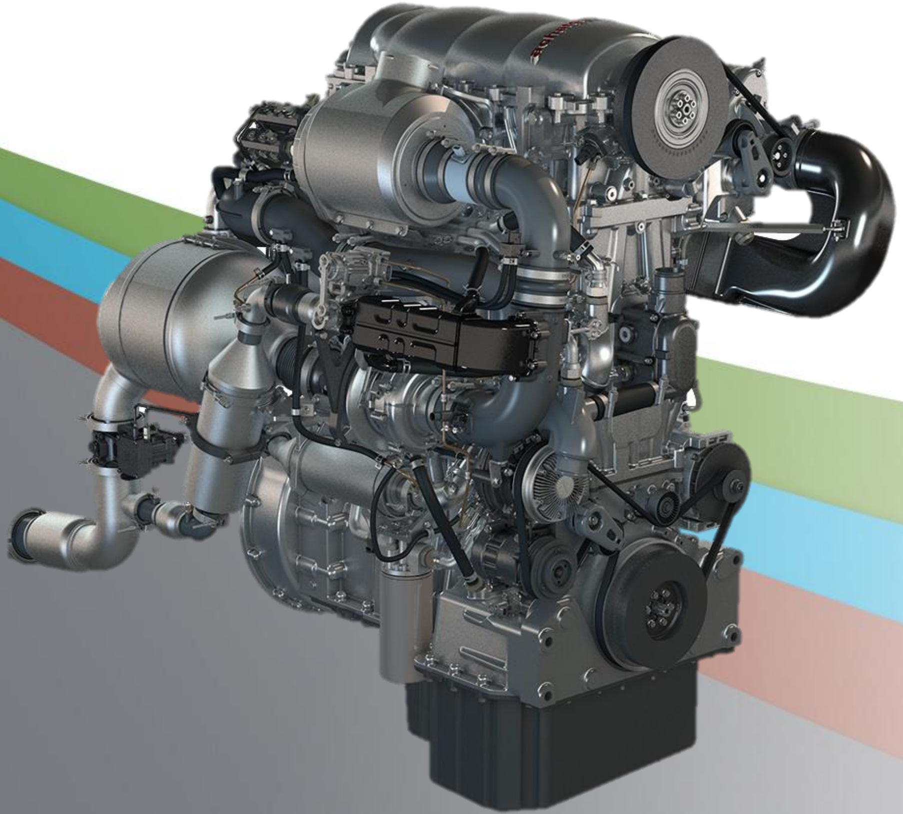


Opposed Piston Engine – Opportunities and Challenges

Ming Huo

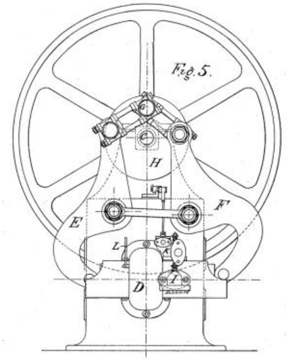
Senior Engineer

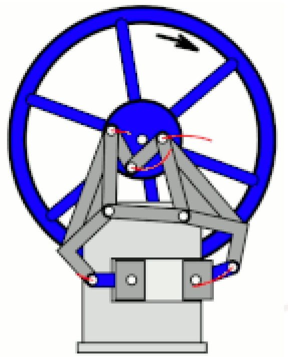
August 2020

achates POWER™ Fundamentally Better Engines®

Opposed Piston History

- 1882 Atkinson differential engine
- 1898 W. Von Oechelhauser OP engine
- 1900 Gobron-Brillie OP engine
- 1914 Simpson’s balanced 2S engine
- 1920 Doxford OP engine
- 1930 Junkers Jumo engine
- 1932 Kharkov 6TD OP engine
- 1934 Fairbanks Morse OP engine
- 1955 Rolls Royce K60 OP engine
- 1960 Leyland L60 OP engine
- 1970 The Clean Air Act
- 2004 Achates Power



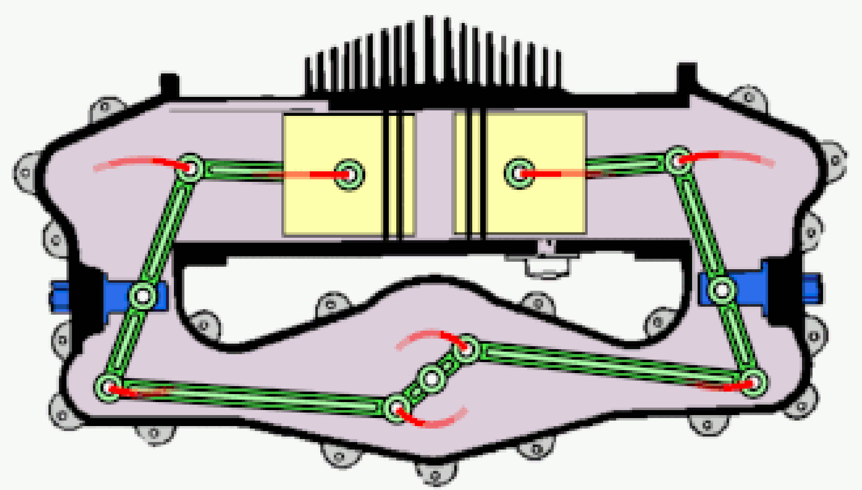


In 1882, James Atkinson developed the Atkinson cycle, the first version of this was an Opposed-Piston Engine, known as the Atkinson differential engine

achates POWER

Opposed Piston History

- 1882 Atkinson differential engine
- 1898 W. Von Oechelhauser OP engine
- 1900 Gobron-Brillie OP engine
- 1914 Simpson’s balanced 2S engine
- 1920 Doxford OP engine
- 1930 Junkers Jumo engine
- 1932 Kharkov 6TD OP engine
- 1934 Fairbanks Morse OP engine
- 1955 Rolls Royce K60 OP engine
- 1960 Leyland L60 OP engine
- 1970 The Clean Air Act
- 2004 Achates Power



Diagrammatic sketch of the Simpson double acting two-stroke engine

1914 *Simpson's Balanced 2-stroke* engine

achates POWER

Opposed Piston History

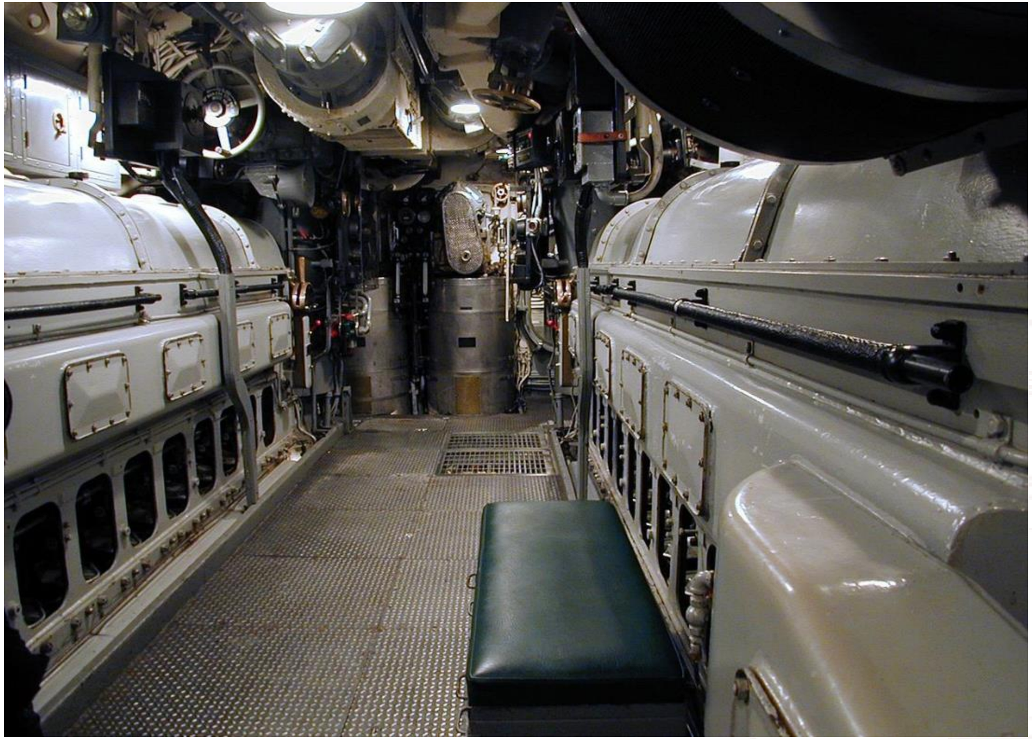
- 1882 Atkinson differential engine
- 1898 W. Von Oechelhauser OP engine
- 1900 Gobron-Brillie OP engine
- 1914 Simpson's balanced 2S engine
- 1920 Doxford OP engine
- 1930 Junkers Jumo engine
- 1932 Kharkov 6TD OP engine
- 1934 Fairbanks Morse OP engine
- 1955 Rolls Royce K60 OP engine
- 1960 Leyland L60 OP engine
- 1970 The Clean Air Act
- 2004 Achates Power

1932 Junkers Jumo 205 diesel aircraft engine

One of the most notable Opposed-Piston Engines in history was the Junkers Jumo engine, which was developed by Professor Hugo Junkers and was a prominent fixture in World War II airplanes.

