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ADVANCED COMBAT ENGINE MILITARIZATION AND COMMERCIALIZATION STUDY

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ABSTRACT

The Opposed Piston Engine is a highly advantageous architecture for military applications due to its power density and efficiency, and the U.S. Army is investing to develop OP engines for Combat Applications. The Cummins / Achates Power team was selected to design, procure, build, test, and advance to TRL 9 the first configuration of a scalable Opposed Piston Engine that can then be used to grow a family of OP Engines across all Combat and Tactical Vehicles. At the same time CALSTART is leading a companion project to demonstrate the Opposed Piston technology in commercial Class 8 trucks. This paper analyzes the commercialization and militarization potential of Opposed Piston technology and attempts to identify the ideal OP Engine configurations to meet those applications.

Citation: S. Sokolsky, J. Major, "Advanced Combat Engine Militarization and Commercialization Study", In *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), NDIA, Novi, MI, Aug. 13-15, 2019.

1. INTRODUCTION

While the US Army continues to consider smart and tactical investments in alternative powertrains, it has already done important work on engine architectures, and the unprecedented amount of uncertainty and choice within global OEMs has made this an opportune time for the Army to invest in its own set of engines.

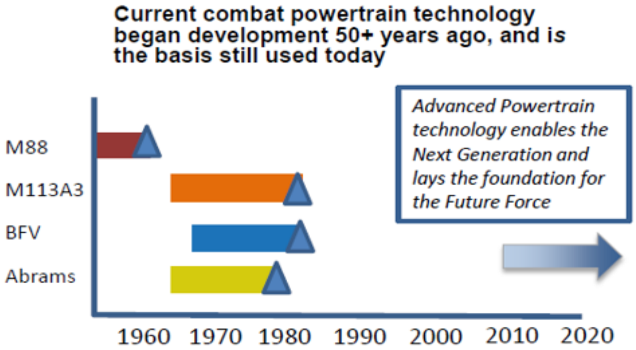


Figure 1: Origins of US Army Combat Powertrain Technology

There are many variants of internal combustion engines. This paper will focus on the unique characteristics and attributes of opposed-piston engines. The Army has decided independently and after 20+ years of study that this engine architecture is superior for combat vehicles. However, the fact that there are multiple parallel projects in the light duty and heavy line-haul commercial segments, and that the engine architecture brings efficiency and emissions advantages over four-stroke equivalents means that the current opportunity to leverage commercial scale and development is strong.

As shown in Figure 2, the adoption of IC Engine-powered vehicles has almost solely fueled the rise in U.S. passenger mobility. The U.S. fleet of registered vehicles stands at around 260 million, and it is the second largest vehicle market in the world next to China. Roughly 16 million vehicles are produced and sold in the U.S. every year. Given that market size and scale, it is easy to understand why the U.S. Army would focus on leveraging commercial engines. That said, with more than 50 years passed since the Army has developed a new engine for ground vehicles, there is a lot of technology and learning that can be put to that cause.

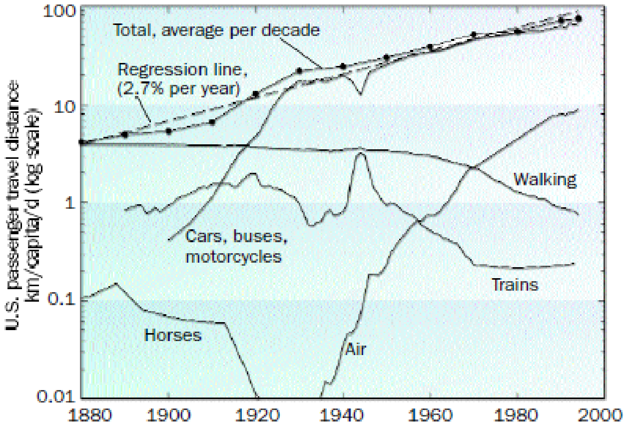


Figure 2. Passenger travel distance per capita per day in the U.S. by all modes shows a decline for horses, walking, and trains; an increase for cars, buses, and motorcyles; and a much more rapid increase for air transportation.

2. THE PROPULSION LANDSCAPE

The auto industry today is at an unprecedented crossroads – global regulatory uncertainty, trade wars, shifting consumer tastes, a growing suite of alternative energy options. All of that, while having to consider a near infinite suite of propulsion possibilities.

Full battery electric vehicles have captured the imagination and discussion, the technology shows promise. When coupled with a renewable charging source the well-to-wheel emissions of vehicles can be dramatically reduced. Further development and research are still needed for BEVs to approach all the functional requirements that are currently made possible with an internal combustion engine. For heavy tracked combat vehicles, it is estimated that batteries will need to achieve a 4-6 times improvement in power density to be on par with the functional capabilities of an IC Engine powered tank. For example, the Abrams would need 30,000 lbs. of today's batteries to maintain its performance. And this does not account for lost capability due to the weight, charge time or method, or cost.

Hybrid vehicles will likely show the biggest market share gains in the next decade, and they come in as many different configurations as the cars and SUVs that they power. From plug-in electric parallel, to mild, to series hybrid, the solutions here are diverse and complicated. Regulations and incentives will play a major role in configurations that are adopted, as we are seeing in China. The reclassification of series hybrid vehicles as "new energy" has already started to shift hundreds of millions of dollars of technology investments after the realization that the billions invested in BEVs have not had the full desired impact. For the military, hybridization offers some very compelling product attributes. The ability to run solely on batteries, even for a short time, could enable a run-silent mode. Heat signatures can be minimized or in some cases, eliminated. A challenge will be how to enable these technological advances without compromising payload, package, cost, or the burst speed that comes along with a powertrain sized for the speed wanted.

