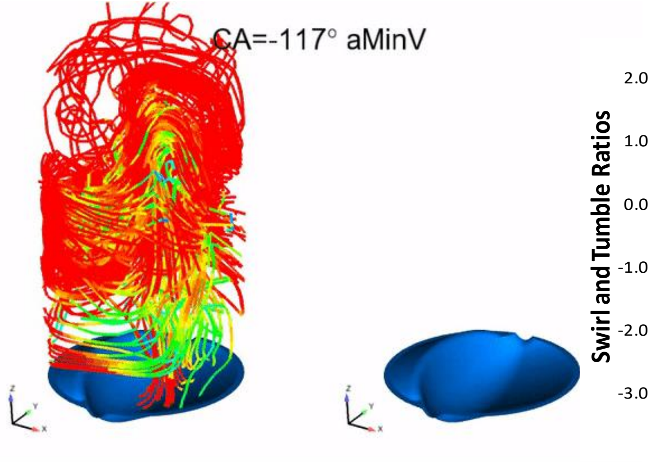


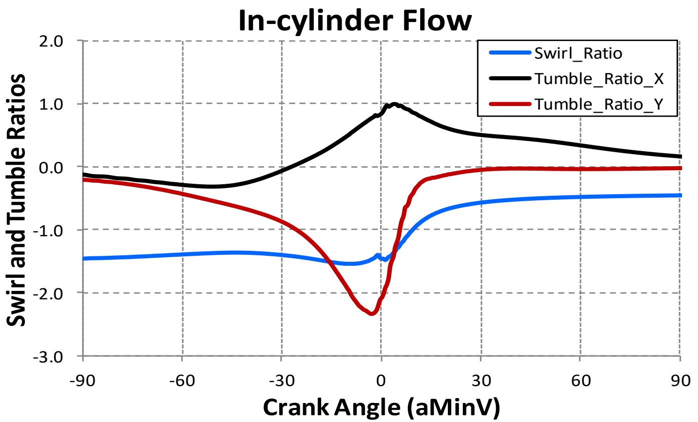
- Larger cylinder volume for a given fuel quantity
- Double volume change rate for OP
- At similar pressure rise rate, OP has a higher rate of heat release and shorter combustion duration
- Shorter combustion and lower heat transfer results in a more advanced combustion phasing

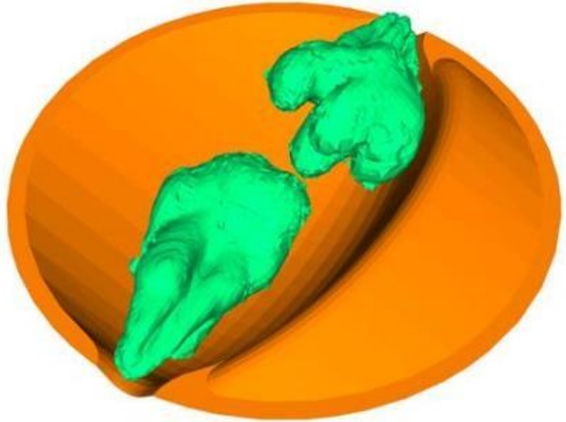


High Turbulence Combustion

- OP provides the flexibility to use both pistons to form the combustion chamber
- API proprietary combustion system design provides high mixing
- Combines swirl and tumble
- Dual injectors spray patterns resulting in less fuel-to-wall impingement
- Further reduction in heat loss because of higher wall temperatures from pistons

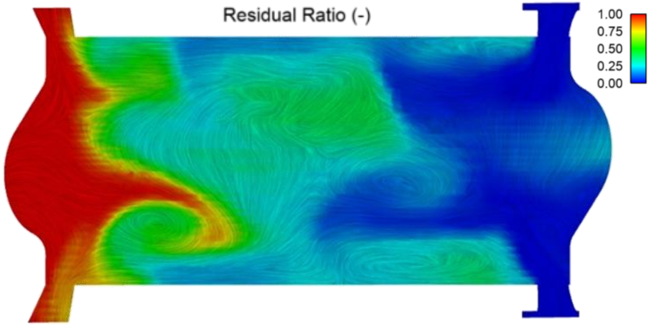


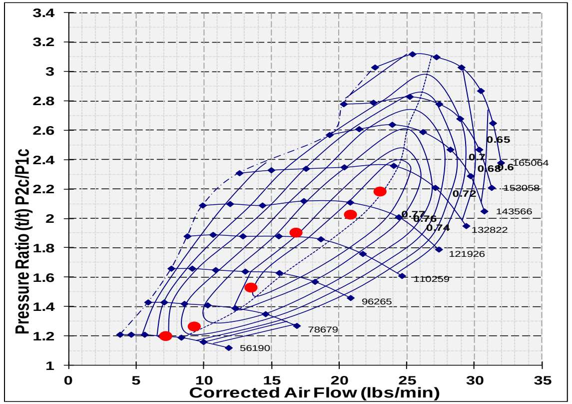


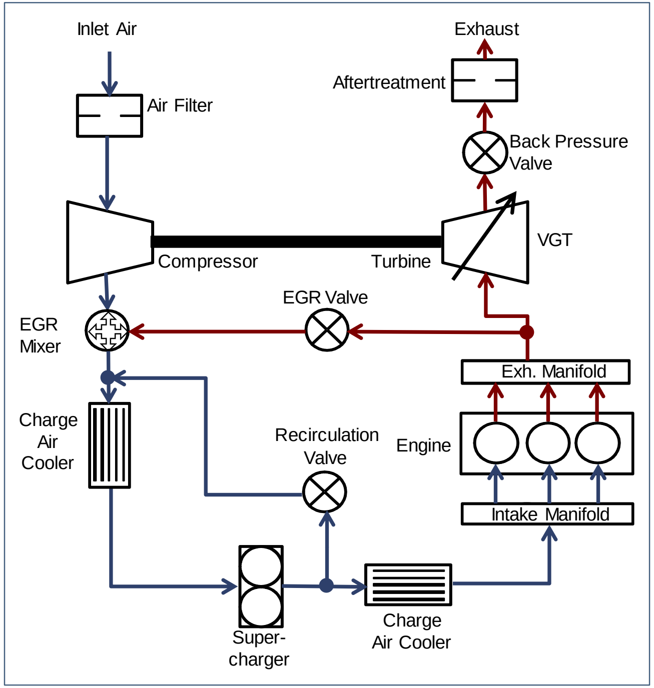


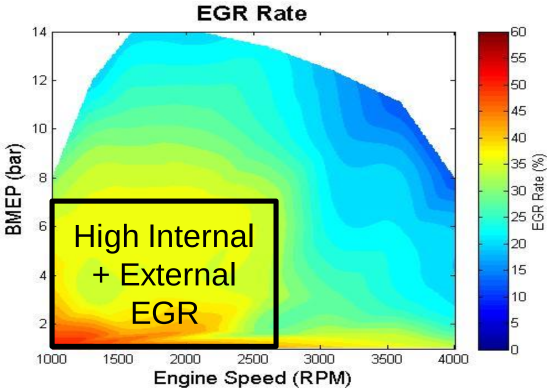
Flexible and Efficient Charging System

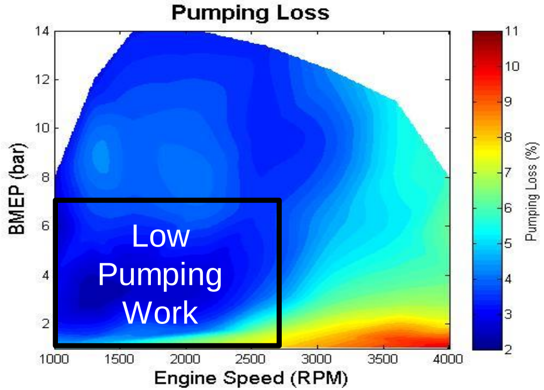
Gas exchange controlled by pressure differential. (OP pistons don't pump!)