Opposed Piston History

- 1882 Atkinson differential engine
- 1898 W. Von Oechelhauser OP engine
- 1900 Gobron-Brillie OP engine
- 1914 Simpson’s balanced 2S engine
- 1920 Doxford OP engine
- 1930 Junkers Jumo engine
- 1932 Kharkov 6TD OP engine
- 1934 Fairbanks Morse OP engine
- 1955 Rolls Royce K60 OP engine
- 1960 Leyland L60 OP engine
- 1970 The Clean Air Act
- 2004 Achates Power



Fairbanks Morse 38 8-1/8 diesel engine on the USS Pampanito submarine

achatesPOWER™

Opposed Piston History

- 1882 Atkinson differential engine
- 1898 W. Von Oechelhauser OP engine
- 1900 Gobron-Brillie OP engine
- 1914 Simpson's balanced 2S engine
- 1920 Doxford OP engine
- 1930 Junkers Jumo engine
- 1932 Kharkov 6TD OP engine
- 1934 Fairbanks Morse OP engine
- 1955 Rolls Royce K60 OP engine
- 1960 Leyland L60 OP engine
- 1970 The Clean Air Act
- 2004 Achates Power

The U.S. enacted the Clean Air Act, which set federal emissions standards for all motor vehicles. The typical two-stroke Engine available at that time featured comparatively high NOx and soot. This stunted development of Opposed-Piston Engines for on-road applications

achatesPOWER™

About Achates Power

James U. Lemke, 2015

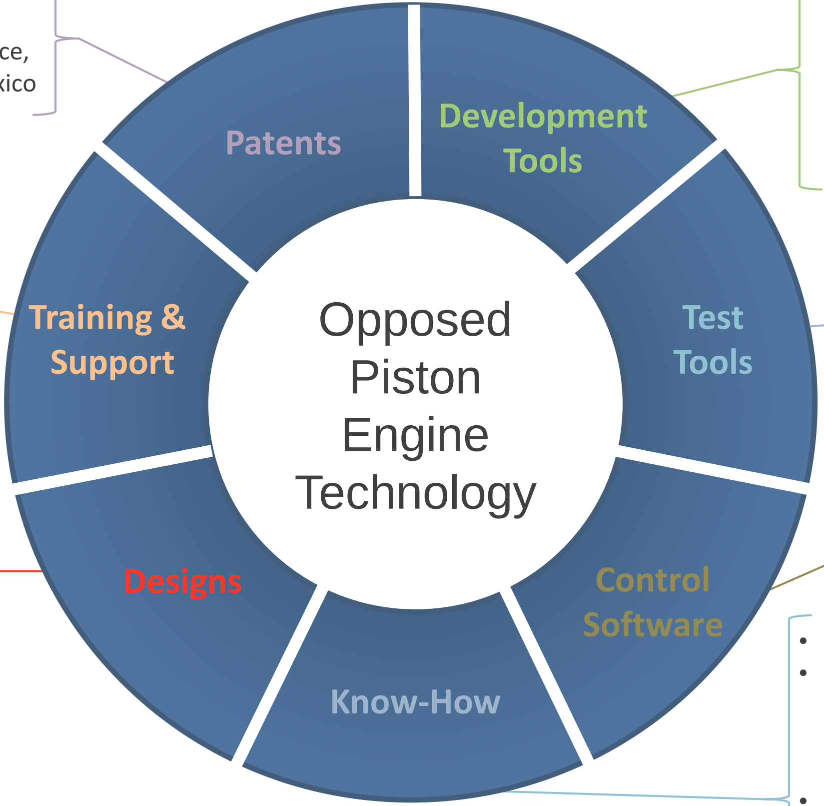
- Achates Power is launched by James Lemke in 2004, with headquarters in San Diego, CA
- Major Awards:
  - In 2015, Achates Power is awarded a $14 million project to support research and development work for the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC).
  - In 2018, Achates Power Opposed-Piston Diesel Engine heavy-duty truck project partnership wins the 2018 CARB Award.
  - In 2019, ARPA-E awards $2 million grant for Hybrid Opposed-Piston Engine to Achates Power

Business Model – License Enabling Suite of IP + Engineering Services

- 348 worldwide patents
- 176 worldwide pending applications
- U.S., China, Japan, India, Germany, France, Great Britain, Italy, Sweden, Russia, Mexico

- Closed cycle CFD (Converge)
- Open cycle CFD (Converge)
- 1D (GT-Power)
- Thermal-structural FEA & Conjugate heat transfer
- Proprietary Bearing Analysis Tool
- Multi-body Simulation (MSC Adams)

- On-site
- San Diego
- Detroit
- Remote



- Calibration guidelines
- Test set-up
- Formulae for real-time calculation
- Post-processing
- Analysis tools

- Pistons (hot & cold sides)
- Liners
- Wrist pin bearings
- Fuel sprays
- Air handling system
- Cooling & lubrication systems
- Gear train
- Front end accessory drive
- Gear noise mitigation
- Light weight techniques
- Oil consumption control measures

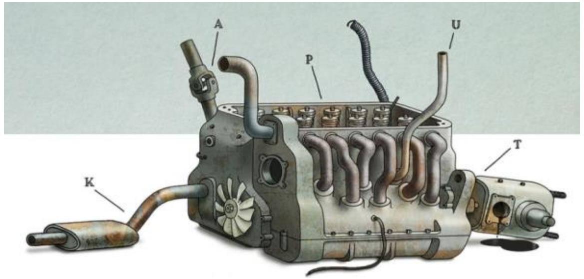
- Prototype controller including ECU
- Control requirements (Written guide or Simulink)
- Support

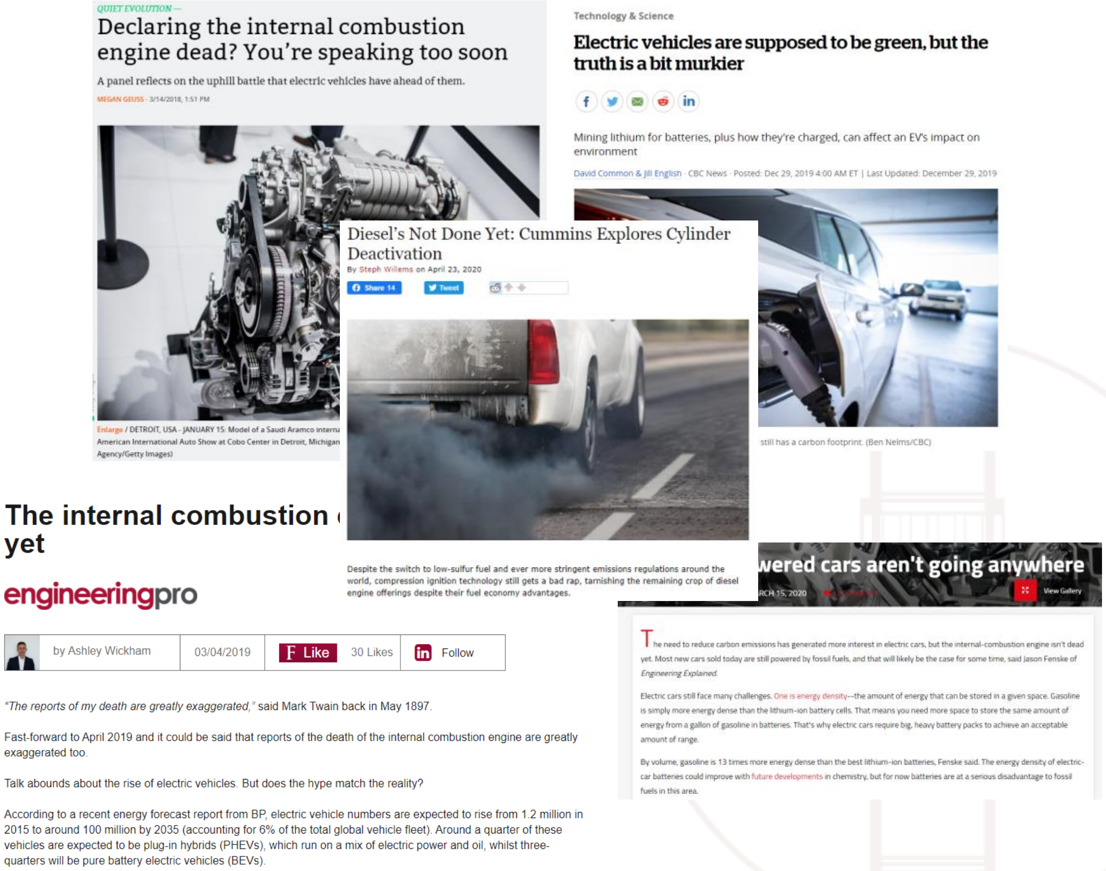
- System engineering considerations
- Design processes for mechanical system design, air system design, combustion system design, piston design, piston ring design, cylinder design, port geometry, wrist pin design, geartrain design
- Design for manufacturing, design for assembly, design for cost.

achatesPOWER™

Is Internal Combustion Engine Dead?

DEAD ???





QUIET EVOLUTION —

Declaring the internal combustion engine dead? You're speaking too soon

A panel reflects on the uphill battle that electric vehicles have ahead of them.

MEGAN GEUSS - 3/14/2018, 1:51 PM

Enlarge / DETROIT, USA - JANUARY 15: Model of a Saudi Aramco interna... American International Auto Show at Cobo Center in Detroit, Michigan... Agency/Getty Images)

Technology & Science

Electric vehicles are supposed to be green, but the truth is a bit murkier

Mining lithium for batteries, plus how they're charged, can affect an EV's impact on environment

David Common & Jill English · CBC News · Posted: Dec 29, 2019 4:00 AM ET | Last Updated: December 29, 2019

still has a carbon footprint. (Ben Nelms/CBC)

Diesel's Not Done Yet: Cummins Explores Cylinder Deactivation

By Steph Willems on April 23, 2020

Share 14 Tweet

Despite the switch to low-sulfur fuel and ever more stringent emissions regulations around the world, compression ignition technology still gets a bad rap, tarnishing the remaining crop of diesel engine offerings despite their fuel economy advantages.