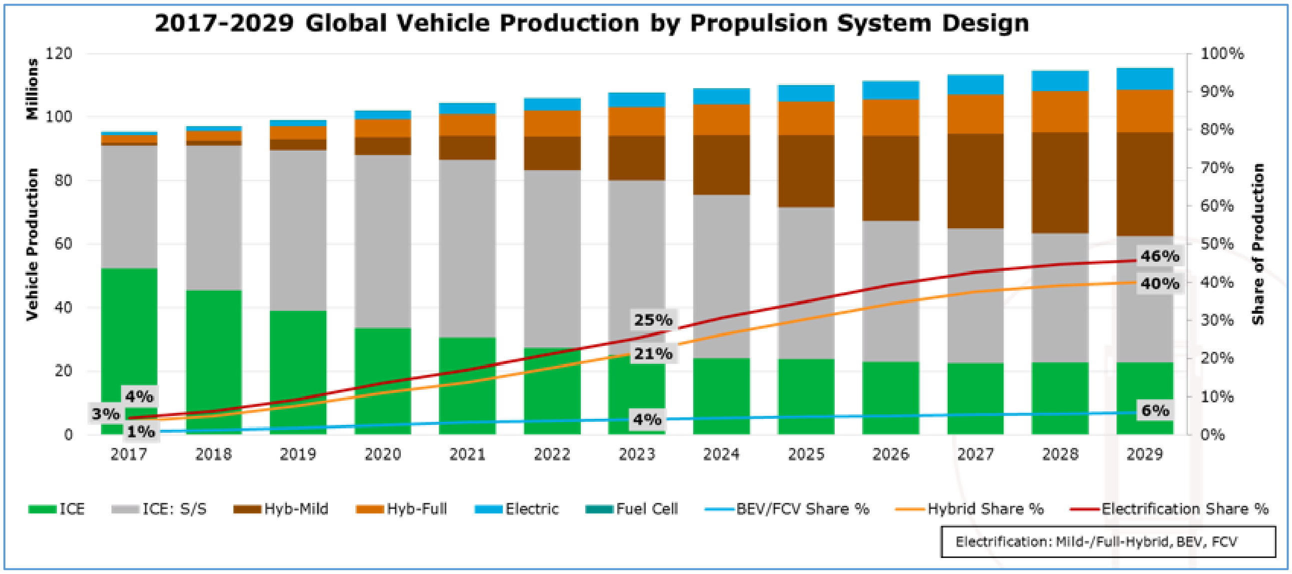


Figure 3: Projected Global Vehicle Production by Propulsion System Design

For the foreseeable future, the internal combustion engine will continue to dominate the propulsion landscape, as detailed in Figure 3. And because the global market is growing and will continue to grow, the share gains by BEVs are offset by growth, i.e. the number of engines required globally will still increase. There is some risk within the auto industry that the massive amount of investments in batteries could starve other needed technology investments.

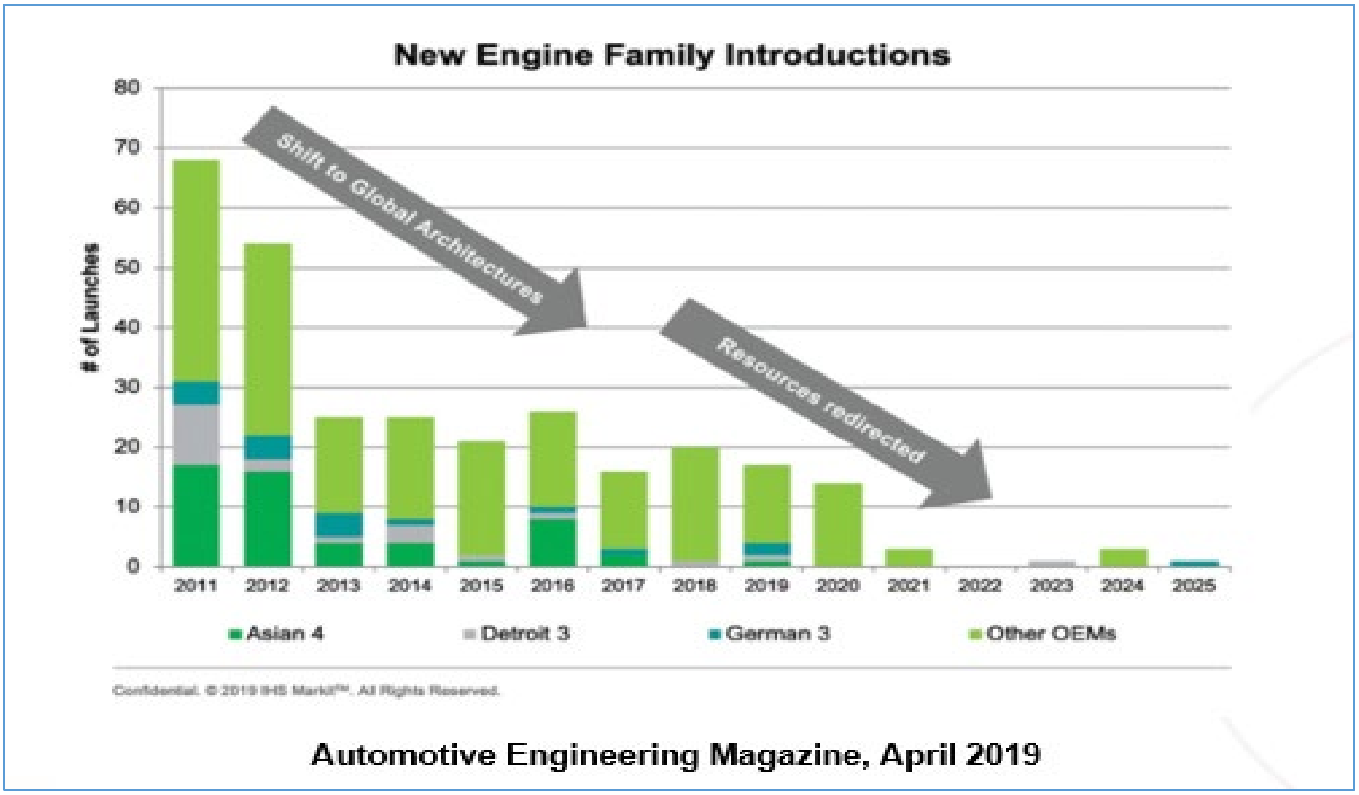


Figure 4: New Engine Family Introductions

If BEV investments do not have the desired impact, the auto industry could find that it is sorely lacking in new IC Engine technology and may need to dramatically shift and accelerate investments in that vein. Figure 4.

3. OPPOSED PISTON ARCHITECTURAL BENEFITS

Opposed-piston, two-stroke engines were developed in the late-1800s in Europe and subsequently industrialized in multiple countries for a wide variety of applications including aircraft, ships, tanks, trucks and locomotives. They maintained their presence throughout most of the twentieth century. A summary of the history of opposed-piston engines can be found in the SAE book, Opposed-Piston Engines: Evolution, Use, and Future Applications by M. Flint and J.P. Pirault. Produced initially for their manufacturability and high-power density, opposed-piston, two-stroke engines have demonstrated superior fuel efficiency compared to their four-stroke counterparts. This section examines the underlying reasons for the superior fuel efficiency and emissions.

The opposed-piston, two-stroke diesel engine has the following efficiency advantages compared to a conventional, four-stroke diesel engine:

Reduced Heat Losses:

The Opposed-Piston Engine (OP Engine), which includes two pistons facing each other in the same cylinder, offers the opportunity to combine the stroke of both pistons to increase the effective stroke-to-bore ratio of the cylinder working volume.

For example, (see Table 1) when coupling two piston trains from a conventional, single-piston engine with a stroke-to-bore ratio of 1.1, the resulting opposed-piston engine bore-to-stroke ratio is twice or 2.2. This can be accomplished while preserving the engine speed capability of the base design.

To achieve the same stroke-to-bore ratio with a single-piston engine the mean piston speed would double for the same engine speed. This would severely limit the engine speed range and, therefore, the power output.