Opposed-Piston Engine Architecture Advantages

Opposed-Piston Architecture

→ Reduced part count and lower manufacturing requirement

- Intake and exhaust ports opened/closed by piston location; no complex valve hardware
- Cranks, rods, pistons and gears are the only moving parts
- Base engine part count is 30% of an equivalent 4-stroke engine

→ Potential for lower engine cost

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Technologies for Efficiency and Emissions Improvements

Not Applicable

- Cylinder de-activation/Variable displacement for higher low load efficiency
- Miller or Atkinson cycle for higher efficiency

Similar Benefits

- Thermal barrier coatings for lower heat losses
- Higher injection pressure for higher power and lower emissions
- FEAD elimination/Electric accessories and pumps
- Waste heat recovery

Inherent

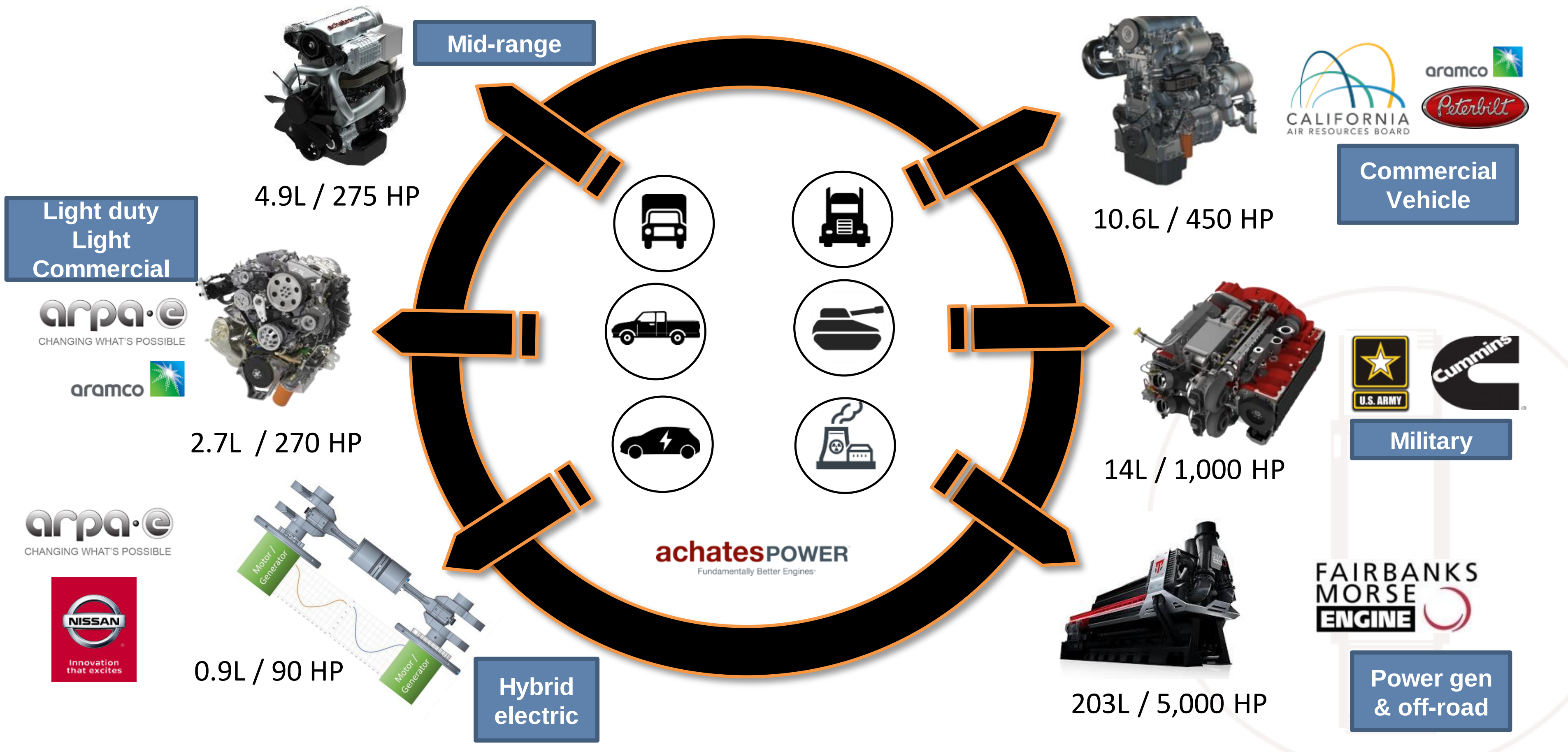
- Higher stroke to bore for reduced heat loss for higher efficiency
- Faster combustion for higher thermal efficiency
- Variable cam phasing/lift for higher efficiency and catalyst light-off
- Cylinder de-activation/Variable displacement for exhaust gas temperatures control

Greater Benefits

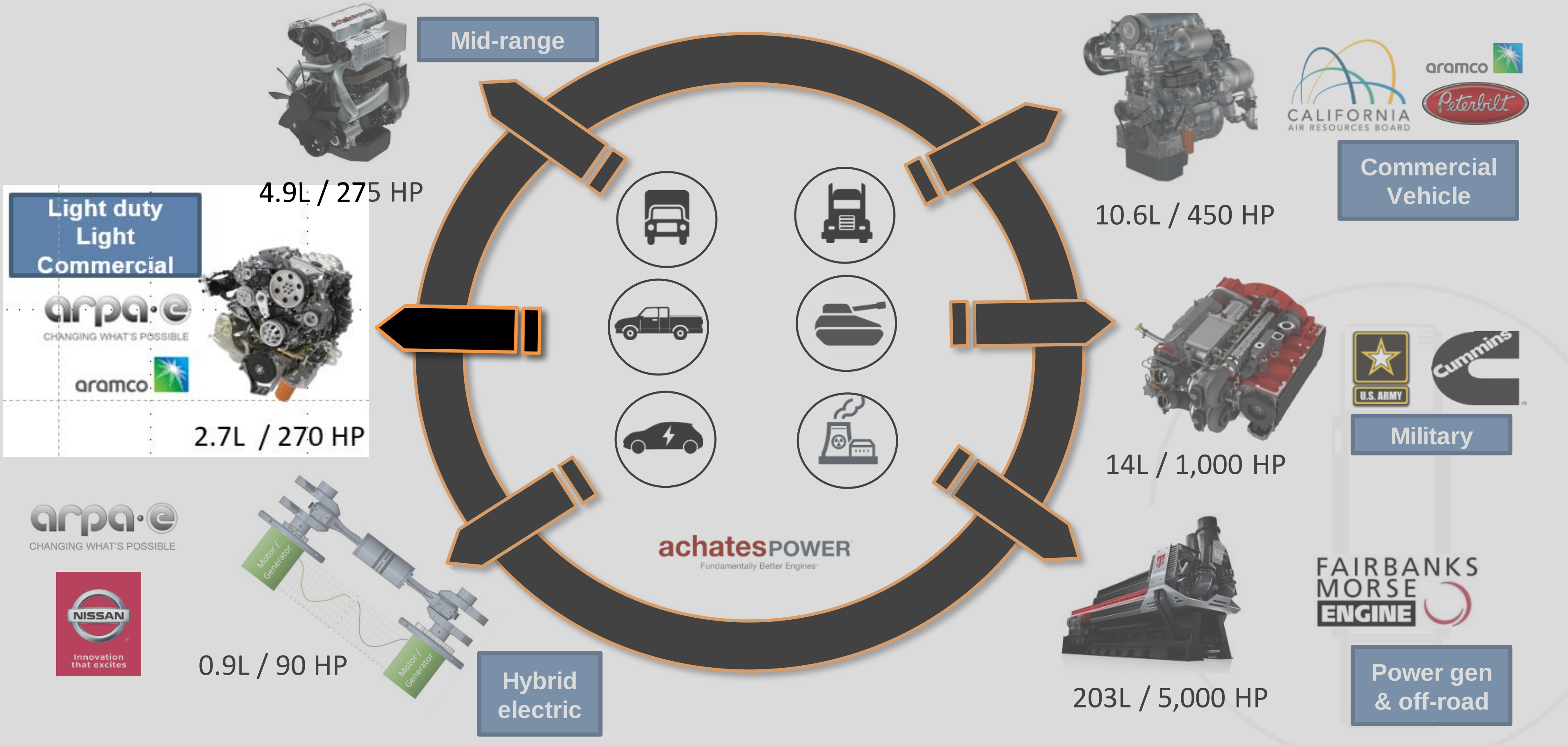
- Improved combustion for higher efficiency and emissions
- Variable compression ratio for higher power output and higher efficiency
- GCI/SPCCI for higher efficiency
- Improved turbo chargers for higher efficiency and power
- E-turbos for faster transient response and further downsizing
- EGR pump for higher efficiency and lower emissions
- Lower friction technologies for higher efficiency
- Down speeding for higher cycle efficiency
- Start/Stop for higher cycle efficiency
- Reduced exhaust backpressure for higher efficiency
- Variable pressure oil pump
- Hybridization for higher cycle efficiency