The internal combustion ... yet

engineeringpro

by Ashley Wickham | 03/04/2019 | Like | 30 Likes | Follow

"The reports of my death are greatly exaggerated," said Mark Twain back in May 1897.

Fast-forward to April 2019 and it could be said that reports of the death of the internal combustion engine are greatly exaggerated too.

Talk abounds about the rise of electric vehicles. But does the hype match the reality?

According to a recent energy forecast report from BP, electric vehicle numbers are expected to rise from 1.2 million in 2015 to around 100 million by 2035 (accounting for 6% of the total global vehicle fleet). Around a quarter of these vehicles are expected to be plug-in hybrids (PHEVs), which run on a mix of electric power and oil, whilst three-quarters will be pure battery electric vehicles (BEVs).

...wered cars aren't going anywhere

...RCH 15, 2020 View Gallery

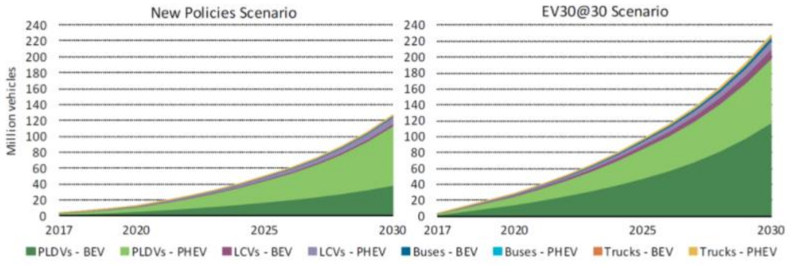
The need to reduce carbon emissions has generated more interest in electric cars, but the internal-combustion engine isn't dead yet. Most new cars sold today are still powered by fossil fuels, and that will likely be the case for some time, said Jason Fenske of *Engineering Explained*.

Electric cars still face many challenges. One is energy density—the amount of energy that can be stored in a given space. Gasoline is simply more energy dense than the lithium-ion battery cells. That means you need more space to store the same amount of energy from a gallon of gasoline in batteries. That's why electric cars require big, heavy battery packs to achieve an acceptable amount of range.

By volume, gasoline is 13 times more energy dense than the best lithium-ion batteries, Fenske said. The energy density of electric-car batteries could improve with future developments in chemistry, but for now batteries are at a serious disadvantage to fossil fuels in this area.

achates POWER™

3 Billion More IC Engines Built by 2050



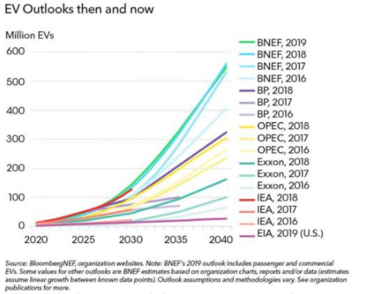
Notes: PLDVs = passenger light duty vehicles; LCVs = light commercial vehicles; BEVs = battery electric vehicles; PHEV = plug-in hybrid electric vehicles.

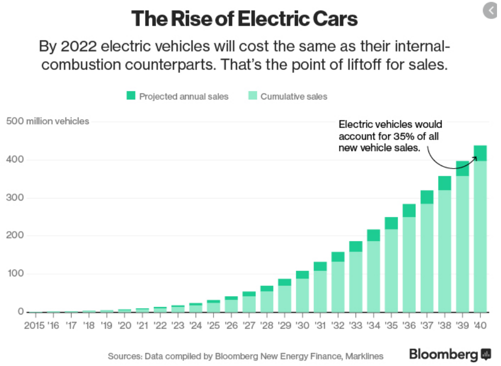
Source: IEA analysis developed with the IEA Mobility Model (IEA, 2018a).

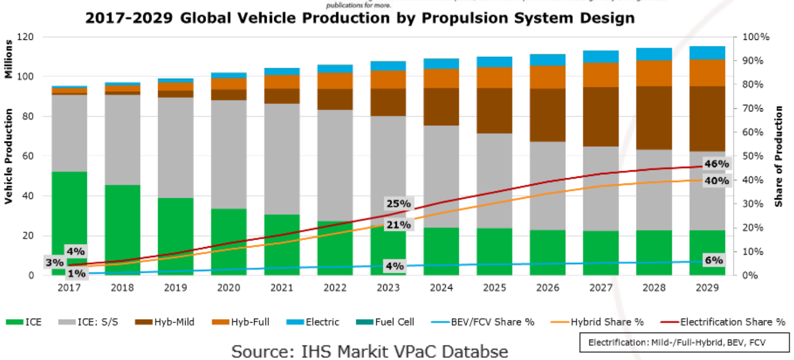
BloombergNEF: electrics to take 57% of global passenger car sales, 81% of municipal bus sales by 2040

16 May 2019

BloombergNEF (BNEF) is out with an aggressive forecast that projects electric vehicles taking up 57% of the global passenger car sales by 2040—slightly higher than it forecast a year ago—and electric buses with 81% of municipal bus sales by the same date.





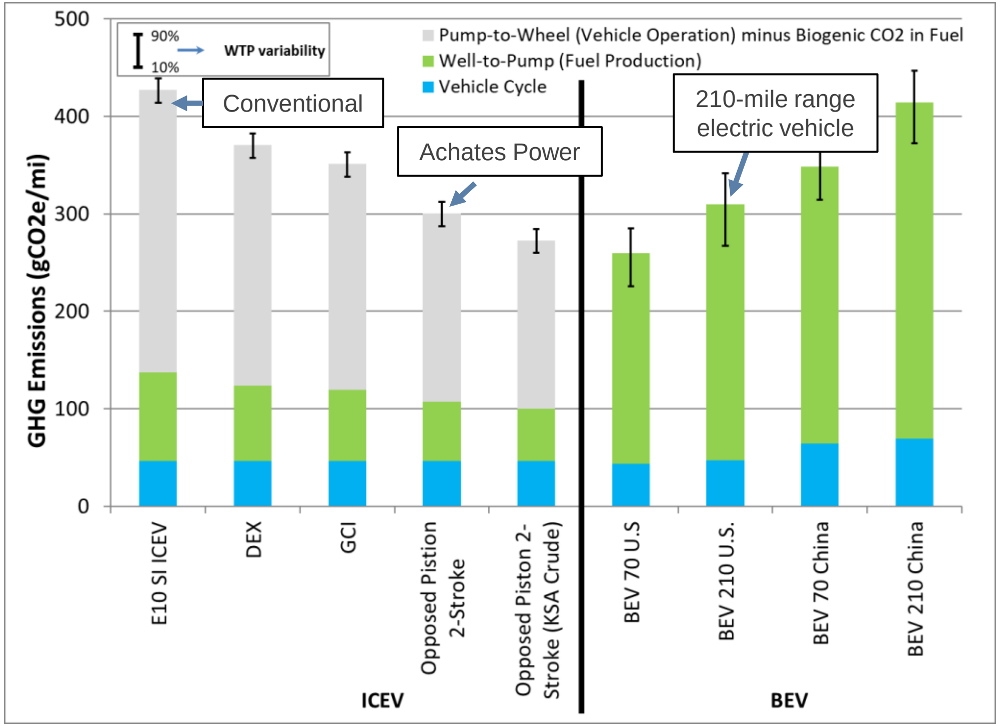


Source: IHS Markit VPaC Databse

achate

Even assume 30% EV sales by 2030; 80% by 2050 – 3 billion more internal combustion vehicles will be sold by 2050 globally

Aggregate GHG Emissions Reduction



- CO_2 signature of opposed-piston powered vehicle is similar to a 210-mile range BEV, *but with lower cost and with existing infrastructure*
- Potential for even lower GHG emissions when powered by a renewable fuel
- Using external Lifecycle Analysis, *~9.5 gigatons* GHG reduction over lifecycle of vehicles

Assumptions:

- Vehicle technologies are mixed
- Most data from 2016 GREET Model- for US only
- Gasoline Compression Ignition results created based on a joint study by ANL and Aramco

Babiker, H., “Energy demand trends and the impact of future mobility,” KAUST Research Conference: The Future of Fuel, March 4-6, 2019.

achatesPOWER™

Emission Reduction Is Imperative

- Transportation related emissions of carbon continue to rise
- Heavy-duty vehicles are the fastest growing sector of transportation
- 93% of the world's children grow up with air polluted above health guidelines
- In the U.S., 128M people live in counties designated non-attainment for ozone or $PM_{2.5}$

achatesPOWER™

Global landscape needs many solutions

“I do not believe there will be a dramatic increase in demand for battery vehicles, and I believe this situation is true globally," **Honda** CEO Takahiro Hachigo said. "There are issues with infrastructure and hardware. (Nov ‘19)

“We cannot overlook the role of internal combustion engine as a bridge to a cleaner future and we believe that in some applications that internal combustion engine will not have a substitute for many, many years”. – Tom Linebarger, **Cummins** Chairman and CEO (Nov ‘19)

“Electric cars won't go mainstream until we fix these problems: Range, Charging infrastructure, Cost” – Mark Reuss, **GM** President (Nov ‘19)