The increase in stroke-to-bore ratio has a direct mathematical relationship to the area-to-volume ratio of the combustion space. For example, when comparing a single-piston engine to an opposed-piston engine with the same piston slider dimensions, the following outcome can be seen:

	Single Piston	**Opposed-Piston**
Trapped Volume/Cyl.	1.0L	1.6L
Bore	102.6	102.6 mm
Total Stroke	112.9	224.2 mm
Stroke-to-Bore Ratio	1.1	2.2
Compression Ratio	15:1	15:1
Surface Area (Min Vol.)	20 cm^2	20 cm^2
Volume (Min Vol.)	71 cm^3	114 cm^3
Area-to-Volume Ratio	0.28	0.18

Table 1. Opposed-piston engine compared to a single-piston engine**.**

In this example the reduction in the surface area top volume ratio is a very significant 36%. The lower surface area directly leads to a reduction in heat transfer.

The following plot (Figure 5) shows that the area-to-volume ratio of a 6-liter opposed-piston engine is equivalent to a 15-liter, conventional diesel engine.

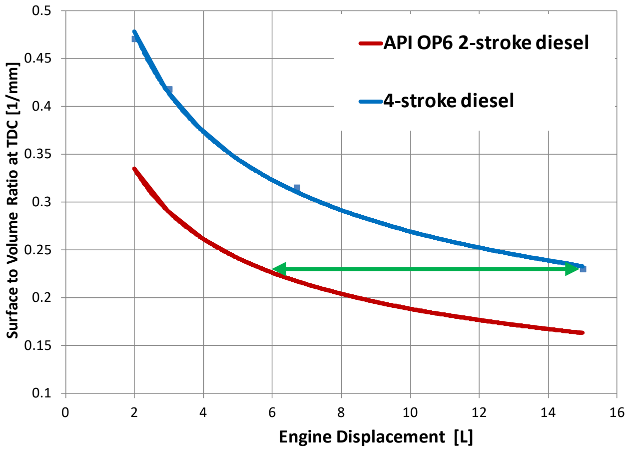


Figure 5. Surface-to-volume ratio versus engine displacement for an opposed-piston and conventional engine.

This reduction in area-to-volume ratio is one of the main reasons why larger displacement engines are more efficient than smaller ones. With the opposed-piston architecture there is the opportunity to achieve the efficiency of much larger engines.

Leaner Combustion:

When configuring an opposed-piston, two-stroke engine of the same displacement as a four-stroke engine—for example, converting a six-cylinder, conventional engine into a three-cylinder, opposed-piston engine—the power that each cylinder must deliver is the same. The opposed-piston engine fires each of the three cylinders at each revolution while the four-stroke engine fires each of its six cylinders one out of two revolutions.

Therefore, the amount of fuel injected for each combustion event is similar, but the cylinder volume is twice as much for the Opposed-Piston Engine. For the same boost conditions the OP Engine will achieve leaner combustion, which increases the ratio of specific heat. Increasing the ratio of specific heat increases the pressure rise during combustion and increases the work extraction per unit of volume expansion during the expansion stroke.

Ideal Engine Efficiency

$$\eta_{ideal} = 1 - \frac{1}{r_c^{\gamma-1}}$$

r_c = compression ratio

γ = ratio of specific heats

Faster and Earlier Combustion at the Same Pressure Rise Rate:

The larger combustion volume for the given amount of energy released also enables shorter combustion duration while preserving the same maximum pressure rise rate. The faster combustion improves thermal efficiency by reaching a condition closer to constant volume combustion. The lower heat losses as described above lead to a 50% burn location closer to the minimum volume. The plot below illustrates how the heat release rate compares between a four-stroke engine and an OP Engine.

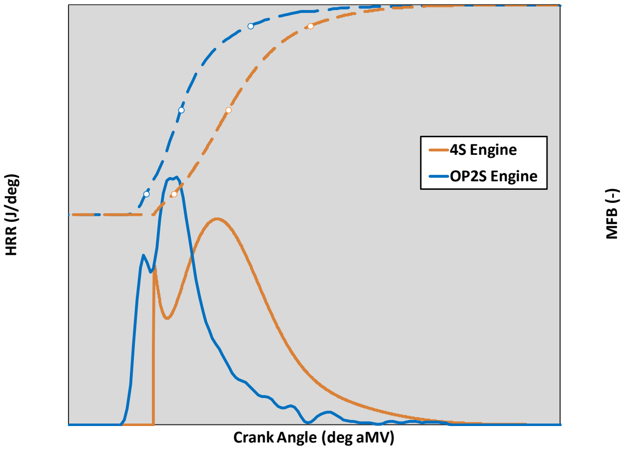


Figure 6. Heat release rate comparison between a four stroke and the opposed-piston, two-stroke.

The ideal combustion should occur at the minimum volume and be instantaneous. The opposed-piston engine is much closer to this ideal condition at the same pressure rise rate. (Figure 6)

The fundamental opposed-piston, two-stroke thermal efficiency advantages are further amplified by:

- Lower heat loss due to higher wall temperature of the two piston crowns compared to a cylinder head. (Reduced temperature delta).
- Reduced pumping work due to uniflow scavenging with the opposed-piston, two-stroke architecture giving a higher effective flow area than a comparable four-stroke or a single-piston, two-stroke uniflow or loop-scavenged engine.
- A decoupled pumping process from the piston motion due to the two-stroke architecture allows alignment of the engine operation with a maximum compressor efficiency line.
- Lower NOx characteristics as a result of lower BMEP requirements due to the two-stroke cycle operation.

Efficiency and Emissions Enablers:

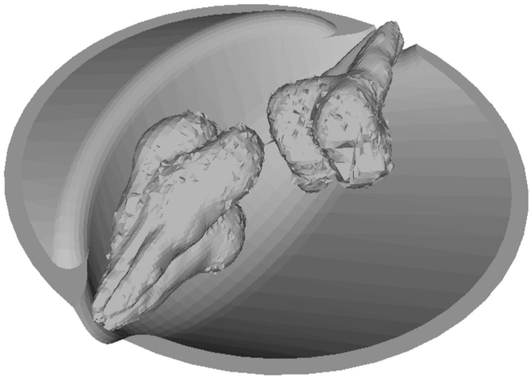


Figure 7. Schematic of the combustion system with plumes coming out of two side-mounted injectors.