Applicability to the OP engine

Present Range of Applications



Present Range of Applications

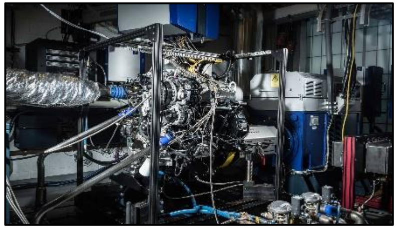


Opposed-Piston Gasoline Compression Ignition

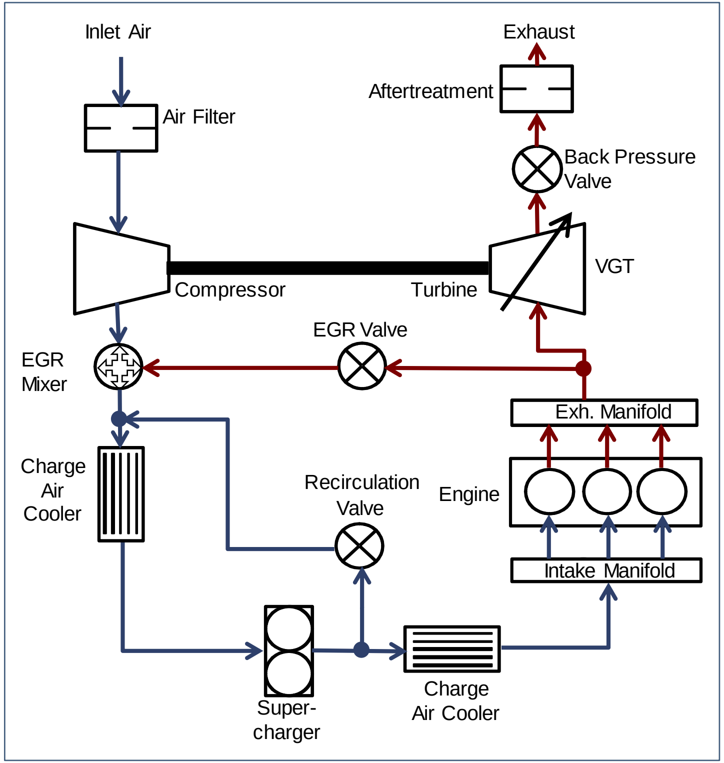
arpa·e

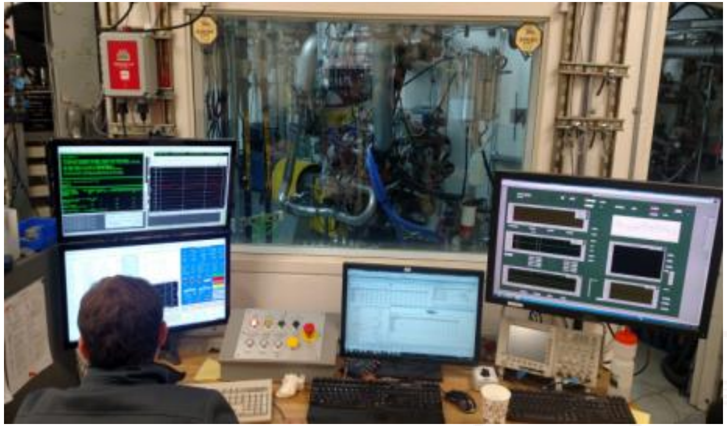
achates POWER
Argonne NATIONAL LABORATORY
Delphi Technologies
EATON
FEDERAL MOGUL
aramco
ROUSH
PIERBURG
MODINE
CORNING
Johnson Matthey
CONVERGENT SCIENCE
BorgWarner

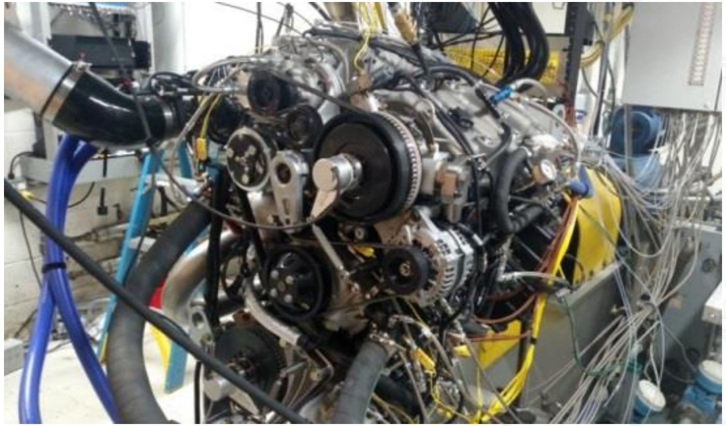
- $9 Million ARPA-e grant
- With Argonne National Labs & Delphi Technologies
- GCI, 2.7L, 3-cylinder engine, Bin 125 emissions with Lean AT
- Fits in Ford F-150