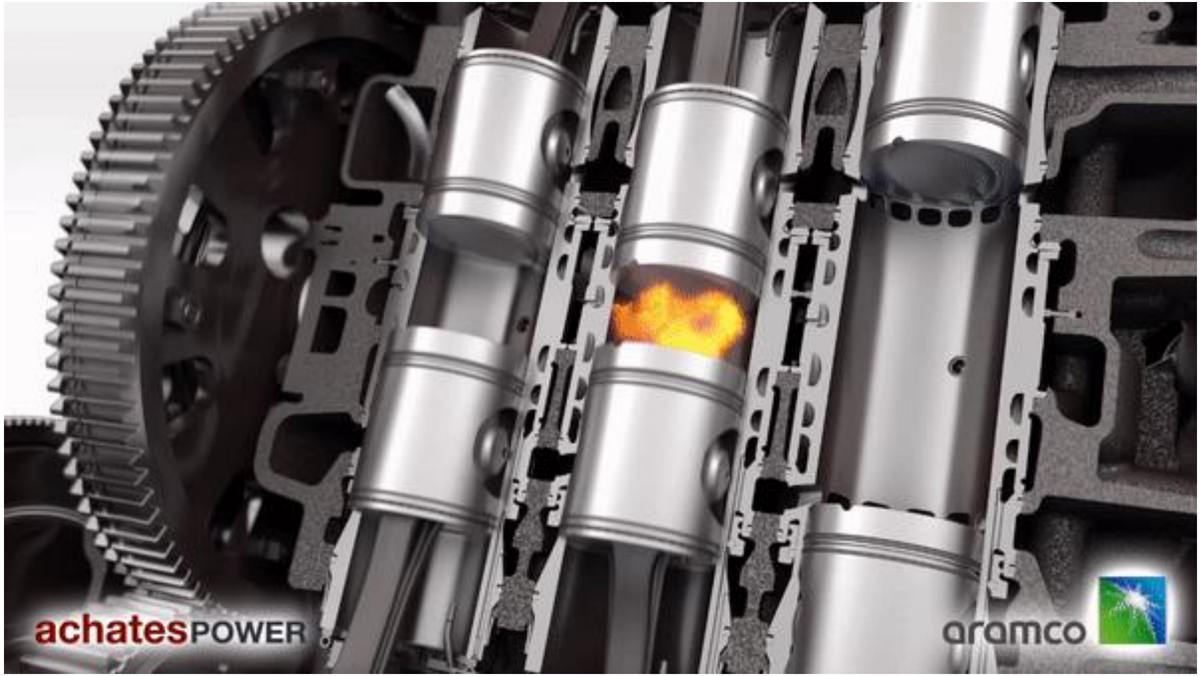
“There is no customer request for BEVs. There are regulator requests for BEVs.” Klaus Frolich, **BMW** Director of Development

“Even with the broader availability of BEV and PEV makes and models, most consumers continue to be unaware or uninterested in buying one.” - **Center for Automotive Research**, (Feb ’18)

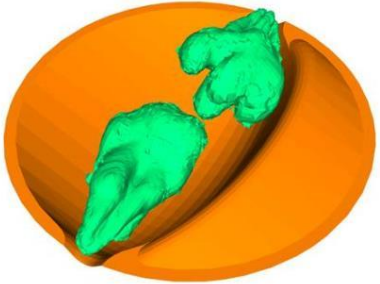
“Even in 2030, 90% of our vehicles will be equipped with an ICE.” - **Toyota** Chief Powertrain Engineer Mitsumasa Yamagata, (Feb ’18)

“More than half of global auto executives say BEVs will fail commercially” – **KPMG** (Jan ’18)

So Why Opposed-Piston Engine ?



Opposed-Piston Engine Architecture Advantages



OP Combustion System

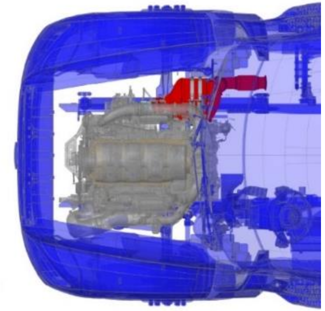
Higher thermal efficiency, lower emissions

- Reduced heat transfer losses
- Optimally phased combustion
- Ideal fuel-air mixing dynamics
- Lower pumping losses
- Broader range of high efficiency

OP Full Engine System

Lower cost engine system

- Reduced cooling requirements
- Higher power density
- Earlier after-treatment catalyst conversion
- Reduced after-treatment size
- Reduced NO_X and CO_2 emissions



Market Benefits

Higher thermal efficiency in real world driving, lower emissions

- Broader range of high thermal efficiency over engine operating range
- Fuel savings, lower CO_2 emissions
- Ultra-low NO_X emissions
- Existing Fuel Infrastructure
- Leverages existing capital investments

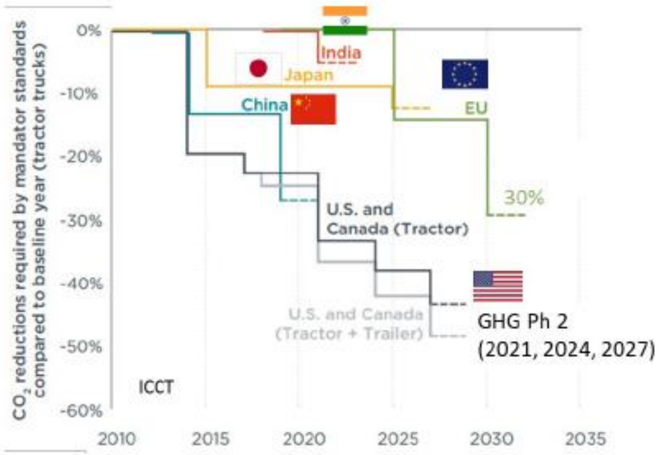
achatesPOWER™

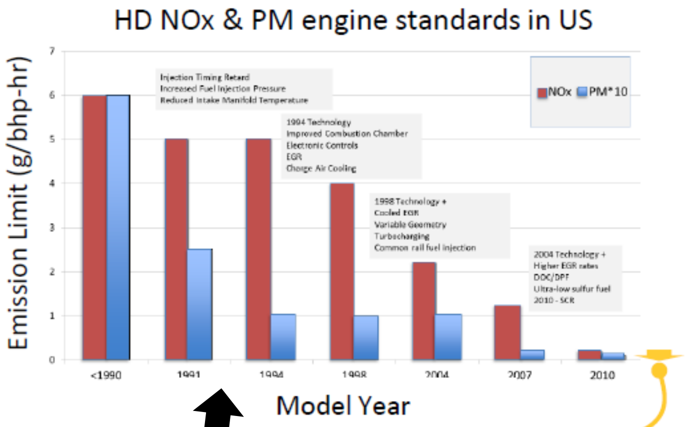
Opposed Piston Engine Opportunities

- Emission Regulations and Compliance Cost
- Team up with “Electrification”

The Opportunity – Emission Regulations & Compliance Cost

The industry faces significant technical and cost challenges





Further 90% reduction in NOx

China, Europe, India also considering lower NO_x standards

Unrelenting pressure for lower $\mathbf{CO_2}$ and $\mathbf{NO_x}$

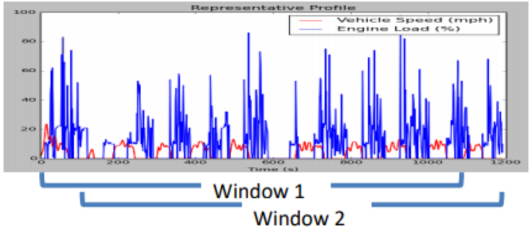
Compliance cost: California seeks to increase aftertreatment warranty period to as much as 800,000 miles. According to the Manufactures of Emissions Controls Association, this will add **$3,550 to $4,800** to the cost of the aftertreatment system. *California traditionally leads the global industry on new emissions mandates.*

achatesPOWER™

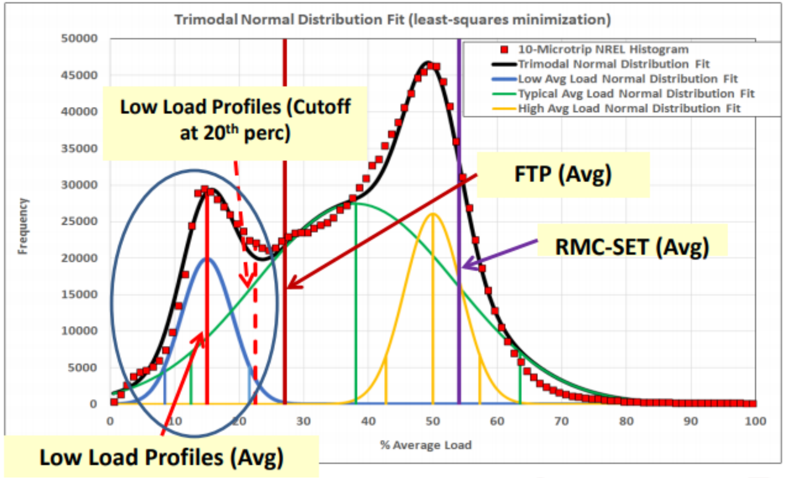
Low Load Cycle (LLC) Development

DEVELOPMENT OF LOW LOAD VEHICLE PROFILES

- Data analyzed using moving windows of 10 microtrips



- ~1.25 million windows (profiles) obtained
- Only profiles with average loads below 20% were further considered for constructing the LLC