Using a proprietary combustion system, composed of two identical pistons coming together to form an elongated ellipsoidal combustion volume, the injectors are located at the end of the long axis (Figure 7). This combustion system allows:

- High turbulence, mixing and air utilization with both swirl and tumble charge motion as is illustrated below with the high turbulent kinetic energy available at the time of auto ignition

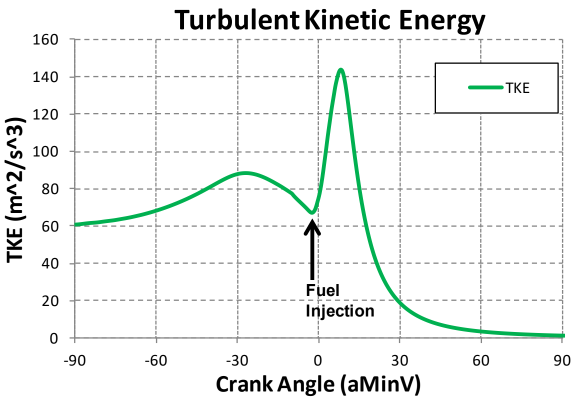
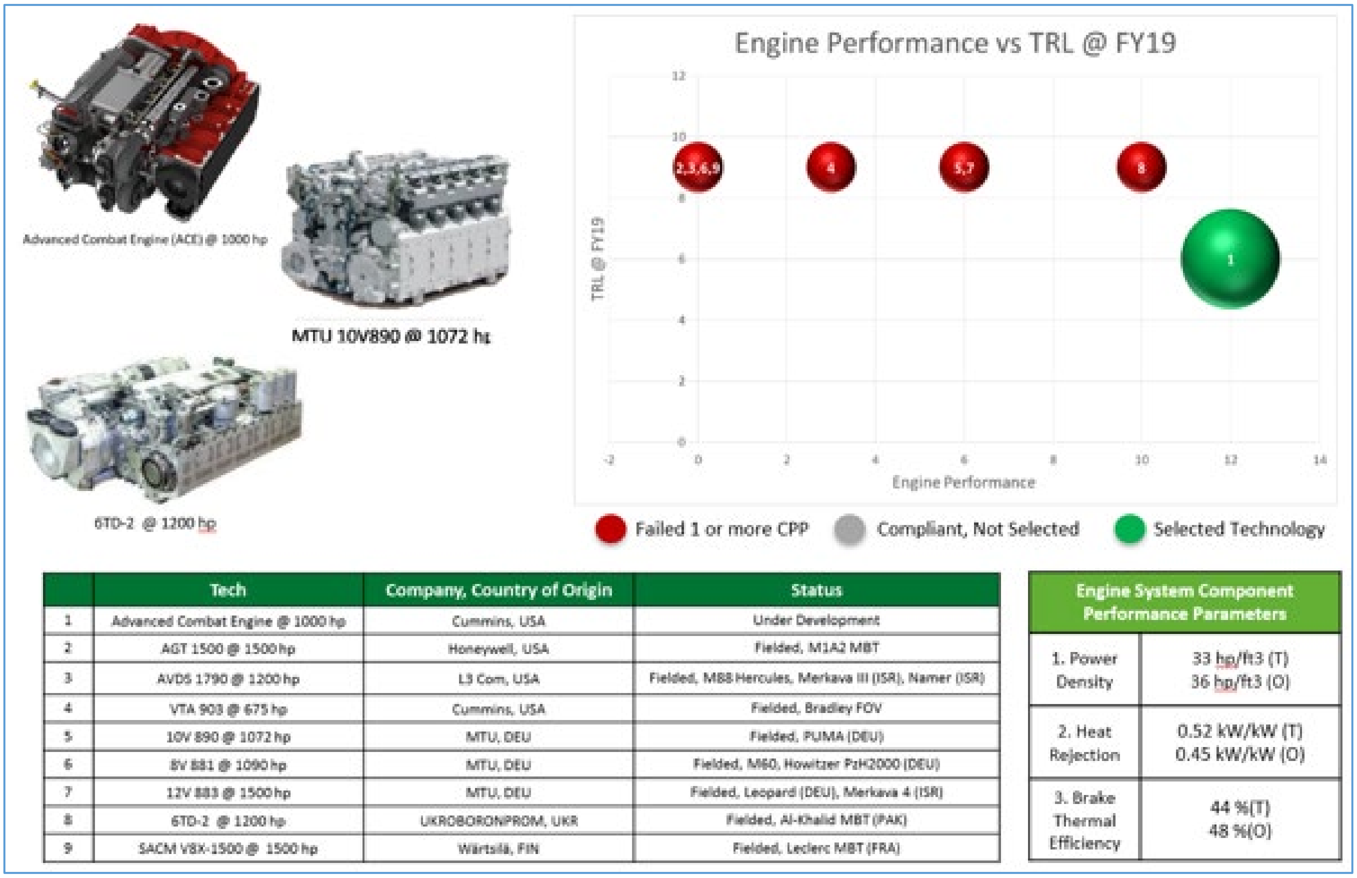


Figure 8. Demonstrated high turbulence, mixing and air utilization with both swirl and tumble charge motion.

- Ellipsoidal combustion chamber resulting in air entrainment into the spray plumes from two sides
- Inter-digitated, mid-cylinder penetration of fuel plumes enabling larger λ=1 iso-surfaces
- Excellent control at lower fuel flow rates because of two small injectors instead of a single higher flow rate
- Multiple injection events and optimization flexibility with strategies such as injector staggering and rate-shaping

The result is no direct fuel spray impingement on the piston walls and minimal flame-wall interaction during combustion. This improves performance and emissions with fewer hot spots on the piston surfaces to further reduce heat losses.

4. THE U.S. ARMY'S GROUND VEHICLE SYSTEMS CENTER'S INVESTMENTS IN OPPOSED PISTON TECHNOLOGY



	Tech	Company, Country of Origin	Status
1	Advanced Combat Engine @ 1000 hp	Cummins, USA	Under Development
2	AGT 1500 @ 1500 hp	Honeywell, USA	Fielded, M1A2 MBT
3	AVDS 1790 @ 1200 hp	L3 Com, USA	Fielded, M88 Hercules, Merkava III (ISR), Namer (ISR)
4	VTA 903 @ 675 hp	Cummins, USA	Fielded, Bradley FOV
5	10V 890 @ 1072 hp	MTU, DEU	Fielded, PUMA (DEU)
6	8V 881 @ 1090 hp	MTU, DEU	Fielded, M60, Howitzer PzH2000 (DEU)
7	12V 883 @ 1500 hp	MTU, DEU	Fielded, Leopard (DEU), Merkava 4 (ISR)
8	6TD-2 @ 1200 hp	UKROBORONPROM, UKR	Fielded, Al-Khalid MBT (PAK)
9	SACM V8X-1500 @ 1500 hp	Wärtsilä, FIN	Fielded, Leclerc MBT (FRA)

Engine System Component Performance Parameters	
1. Power Density	33 hp/ft3 (T) 36 hp/ft3 (O)
2. Heat Rejection	0.52 kW/kW (T) 0.45 kW/kW (O)
3. Brake Thermal Efficiency	44 %(T) 48 %(O)

Figure 9: Army Study of MOTS Powerpacks versus ACE specifications

The Army studied engine architectures for over 20 years and based on thousands of hours of testing independently concluded that the opposed-piston engine architecture is the superior platform on which to base the future of combat vehicle propulsion. The architecture is most closely akin to that designed by Hugo Junkers, the Junkers Jumo 207, which set efficiency records in the 1930's in German Aircraft. The architecture fell out of favor in the decades after WWII because it was very difficult to engineer, and as emissions and durability requirements became more stringent and prevalent the industry focused on optimization of four-stroke engines. Ironically, a descendant of the Junkers Jumo 207 still operates in Ukrainian tanks to this day. Hugo Junkers clashed with the Nazis and died under house arrest in 1935. Some of his technicians ended up in Russia after WWII, who reverse engineered his designs and facilitated their use in these tanks.