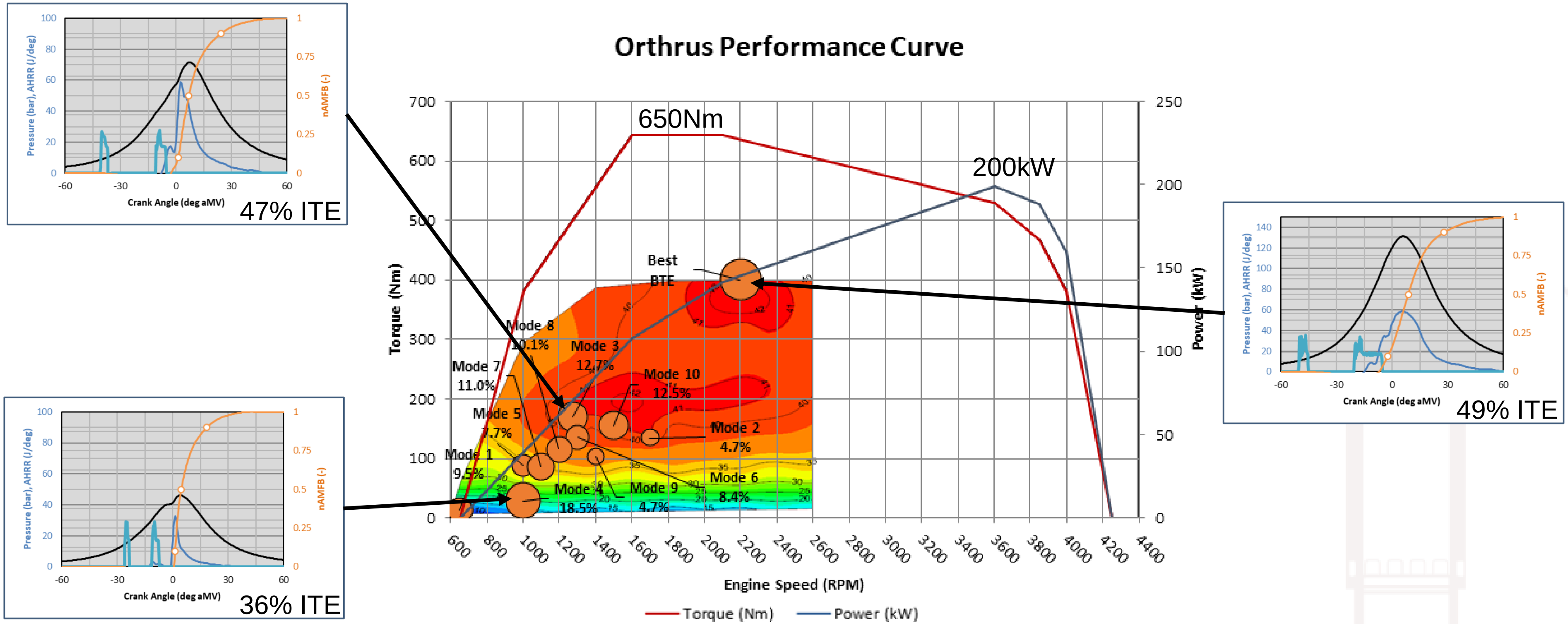
Test cell and Air System Set-up



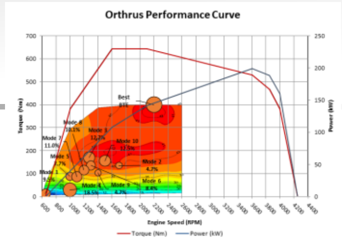


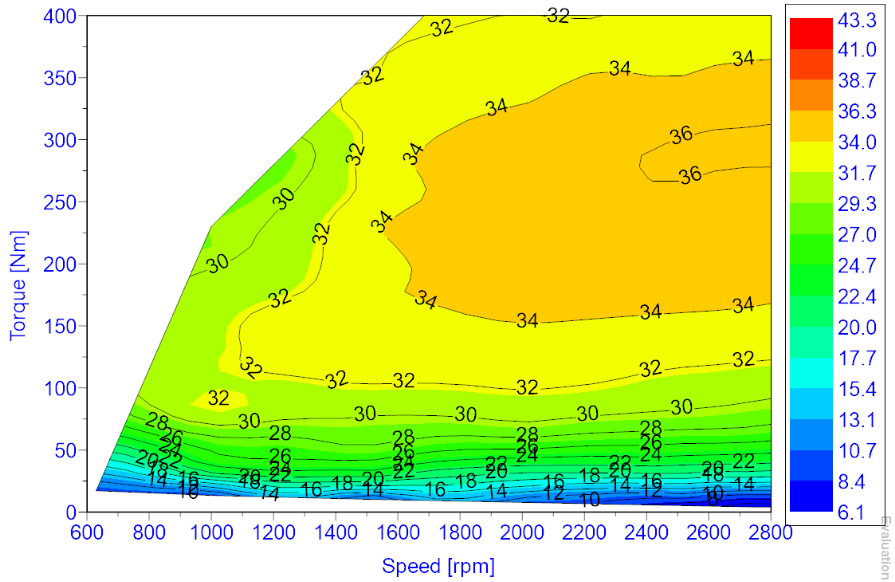


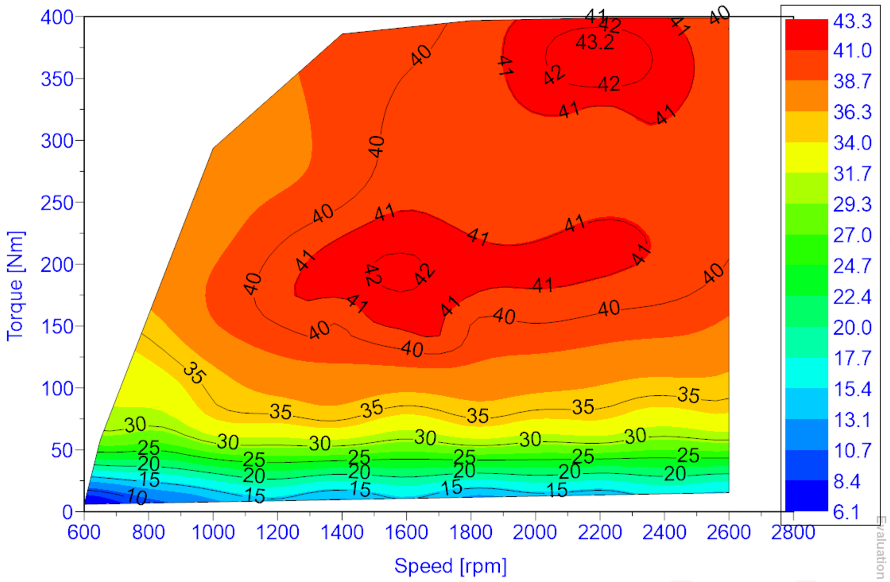
10 Modes and Performance Curves



F150 Ecoboost 2.7L 2015 Vs. OPGCI



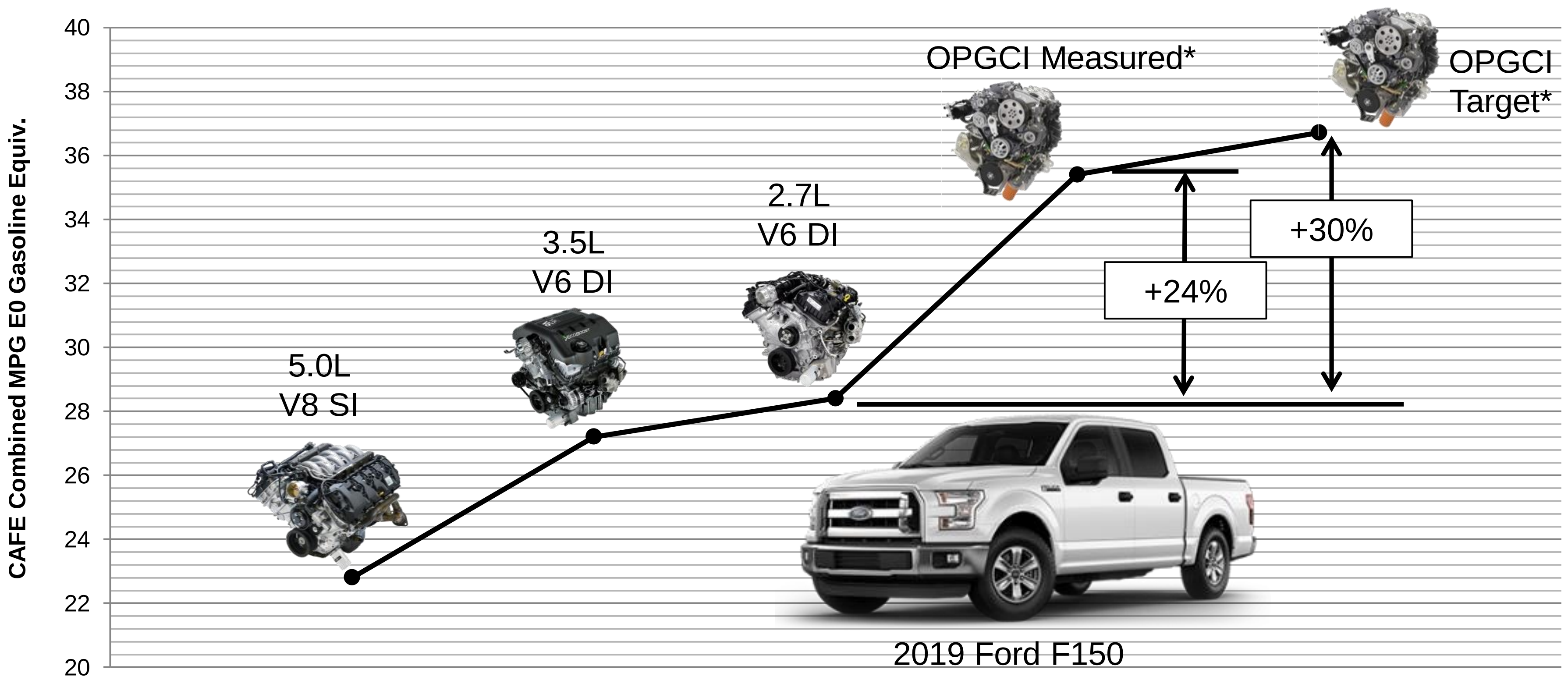




Partial map: 2015 Ford Ecoboost 2.7-Liter (SIDI Twin turbo) (US EPA measurement)