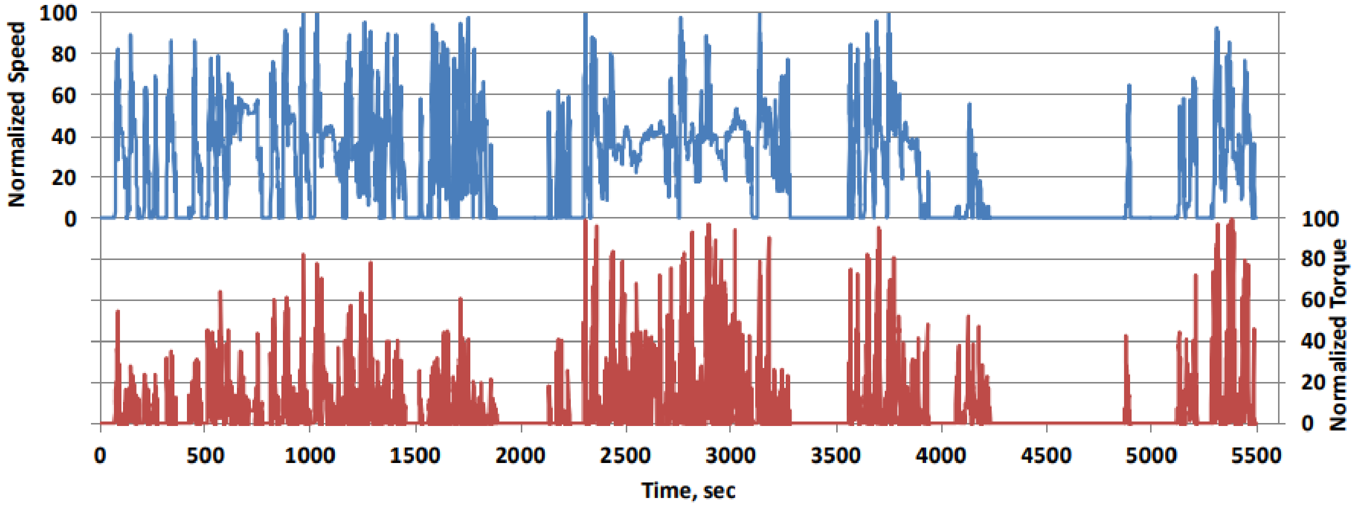
- https://ww2.arb.ca.gov/sites/default/files/classic//msprog/hdlownox/files/workgroup_20190123/02-llc_ws01232019-1.pdf

Low Load Cycle (LLC) Development

- Current engine certification cycles (HD-FTP and RMC-SET):
  - Do not account for sustained low load operations
  - Too short to adequately test for active thermal management of aftertreatment system
- Objective is to develop a new Low Load Cycle (LLC) that:
  - Is representative of real-world urban tractor and vocational vehicle operations that are characterized by low engine loads
  - Has average power and duration adequate for demonstrating that hardware and controls needed to deal with low load challenges are present and functional
  - Has emission standard that balances the need for NOx emission reductions and any associated GHG emission impacts

- https://ww2.arb.ca.gov/sites/default/files/classic//msprog/hdlownox/files/workgroup_20190123/02-llc_ws01232019-1.pdf

Low Load Cycle (LLC) Development

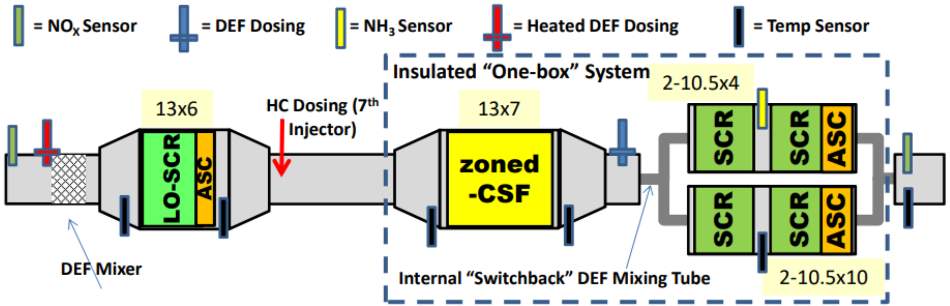


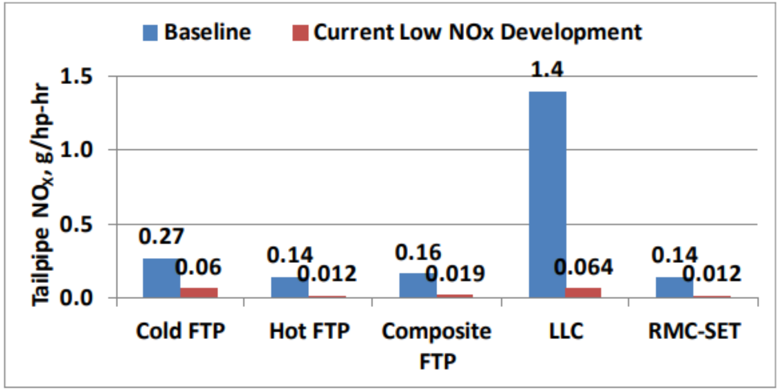
- Developed from real world vehicle operations at Low Load by SwRI
- Average power generally 7-8% of engine max (with idle load)
- Run with accessory load at idle

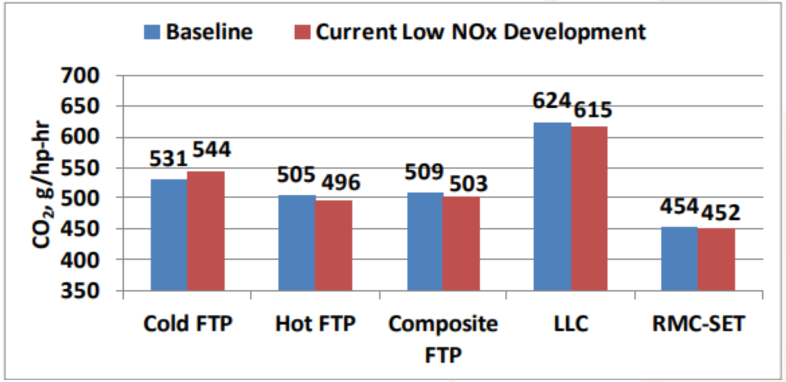
https://ww2.arb.ca.gov/sites/default/files/classic//msprog/hdlownox/files/workgroup_20190926/guest/swri_hd_low_nox_demo_programs.pdf

Southwest Research Institute (SwRI) Study

- Production 2017 Cummins X15 platform
- Program targets are 0.02 g/hp-hr regulatory cycles and control on LLC
- Cylinder Deactivation & EGR cooler bypass







https://ww2.arb.ca.gov/sites/default/files/classic//msprog/hdlownox/files/workgroup_20190926/guest/swri_hd_low_nox_demo_programs.pdf

Industry Research

72nd Conference of the Italian Thermal Machines Engineering Association, ATI2017, 6-8 September 2017, Lecce, Italy

Combustion System Development of an Opposed Piston 2-Stroke Diesel Engine

Enrico Mattarelli*, Giuseppe Cantore, Carlo Alberto Rinaldini, Tommaso Savioli

Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via P. Vivarelli, 10, 41125 Modena, Italy

Abstract

Today, the interest towards 2-stroke, opposed-piston compression-ignition engines is higher than ever, after the announcement of imminent production of a 2.7L 3-cylinder light truck engine by Achates Powers. In comparison to other 2-stroke designs, the advantages in terms of scavenge and thermal efficiency are indisputable: a perfect "uniflow" scavenge mode can be achieved with inexpensive and efficient piston controlled ports, while heat losses are strongly reduced by the relatively small transfer area. Unfortunately, the design of the combustion system is completely different from a 4-stroke DI Diesel engine, since the injectors must be installed on the cylinder liners: however, this challenge can be converted into a further opportunity to improve fuel efficiency, adopting advanced combustion concepts.

This paper is based on a previous study, where the main geometric parameters of an opposed piston engine rated at 270 kW (3200 rpm) were defined with the support of CFD 1D-3D simulations. The current work will focus on the influence of an innovative combustion system, developed by the authors by means of further CFD-3D analyses, holding constant the boundary conditions of the scavenging process.

"In the [OP] 2-stroke engine the ratio of trapped air to fuel is 20% higher, enabling a **reduction of soot**."

"**NO_x emissions are expected to be lower**, since the fresh charge is always diluted by burnt gas."

BASF
We create chemistry

Achates Opposed Piston Engine

Class 8 Demonstration Program Review

Aftertreatment Design to demonstrate
Real-world Ultra Low NO_x ($ULNO_x$) capabiltiy

David Youngren, Senior Application Engineer, BASF
November 7, 2019 • San Diego, CA

"The Achates engine provides fast catalyst warmup without active thermal management. [The] combination of high turbo-out temperatures and low No_x [are] **ideal for $ULNO_x$**. [Its] flexible capabilities [are] **ideal for LoSCR de-sulfation** capability – [it has the] ability to reach ~500°C without fuel based exotherm"

"Standard calibration is also **ideal for feeding the SCR**. [Its] typical temperatures [are] between 250°C and 400°C for efficient SCR function. [The] high floor [is] ideal for NO_x reduction over proposed Low Load Cycle. Mild thermal exposure is easy on the aftertreatment. [The] temperature range [is] also **ideal for DOC function** with moderate precious metal loadings [for] low cost."

"[It has] **ideal engine-engine out conditions to reach $ULNO_x$**."