Achates Power has been solving the inherent problems of the OP Engine architecture for the last 15 years, applying modern engineering tools and simulation to bring the engine to the market – the pull from the Army has been the catalyst that has put an OP Engine program on the path to production.

Two years of 250 HP single cylinder two-piston engine development, and a successful 80-hour durability test on that hardware have led to the development of the 1,000 HP multi-cylinder engine (MCE), prototypes which are now being tested at Cummins Technical Center. The Army will receive a test engine later in 2019 and multiple vehicle demonstrations with the Army are planned over the next 2-3 years. Low-rate initial production is slated for 2023, and the platform is poised to be the most power dense ever tested by the Army by a factor of two. This incredible power density, coupled with superior efficiency and heat rejection, will enable vehicle optimization and enhanced power output that was previously unachievable.

The 1,000 hp Advanced Combat Engine brings an unparalleled opportunity to the future of ground combat vehicles. Figures 10 and 11 detail the power density electrical power requirement impacts to the vehicle:

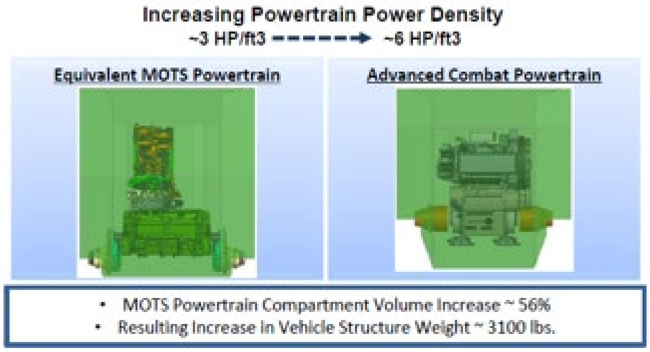


Figure 10: Power density impacts

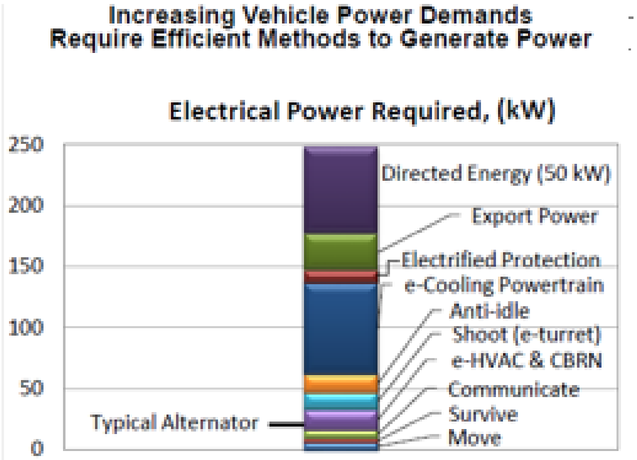
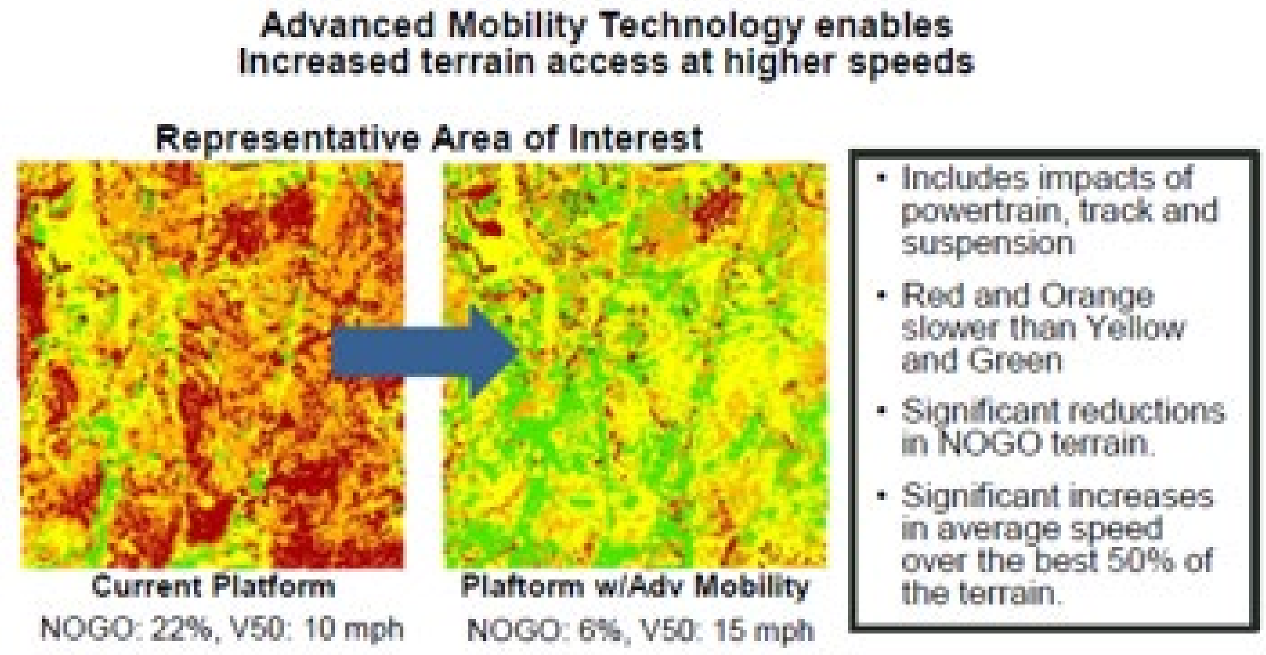


Figure 11: The electrical output enhancement

And finally, when coupled with an advanced combat transmission and track enhancements, a future combat vehicle can achieve the following performance when compared to a Bradley (figure 12):