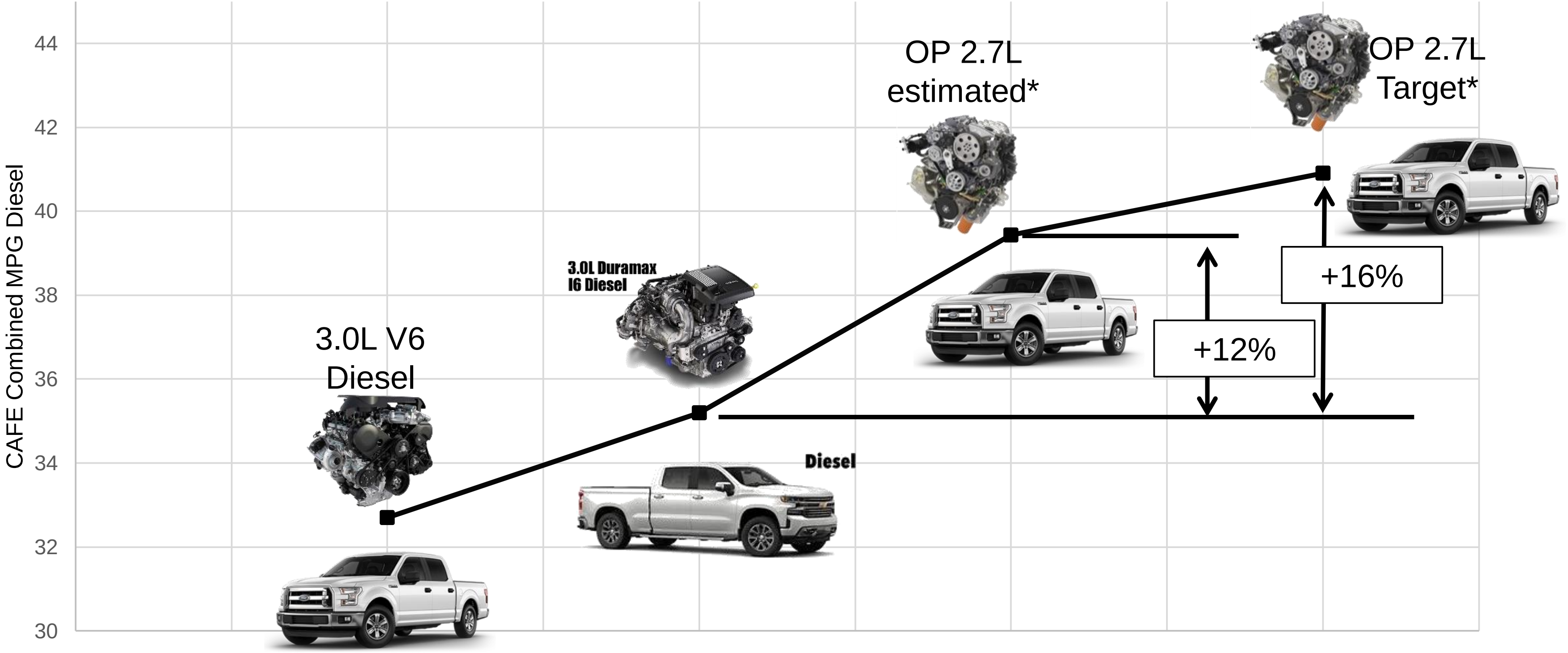
Partial map: OPGCI Engine 12 ECL measured

Vehicle fuel economy comparison (Gasoline E0 Equivalent)



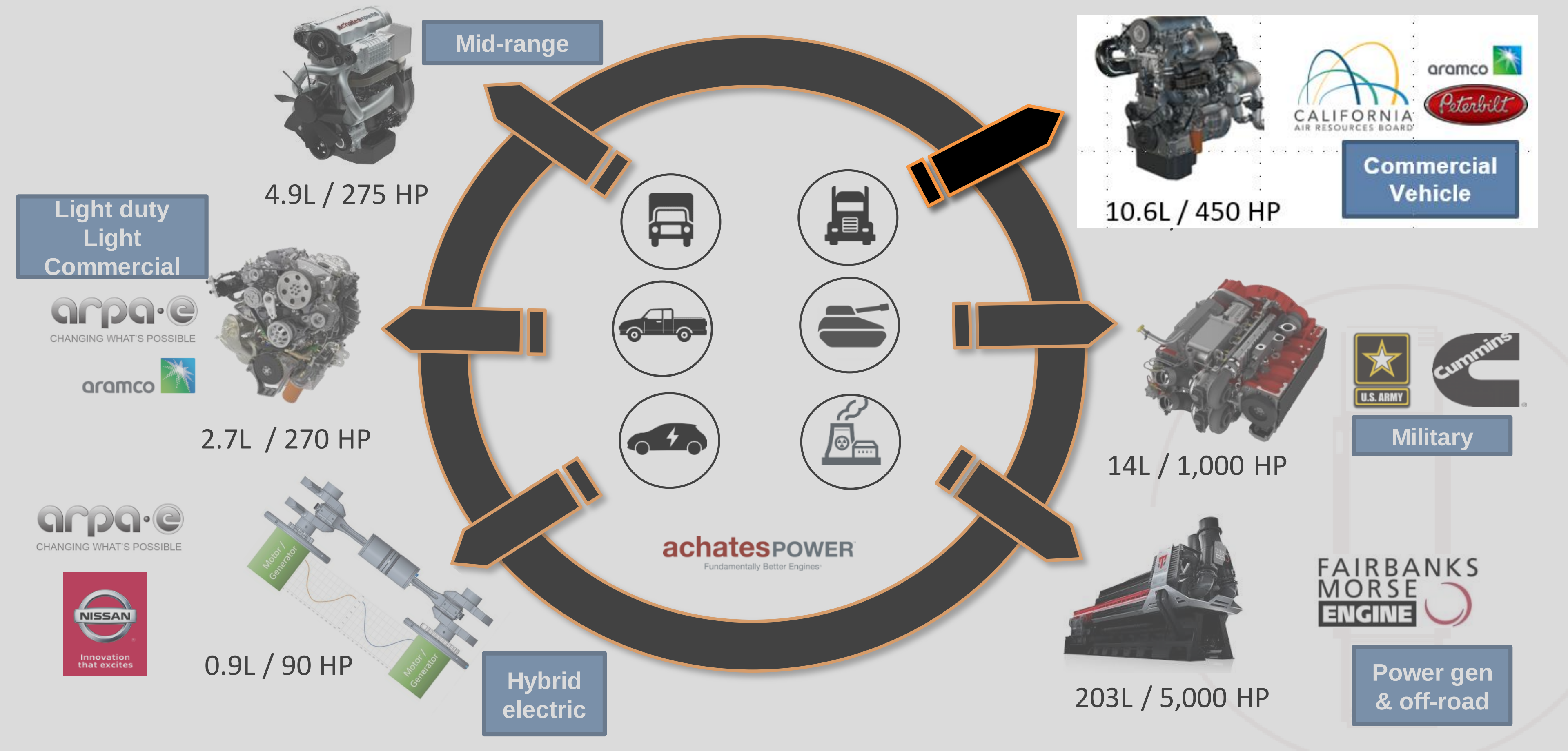
*Adjusted from 2009 Nissan Titan results to compensate for vehicle weight reduction (5000lbs test weight), 10 speed transmission, integrated accessories and active aero using NAS adjustment factors. 70% Stop/Start

Vehicle fuel economy comparison (Diesel equivalent)

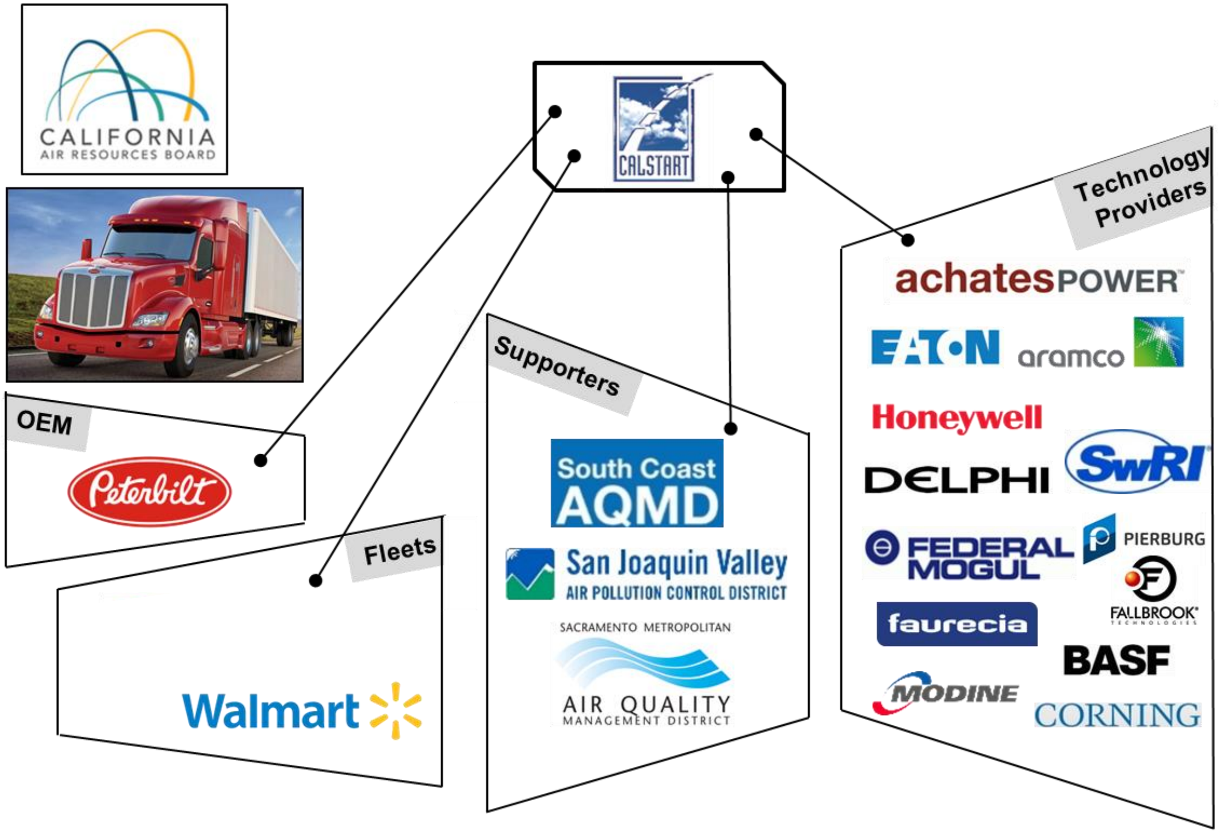


*Adjusted from 2009 Nissan Titan results to compensate for vehicle weight reduction (5000lbs test weight), 10 speed transmission, integrated accessories and active aero using NAS adjustment factors. Measured on gasoline compression ignition and adjusted for fuel density. 70% Stop/Start