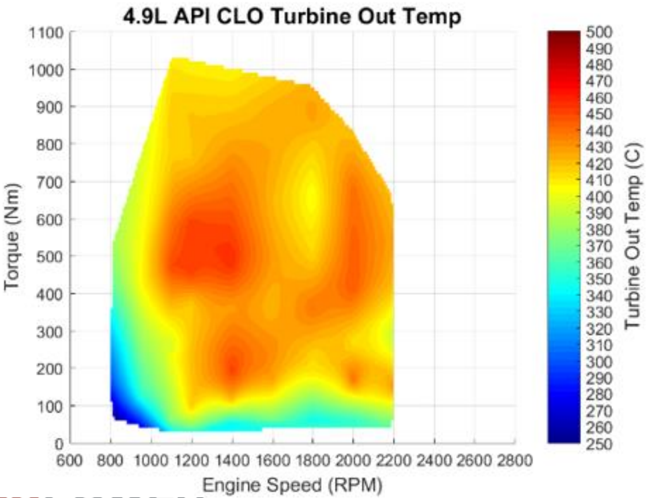
Exhaust Temperature and NOx Control

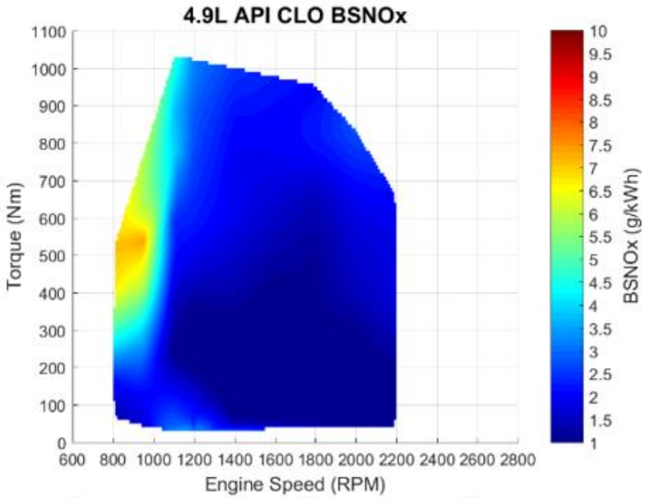
Normal operation

- OP engine exhaust temperature aligned with SCR effective operation range (200C -400C)
- Lower max exhaust gas temperature; Higher temperatures at low loads for low low-load NO_x
- Exhaust cutoff during decelerations to keep aftertreatment hot

Catalyst Light Off (CLO) Mode:

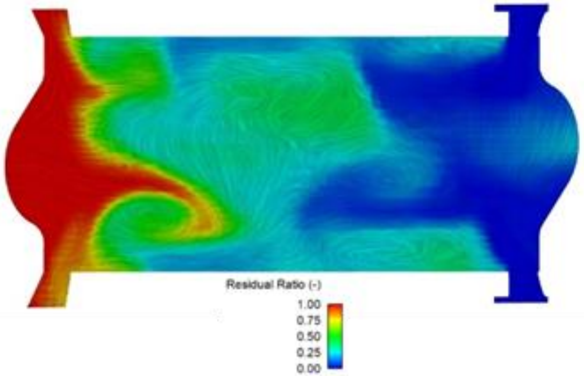
- High exhaust gas temperature and enthalpy
- Very low engine-out NO_x before catalyst light-off

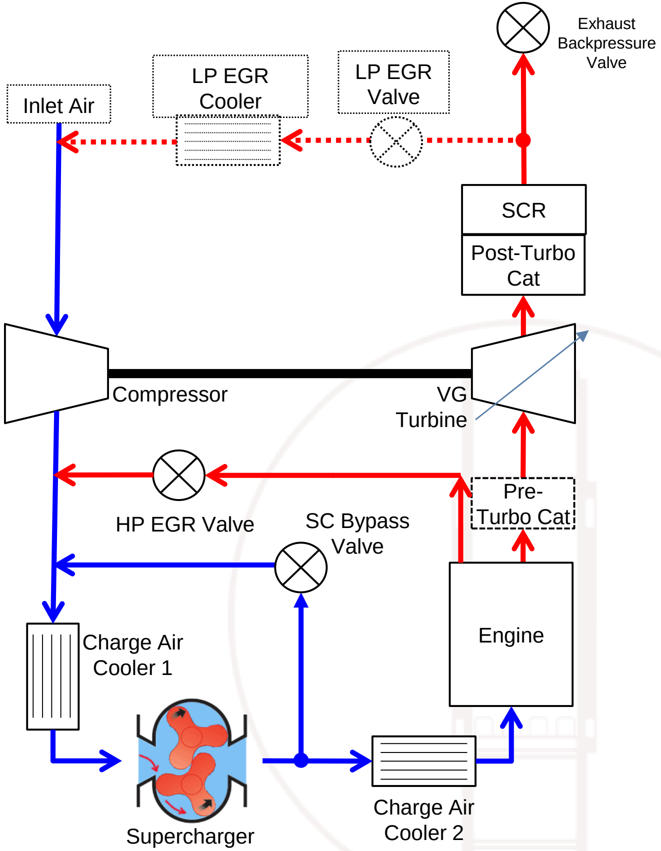




Dynamic Scavenging Control

- In FTP cycle, nearly all tail-pipe emissions come from CLO mode
- In OP engine, LO duration is shorter with “internal EGR” and higher exhaust enthalpy
- NOx during CLO is also lower because the mixture is more diluted

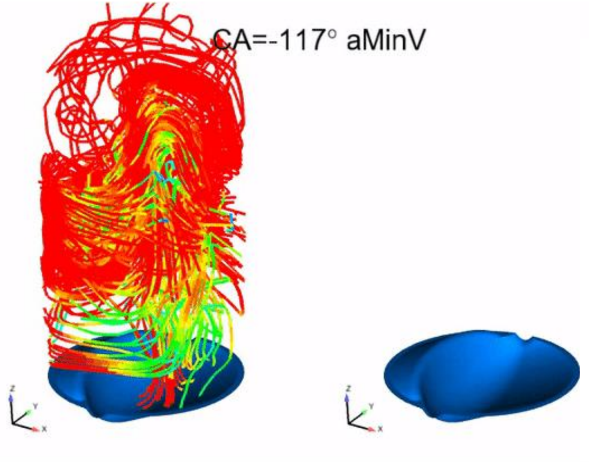


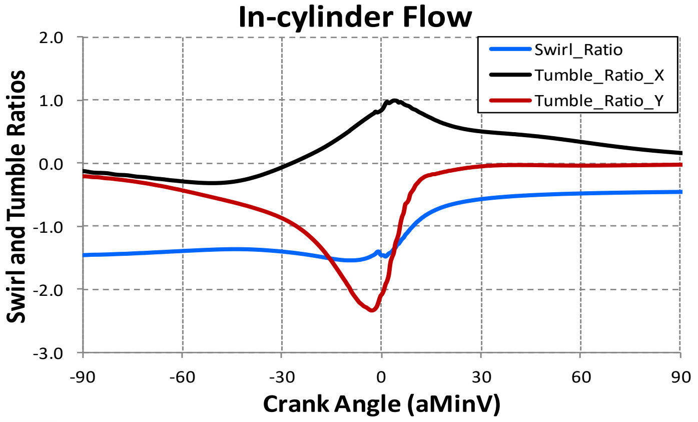


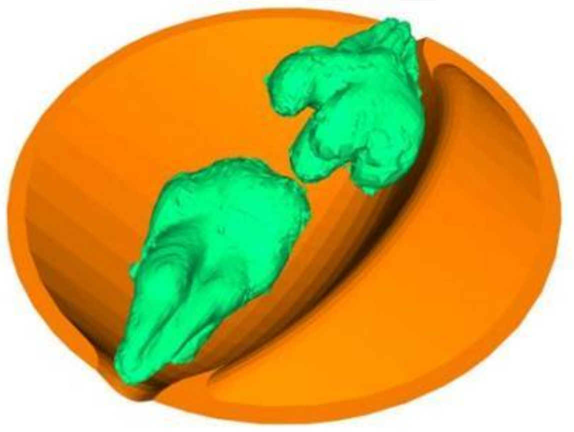
achatesPOWER™

High Turbulence Combustion

- OP provides the flexibility to use both pistons to form the combustion chamber
- Optimum mixture formation with CFD tool
- Extremely late combustion is possible

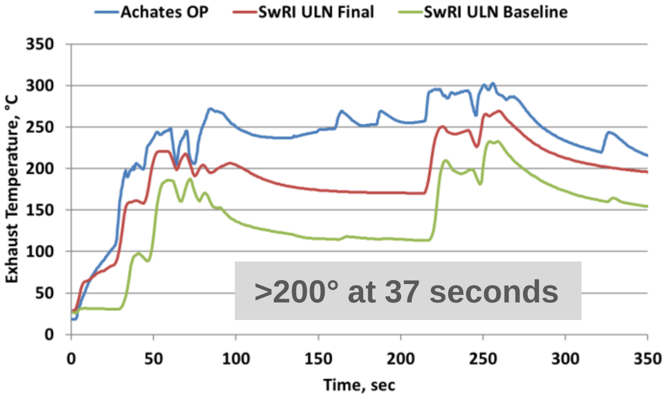


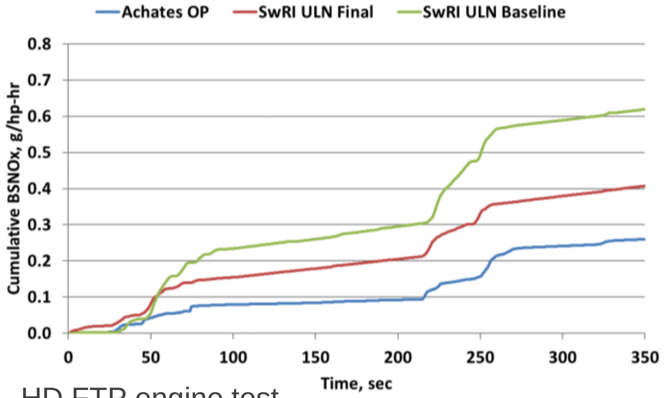




Fast Catalyst Light-off and Low NO_x at Cold Start

- 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:

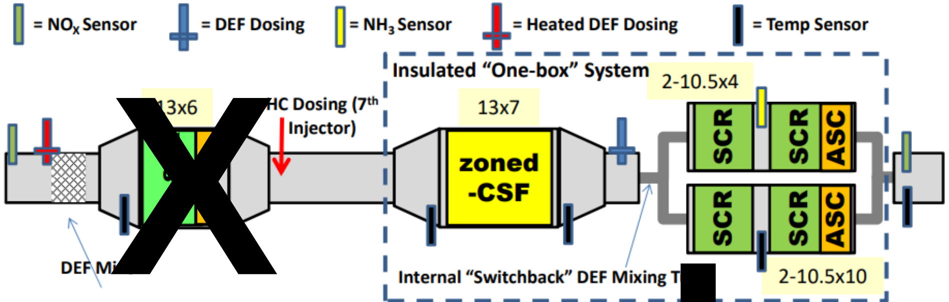
Achates Power OP Engine
SwRI Baseline Volvo 13L HD 2014
SwRI ULN Final Volvo 13L HD 2014 w. modified calibration

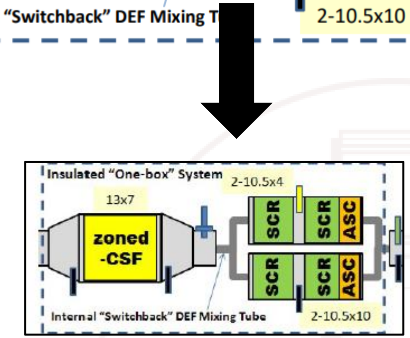
achatesPOWER

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.

Simplify Aftertreatment System

ATS testing at SwRI confirms attainment of 0.02g bhp/hr NO_x on FPT cycle using **current** ATS design

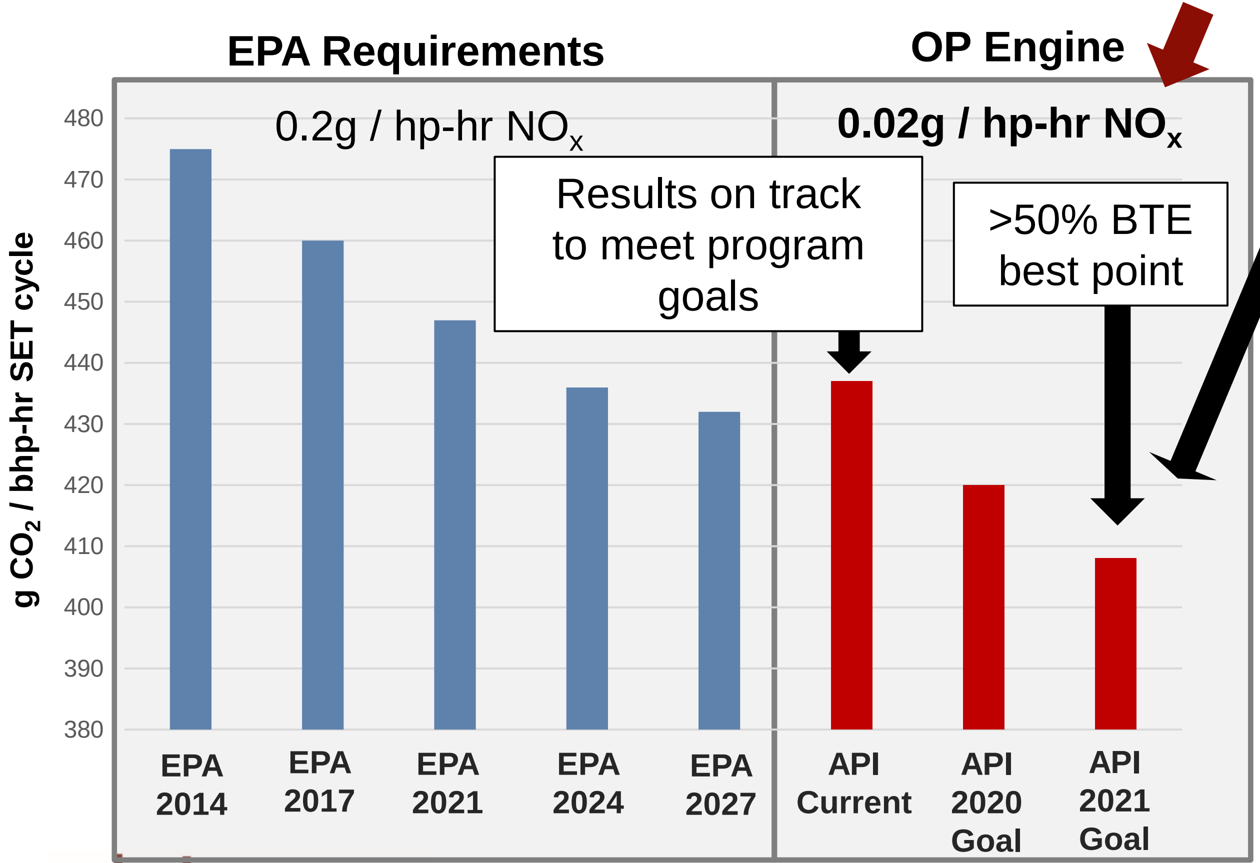




BASF aged catalyst model predicts **0.006 g / bhp-hr NO_x** in combined hot & cold FTP

achates POWER

CO_2 goals already achieved – with 90% reduction in NO_x



Opportunity for substantial further reduction

OP Engine in Peterbilt Truck

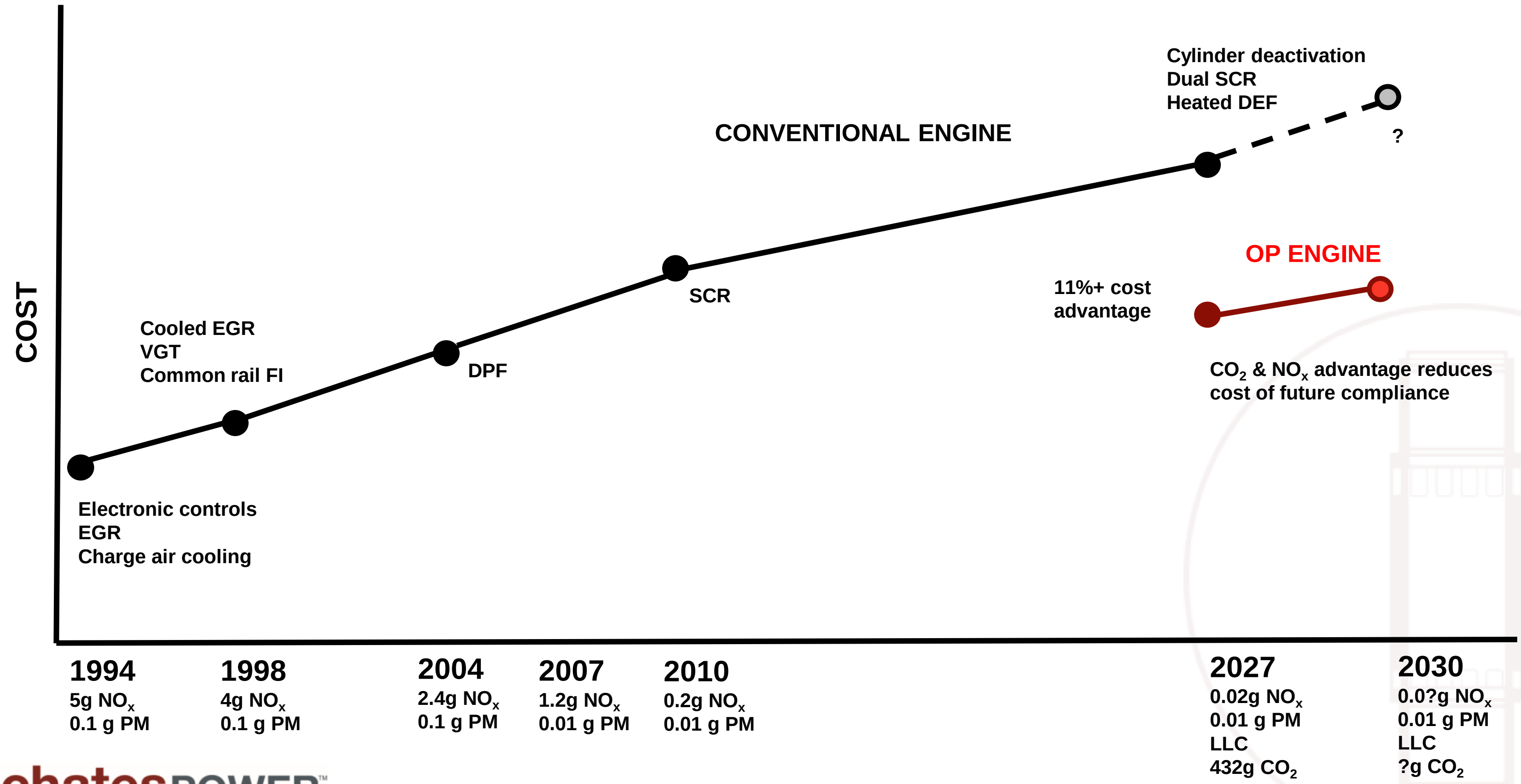
Lower variable cost

Opposed piston engine from Achates Power provides

- **11%** cost savings compared to a conventional 4-stroke engine with 10x NO_x
- **6%** cost savings from base engine (excluding exhaust aftertreatment hardware)
- The OP engine has **260** fewer components to assemble – no cylinder head or valve train
- The OP engine has **31%** less substrate volume for exhaust aftertreatment
- ULNOx ATS adds **2.7%** to conventional engine cost…OPE is already compliant

achatesPOWER™

Increasing Complexity & Cost…Any End In Sight?