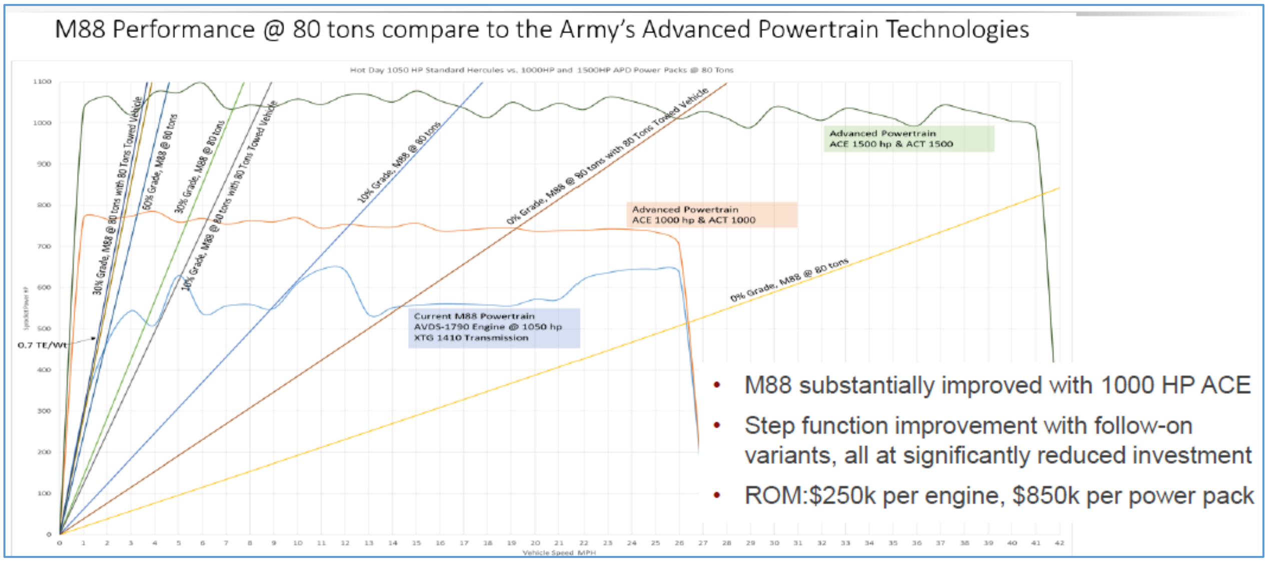
Advanced Mobility Technology enables Increased terrain access at higher speeds

Representative Area of Interest

- Includes impacts of powertrain, track and suspension
- Red and Orange slower than Yellow and Green
- Significant reductions in NOGO terrain.
- Significant increases in average speed over the best 50% of the terrain.

Figure 12: Performance compared to current Bradley platform

The performance impact on an M88 Hercules is significant, even with the 1000 HP variant. The 1500 HP variant is even more impactful (Figure 13).

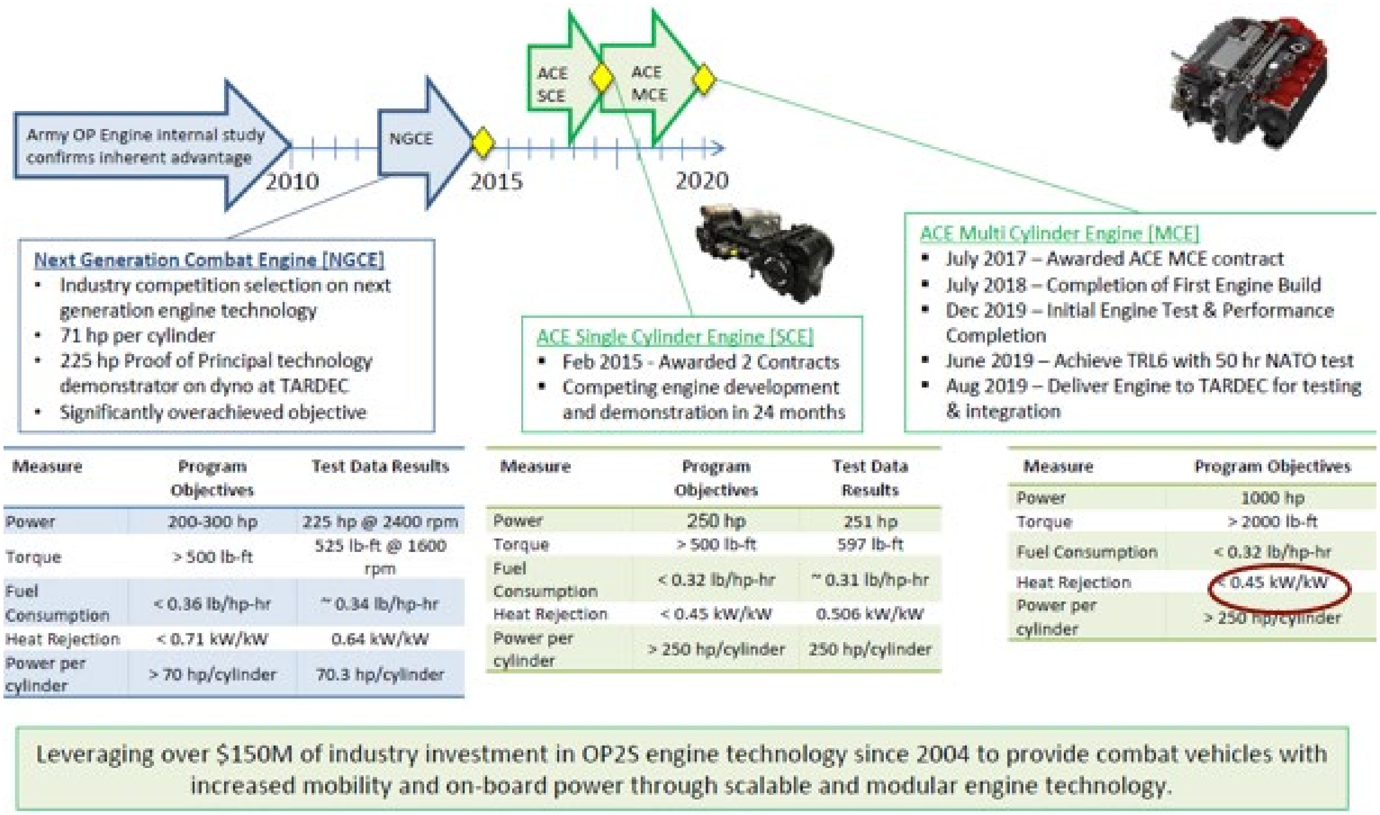


M88 Performance @ 80 tons compare to the Army's Advanced Powertrain Technologies

- M88 substantially improved with 1000 HP ACE
- Step function improvement with follow-on variants, all at significantly reduced investment
- ROM:$250k per engine, $850k per power pack

Figure 13: Performance on M88 Hercules

To really deliver the next generation of combat vehicles, the vehicle must be optimized around a leap ahead technology. The Advanced Combat Engine enables that leap ahead.