Present Range of Applications

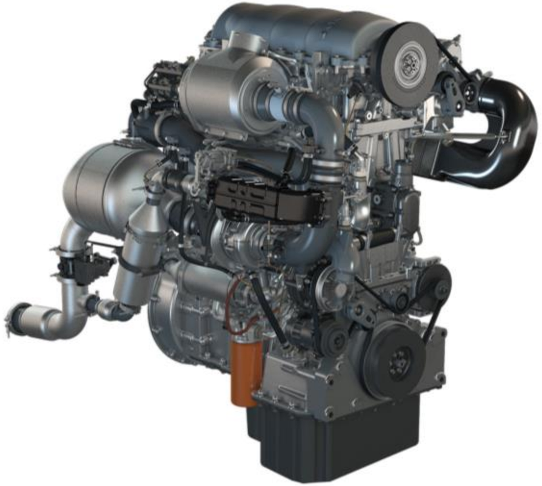


CARB Ultra-Low NOx Heavy Duty Demonstration



PROGRAM GOALS

NO_x	0.02 g/bhp-hr (90% reduction)
CO_2	2027 EPA Standards



Superior Exhaust Gas Temperature and Emisions Management

Case Name	Units	Warm-Up Point
Speed	rpm	1098
Brake Power	kW	0.8
NOx Flow	g/h	6.6
Soot Flow	g/h	8.1
CO Flow	g/h	288
HC Flow	g/h	7.7
Exhaust Temp Post Turbine	degC	493.3
Total Exhaust Massflow	kg/h	148.5
Exhaust Enthalpy	kW	21.1
MPRR	Bar/ deg	2.2
COV (IMEP)	%	2.25

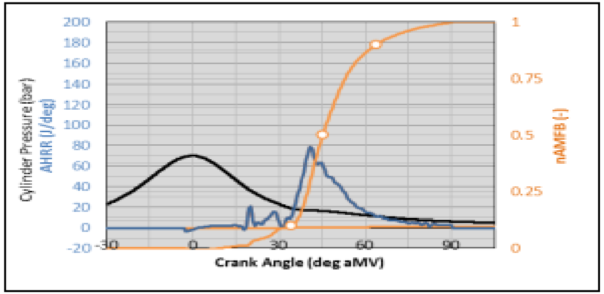
Idle (Speed, Brake Power)

Low Emissions (NOx Flow, Soot Flow, CO Flow, HC Flow)

High Exhaust Enthalpy (Exhaust Temp Post Turbine, Total Exhaust Massflow, Exhaust Enthalpy)

Low Comb. Noise (MPRR)

Good Comb. Stability (COV (IMEP))



Air system

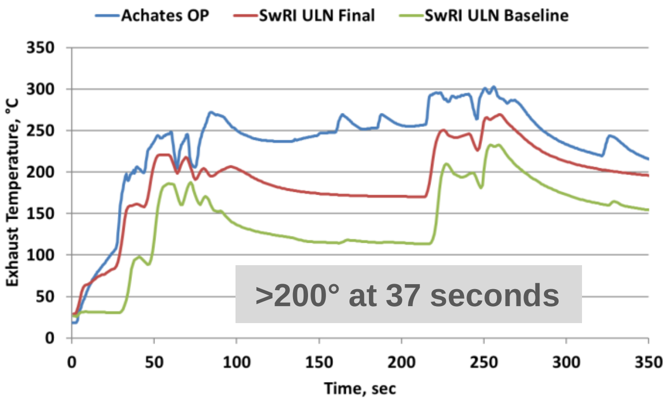
- Air pumping decoupled from the engine cycle
- Independent intake and exhaust pressure control
- Inherent internal EGR
- Independent external EGR

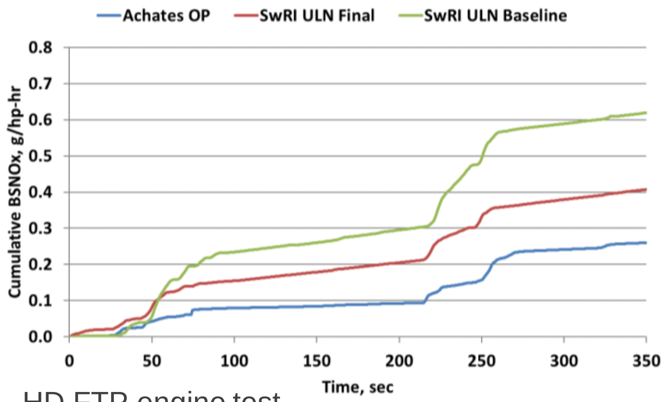
Combustion system

- Uniflow scavenging
- Twin injector
- Proprietary combustion chamber design

Fast Catalyst Light-off and Low NO_x at Cold Start

- Baseline engine was unable to provide sustained exhaust heat (above 200°C) until **400 seconds into cycle**.
  - NO_X reduction does not start until 550-600 seconds into the cycle
- Turbo-out temperature on the OP engine exceeded 200°C, within **40 seconds into the cycle**, and remained above this light-off threshold for the entire cycle.
  - NO_X and HC conversion starts early (200s-300s) into the cold-start cycle
- No additional hardware required





HD FTP engine test

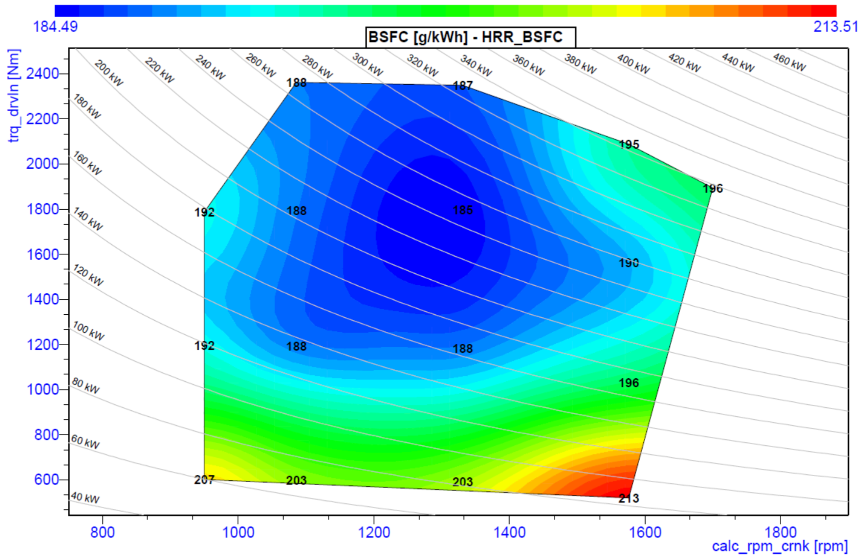
Information on engine configurations:

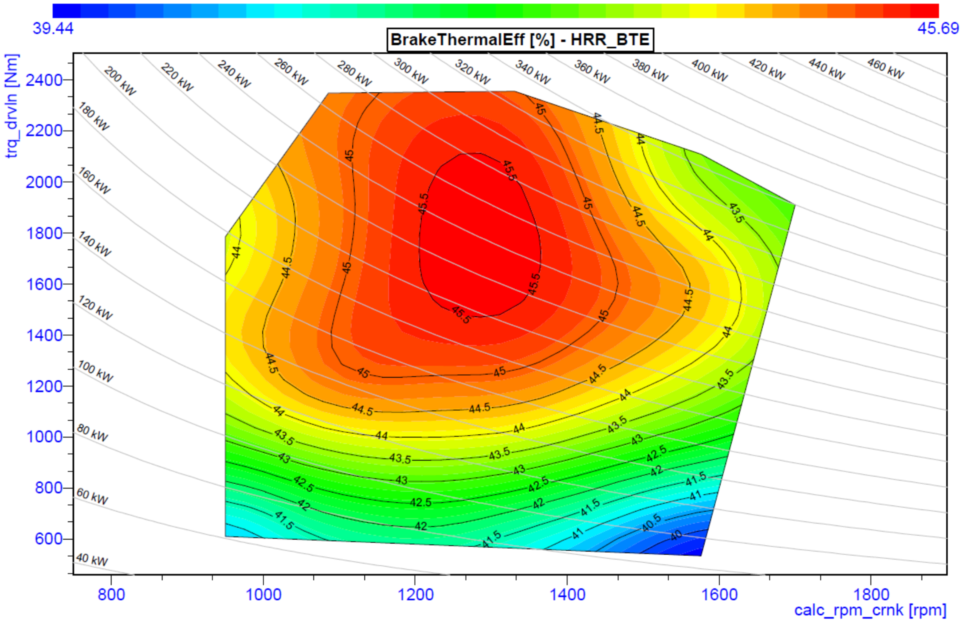
Achates Power OP Engine
SwRI Baseline Volvo 13L HD 2014
SwRI ULN Final Volvo 13L HD 2014 w. modified calibration

Patil, S., et al., "Cold Start HD FTP Test Results on Multi-Cylinder Opposed-Piston Engine Demonstrating Rapid Exhaust Enthalpy Rise to Achieve Ultra Low NOx," SAE Technical Paper 2018-01-1378, 2018, doi:10.4271/2018-01-1378.

HD OP Testing Update – Break-in results 2nd engine

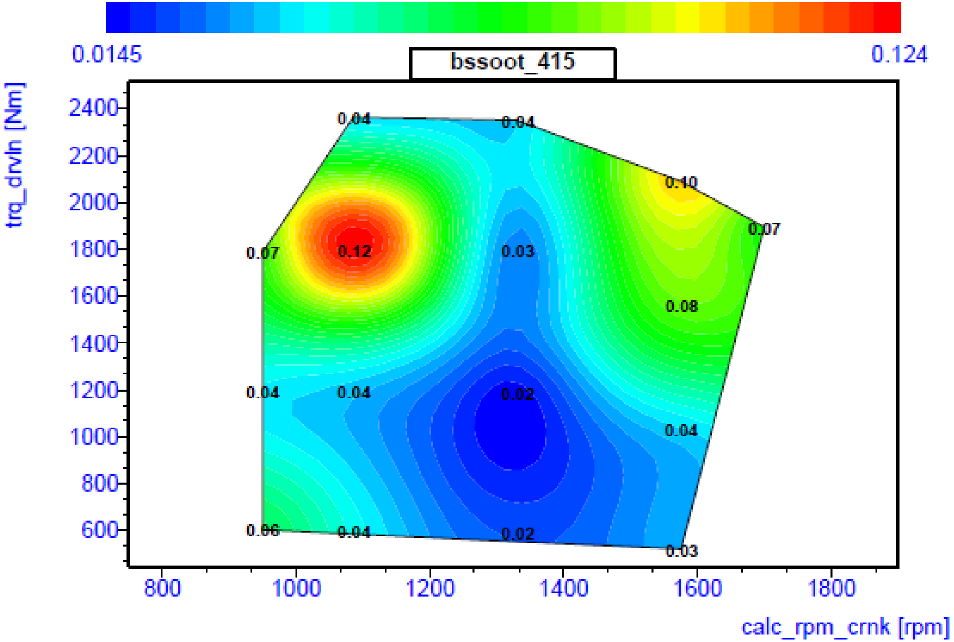
Considering optimization has not begun, best **break-in** point was recorded 186 g/kWh BSFC or 45.6% BTE.

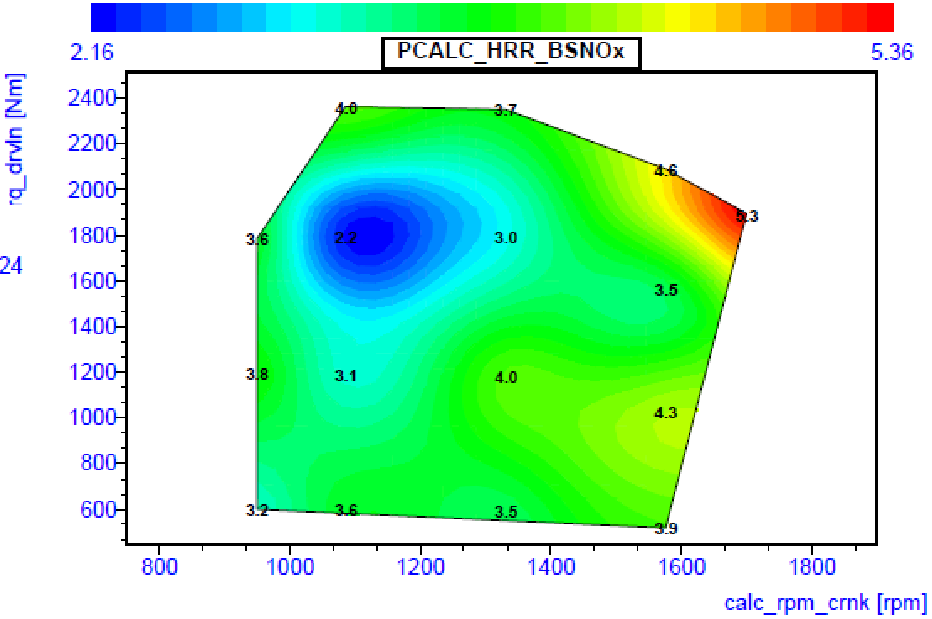




HD OP Testing Update – Break-in results 2nd engine

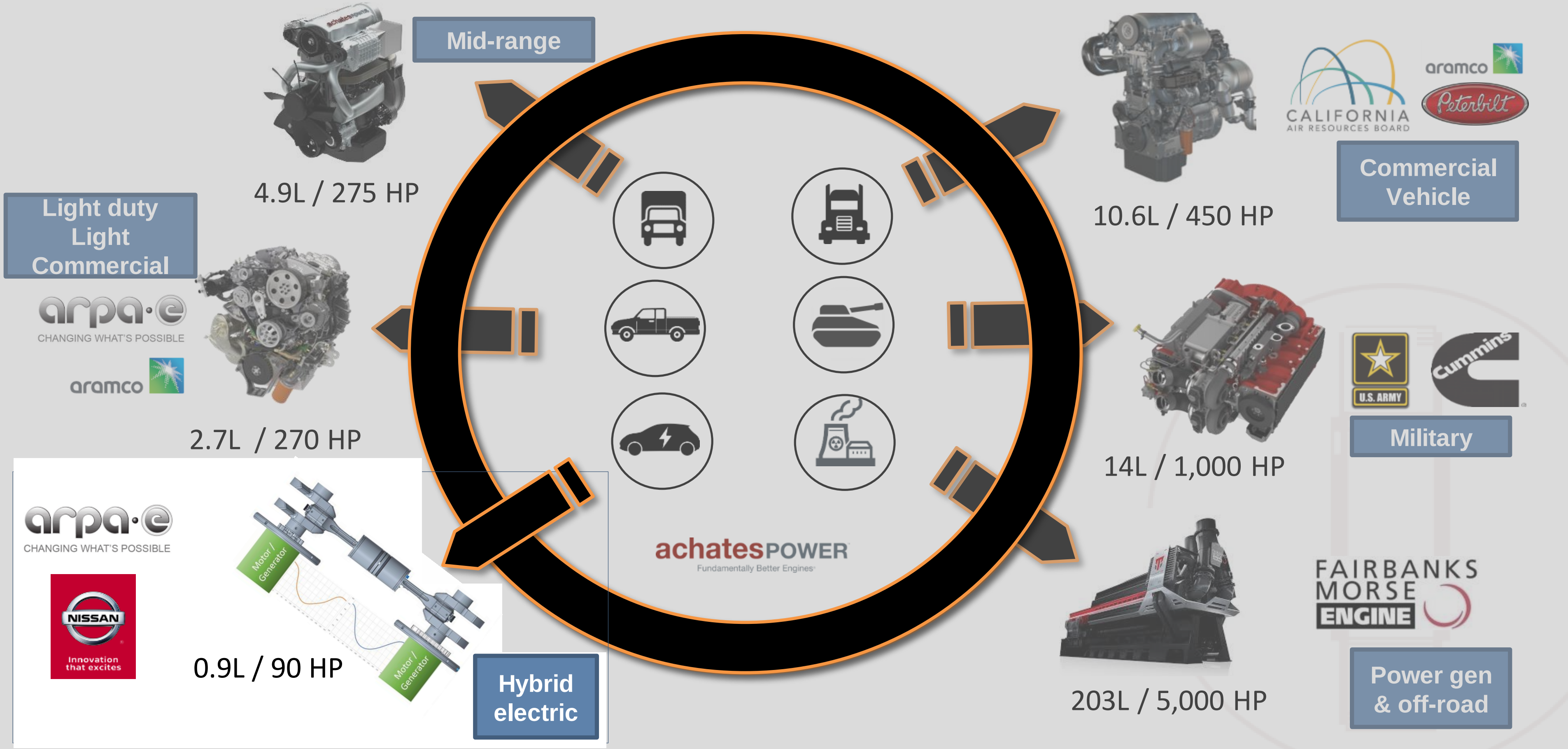
All break-in data was tuned around 2-5 g/kWh BSNOx for reasonable ULNOx aftertreatment conversion.