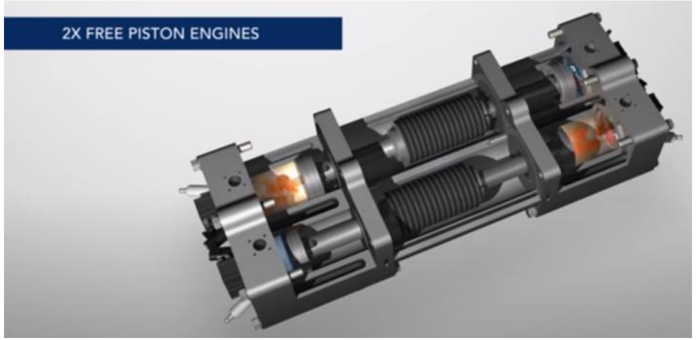
achates POWER™

The Opportunity – Team up with "Electrification"

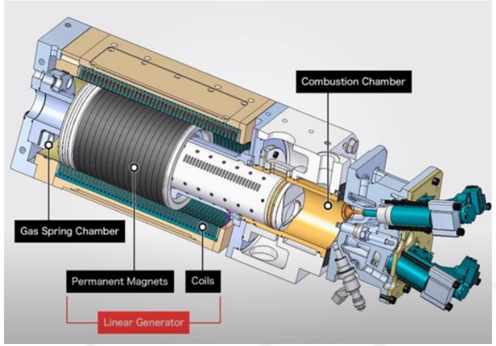
- Hybrid / Range Extender EV Engine
  - High efficiency
  - Low NVH
  - Low Emission
  - Easy Packaging & Lower Cost
- Electrical Accessories
  - E-turbo, E-booster, etc.
- Electrical Powertrain

Free Piston Engine?

Free-piston linear generator
DLR research



Free piston range extender
Sir Joseph Swan Centre for energy research at Newcastle University



Free-piston linear generator
Toyota R&D research

Opposed-Piston Engine Architecture Advantages

- Intake and exhaust ports opened/closed by piston location; no complex valvetrain
- Cranks, rods, pistons and gears are the only moving parts
- Base engine part count is 70% less than an equivalent 4-stroke engine
- Common 4-stroke failure modes eliminated – cylinder heads, head gaskets, exhaust valves.
- OP engines use common materials, processes, tools.
- OP engines largely use existing supply base.

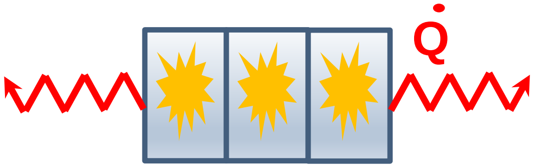
OP Engines - Enabling Low Cost Electric And Hybrid Vehicles

Capacity (kWh) is the limiting factor for battery EV

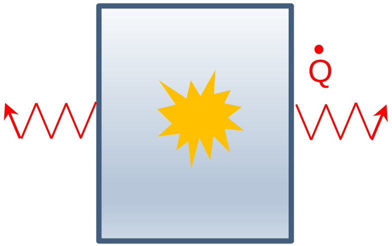
- Higher Range → Bigger Battery → Higher Cost

An OP Engine in a Range Extended EV/Series hybrid would *reduce battery size and cost* while maintaining the same or even higher driving range as a conventional vehicle

- Small conventional engines result in high surface area/volume ratio and high heat transfer loss through the cylinder wall
- Replace small multi-cylinder conventional engine with a larger, balanced single cylinder OP engine → Higher Efficiency



Larger cumulative heat loss from conventional engine



Smaller cumulative heat loss from larger single OP cylinder

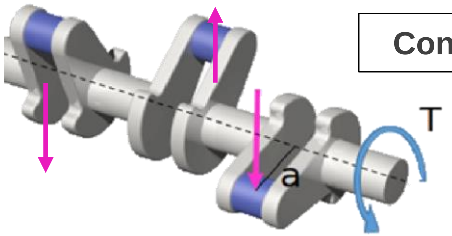
achatesPOWER™

OP Engines - Enabling Low Cost Electric And Hybrid Vehicles

Conventional engines need at least THREE cylinders to balance the torque on the crankshaft

→ Smaller volume/cylinder → Lower thermal efficiency

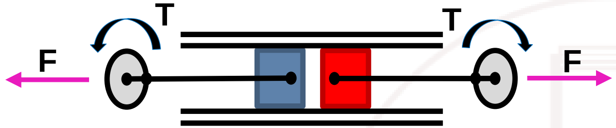
Conventional engine



With an OP Engine the force and torque exerted result in a naturally balanced system with just a single cylinder

→ Larger volume/cylinder → Higher thermal efficiency

OP engine

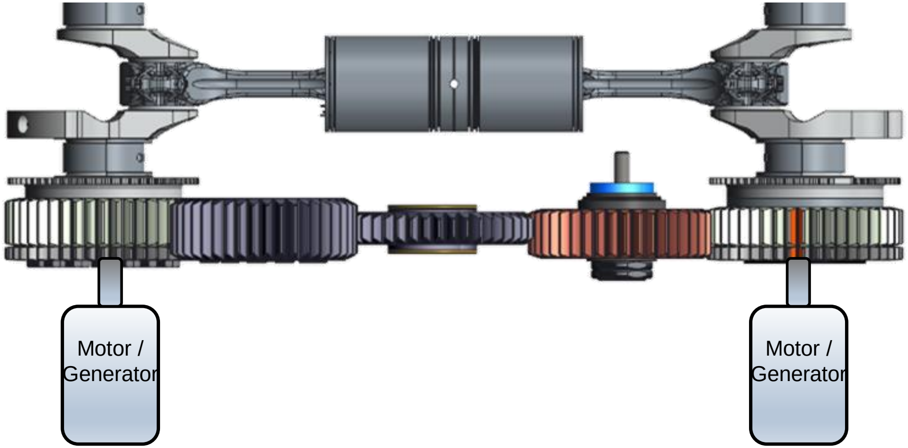


Single - Cylinder Engine Becomes A Possibility for Vehicle Application

achatesPOWER™

HOPE Project

- In 2019, ARPA-E awards $2 million grant for Hybrid Opposed-Piston Engine (HOPE) to Achates Power
- Collaborate with University of Michigan at Ann Arbor



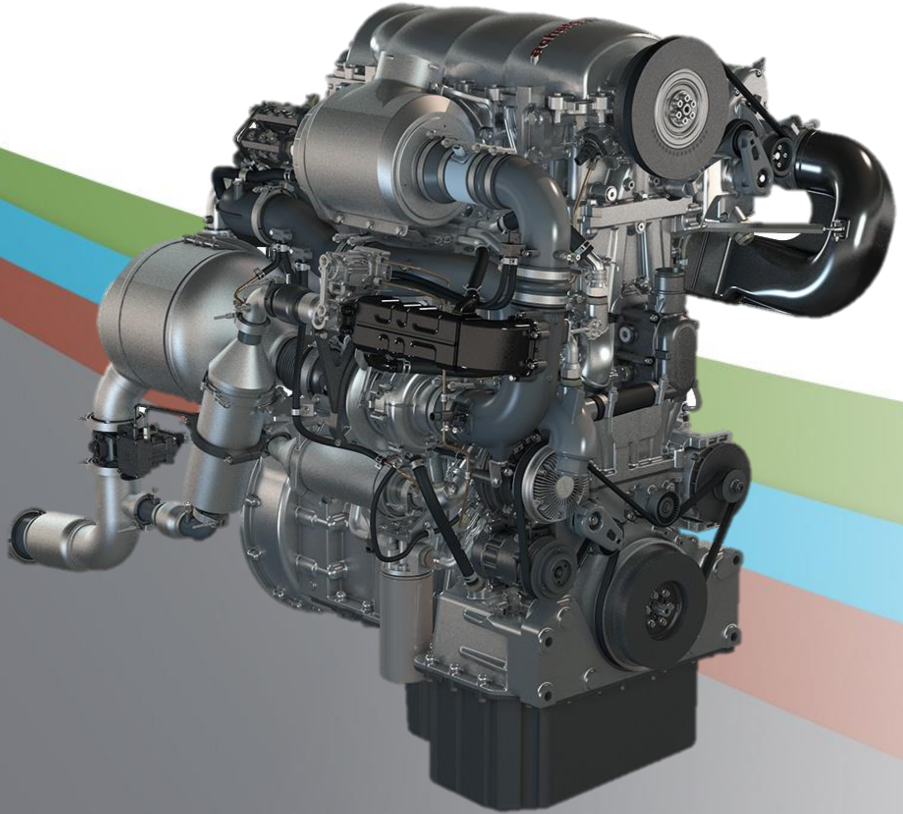
OP Engine Challenges & Concerns

Manufacturing related

- Manufacturing cost
- Capital cost
- Supply base

Technology related

- Reliability
- Emissions
- Packaging
- Supplier technology



Thank you

achates POWER™ Fundamentally Better Engines®