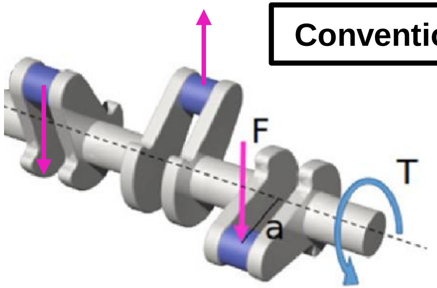
Being installed in a Peterbilt truck

Present Range of Applications



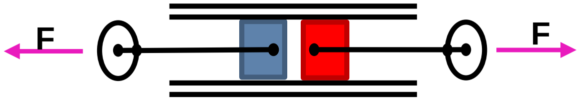
Well Balanced In A Single Cylinder OP

Conventional engine



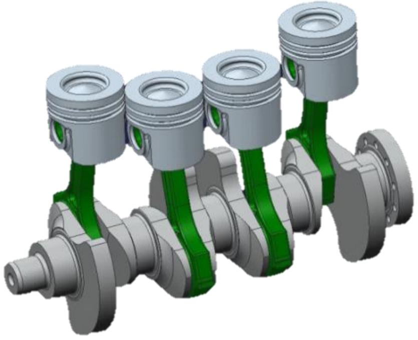
For conventional 4S engine, need at least **THREE** cylinder to balance the torque on the crankshaft

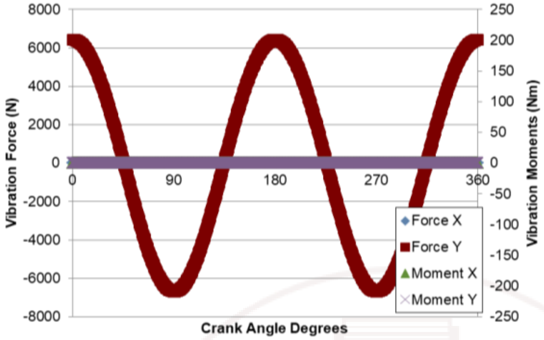
OP engine



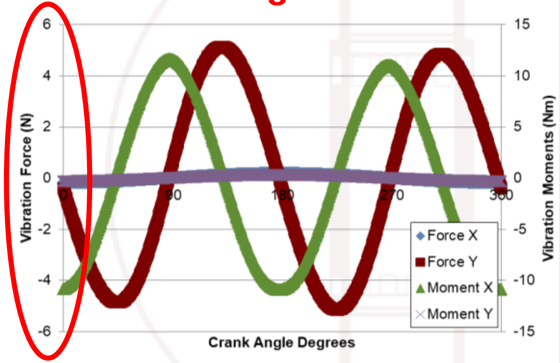
For OP engine, the force and torque exerted by the two pistons canceled out, resulting in a naturally balanced system even with just a single cylinder

Test Data Comparison: I4 vs OP

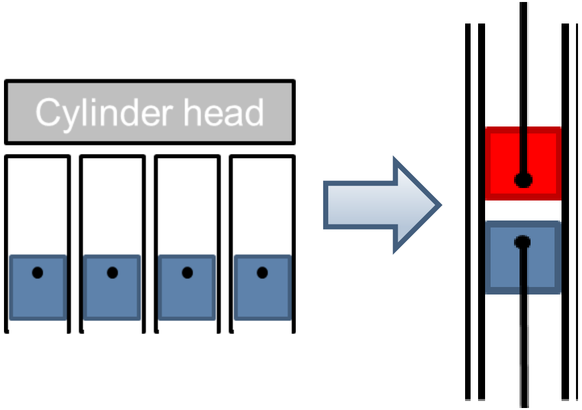




Force 3 Orders of Magnitude Lower!



Reduced Heat Transfer

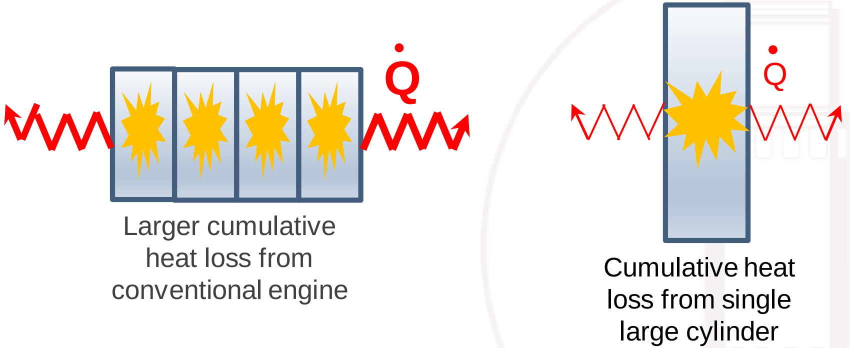


Engine	4 stroke	OP
Cylinders	4	1
Trapped Volume/Cylinder	0.3 L	0.9 L
Bore (mm)	78	80
Stroke/Bore Ratio	1.0	**2.2**
Trapped Compression Ratio	17:1	17:1
Combustion Chamber Surface Area/Volume (mm^{-1})	0.611	**0.224**

Rule of Thumb:

The smaller displacement/cylinder, the more difficult to achieve high efficiency!

- Smaller displacement/volume results in high surface area/volume ratio, consequently higher heat transfer loss through the cylinder wall
- Flame quenching effect on the cylinder wall; difficult to achieve super lean burn



Combustion chamber surface area to volume ratio reduced by **63%**

Highly-Efficient Opposed Piston Engine - Hybrids

DEPARTMENT OF ENERGY ANNOUNCES $98 MILLION FOR 40 TRANSFORMATIVE ENERGY TECHNOLOGY PROJECTS

November 15, 2018

ARPA-E's OPEN 2018 Program Selects Innovative Technologies to Advance Energy Security and Competitiveness

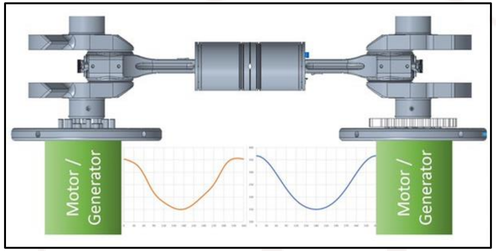
achatesPOWER™

Transportation Energy Conversion

Achates Power, Inc. – San Diego, CA

Highly Efficient Opposed Piston Engine for Hybrid Vehicles ("HOPE-Hybrid") – $2,000,000

Achates Power will develop an opposed-piston engine suitable for hybrid electric vehicle applications, using a unique engine design that minimizes energy losses typical in conventional internal combustion engines. A motor-generator integrated on each engine crankshaft will provide independent control to each piston and eliminate all torque transmitted across the mechanical crankshaft connection, thus reducing engine size, mass, cost, friction, and noise. The application of high-bandwidth power electronics will further improve engine efficiency through the real-time control of the piston motion and combustion process. If successful, the proposed technology will offer light- and heavy-duty vehicle manufacturers a cost-effective solution to improve vehicle fuel efficiency and reduce transportation carbon dioxide (CO_2) emissions.



Final Thoughts and Conclusion

- Push for lower CO_2 is the focus, and the right one
- But total life cycle impact has to be considered to make constructive policy and technology choices
- Transportation is not like cell-phones, it uses real energy and the laws of physics apply
- Even if electric vehicles achieve mass adoption, billions of internal combustion engines will be manufactured over the next decades

We (as a species; as an industry) have an obligation to make them as benign as possible. It can be done and must be done

This is "The Engine Imperative"


THANK YOU
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Fundamentally Better Engines