Next Generation Combat Engine [NGCE]

- Industry competition selection on next generation engine technology
- 71 hp per cylinder
- 225 hp Proof of Principal technology demonstrator on dyno at TARDEC
- Significantly overachieved objective

Measure	Program Objectives	Test Data Results
Power	200-300 hp	225 hp @ 2400 rpm
Torque	> 500 lb-ft	525 lb-ft @ 1600 rpm
Fuel Consumption	< 0.36 lb/hp-hr	~ 0.34 lb/hp-hr
Heat Rejection	< 0.71 kW/kW	0.64 kW/kW
Power per cylinder	> 70 hp/cylinder	70.3 hp/cylinder

ACE Single Cylinder Engine [SCE]

- Feb 2015 - Awarded 2 Contracts
- Competing engine development and demonstration in 24 months

Measure	Program Objectives	Test Data Results
Power	250 hp	251 hp
Torque	> 500 lb-ft	597 lb-ft
Fuel Consumption	< 0.32 lb/hp-hr	~ 0.31 lb/hp-hr
Heat Rejection	< 0.45 kW/kW	0.506 kW/kW
Power per cylinder	> 250 hp/cylinder	250 hp/cylinder

ACE Multi Cylinder Engine [MCE]

- July 2017 – Awarded ACE MCE contract
- July 2018 – Completion of First Engine Build
- Dec 2019 – Initial Engine Test & Performance Completion
- June 2019 – Achieve TRL6 with 50 hr NATO test
- Aug 2019 – Deliver Engine to TARDEC for testing & integration

Measure	Program Objectives
Power	1000 hp
Torque	> 2000 lb-ft
Fuel Consumption	< 0.32 lb/hp-hr
Heat Rejection	< 0.45 kW/kW
Power per cylinder	> 250 hp/cylinder

Leveraging over $150M of industry investment in OP2S engine technology since 2004 to provide combat vehicles with increased mobility and on-board power through scalable and modular engine technology.

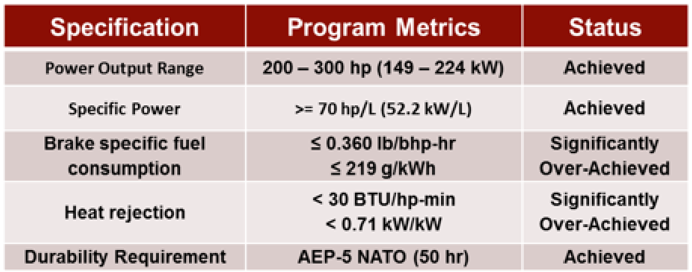
Figure 14: Optimization around a leap-ahead technology

The technology is modular, scalable and will eventually give rise to a family of engines that can power the entire combat vehicle fleet, with each variant requiring only a fraction of the capital investment of the first (Figure 15).

Figure 15: Scalability of the Advanced Combat Engine

5. DEVELOPMENT OF THE MEDIUM-DUTY APPLICATION OF OPPOSED-PISTON ENGINE TECHNOLOGY

The Next Generation Combat Engine, or Topic 27 project was the Army's first successful demonstration of the opposed piston architecture.



Specification	Program Metrics	Status
Power Output Range	200 – 300 hp (149 – 224 kW)	Achieved
Specific Power	>= 70 hp/L (52.2 kW/L)	Achieved
Brake specific fuel consumption	≤ 0.360 lb/bhp-hr ≤ 219 g/kWh	Significantly Over-Achieved
Heat rejection	< 30 BTU/hp-min < 0.71 kW/kW	Significantly Over-Achieved
Durability Requirement	AEP-5 NATO (50 hr)	Achieved

Table 2: Next Generation Combat Engine performance vs. program objectives

The resulting three-cylinder six piston research engine met the brake specific fuel consumption target on the first day of testing, achieved all program objectives within 6 weeks of first fire, and met all program objectives four months early and under budget. The success of this project was the deciding factor in the inception of the ACE program, as the larger bore size was needed for a true combat platform. Still, the technology has significant value, and the Achates Power / Cummins team is preparing to kick off a tactical engine project in FY20. The notional specifications of that engine are detailed here (Figure 16):

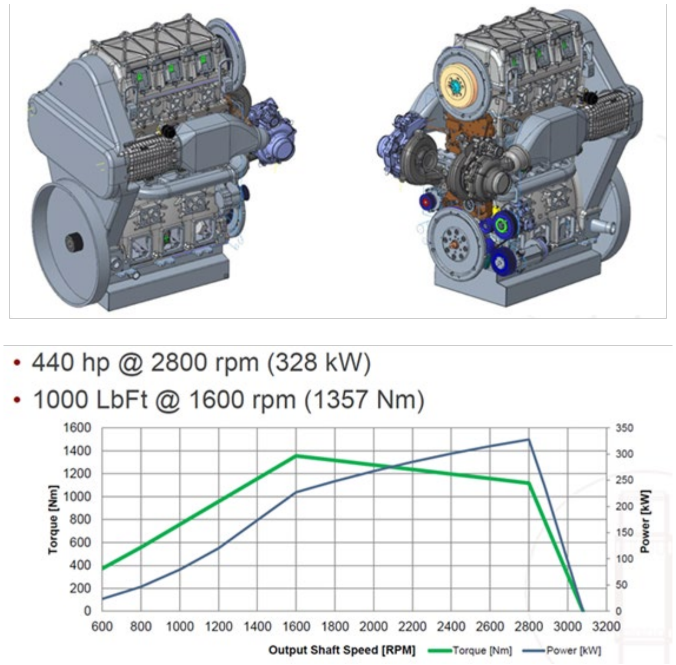


Figure 16: Notional specifications of the 3-cylinder engine

With the same strategic advantage, a low-capital family of engines is also possible:

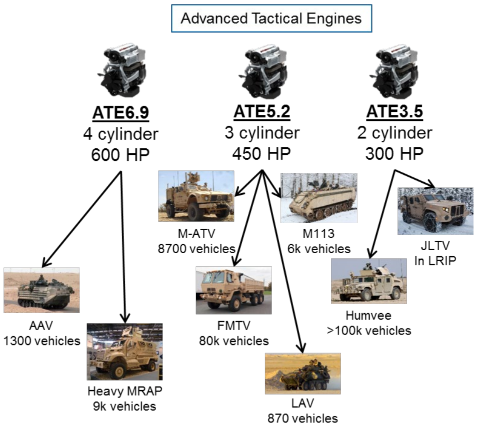
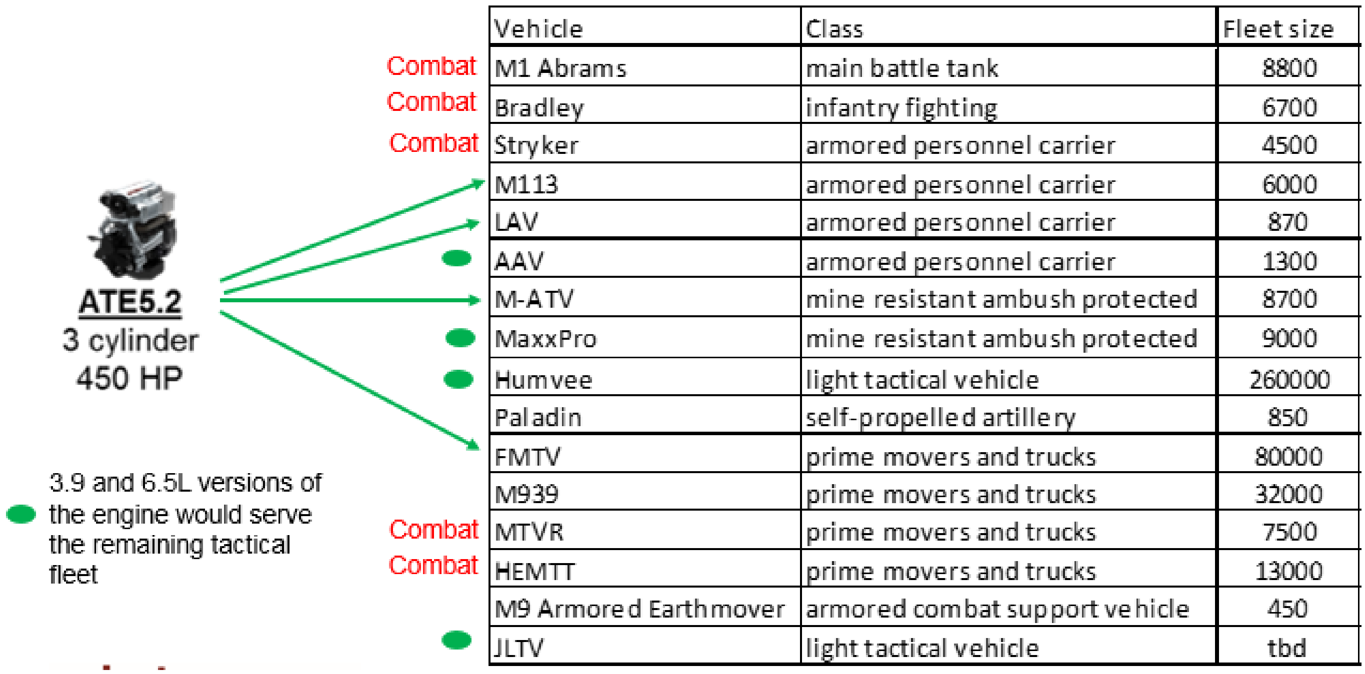


Figure 17: Future family of advanced tactical engine applications

The first variant to be developed will be the three-cylinder six piston configuration with the first prototypes arriving in early 2021. This will enable upgrades across the tactical vehicle fleet as the M113 and LAV emerge as candidates for early adoption (Figure 17).



	Vehicle	Class	Fleet size
Combat	M1 Abrams	main battle tank	8800
Combat	Bradley	infantry fighting	6700
Combat	Stryker	armored personnel carrier	4500
	M113	armored personnel carrier	6000
	LAV	armored personnel carrier	870
●	AAV	armored personnel carrier	1300
	M-ATV	mine resistant ambush protected	8700
●	MaxxPro	mine resistant ambush protected	9000
●	Humvee	light tactical vehicle	260000
	Paladin	self-propelled artillery	850
	FMTV	prime movers and trucks	80000
	M939	prime movers and trucks	32000
Combat	MTVR	prime movers and trucks	7500
Combat	HEMTT	prime movers and trucks	13000
	M9 Armored Earthmover	armored combat support vehicle	450
●	JLTV	light tactical vehicle	tbd

Figure 18: Potential U.S. Army platform applications of the 3-cylinder engine

6. THE CLASS 8 LINE-HAUL APPLICATION DEVELOPMENT AND DEMONSTRATION

In 2016 CALSTART brought together a comprehensive team to propose a demonstration project to the California Air Resources Board (CARB). The team, including suppliers, an OEM and fleets, proposed to demonstrate a commercial variant of the opposed-piston engine technology in class-8 line-haul applications. The team was awarded funds totaling $16 million (including in-kind cost share) to undertake the demonstration in the San Joaquin Valley of California.

CARB was attracted to this proposal due to the opposed-piston technology's ability to achieve extremely low NOx emissions (0.02 grams per brake-horsepower hour with diesel). In addition, overall fuel efficiency gains of 10-15% met CARB's greenhouse gas reduction aims.

The inclusion of opposed-piston engine technology provides an opportunity to downsize the engine. The typical class 8 truck for over-the-road applications typically utilizes a 13-15-liter engine. The opposed-piston engine is 10.6 liters, thereby contributing to increased efficiency and lower greenhouse gas emissions.

The project team is currently completing final designs. The engine will be integrated into a Peterbilt truck in late 2019 and will be demonstrated in connection with Wal-Mart and Tyson Foods facilities in 2020. Detailed data on efficiency and emissions will be collected and reported to CARB. CALSTART will also share demonstration results with GVSC's Power and Mobility team. In addition, CALSTART is working to secure funding to perform additional tests of the commercial variant engine at GVSC's test facility using military test cycles.

7. THE USE OF OPPOSED PISTON TECHNOLOGY IN DRONE ENGINES

The Army has recently received a Presidential Determination under Title III that allocates a significant amount of capital to develop a US supply chain for drones. The lighter weight classes of drones are particularly controlled by foreign supply and this is a strategic risk for America. While the OP Engine is not a likely propulsion candidate for drones under 55 pounds, the supply chain risk is similar for Class 3-5 drones and warrants consideration. The inherent qualities of the Opposed-Piston Engine also lend themselves to the heavier drones. For example, a typical class 4 drone would use a ~250 HP engine weighing ~250 pounds and carrying ~800 pounds of fuel. The competitive OP Engine would be slightly heavier (~100 pounds) without significant lightweighting. However, it would double the fuel economy of its competitor. This means that the overall vehicle could carry between 200-300 pounds less fuel and still experience a double-digit percent increase in mission duration. The vibration and durability requirements of an OP Engine designed specifically for drone use would offer compelling improvements over the incumbent set.

Figure 19 shows an OP Engine packaged in a drone environment:

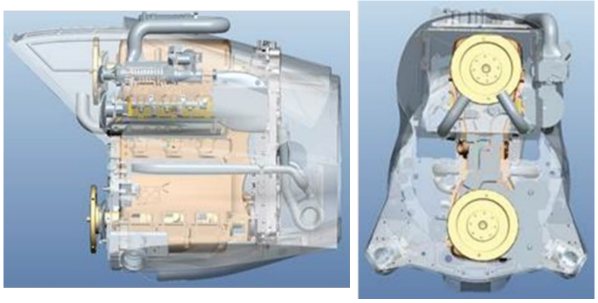


Figure 19: OP engine packaged in a drone environment

8. THE USE OF OPPOSED PISTON TECHNOLOGY IN POWER GENERATION

Fairbanks Morse has manufactured an Opposed Piston variant for stationary power, marine hotel loads, and backup power for nuclear submarines for almost 100 years. It is a 12-cylinder, 24-piston configuration, producing 5,000 hp, that is being updated with Achates Power's OP Engine technology and designs.

Achates Power / Cummins team will seek parallel markets to leverage the dual use nature of the OP Engine architecture and help achieve economies of scale in adjacent market segments, thereby defraying some of the costs to the Army.

9. CONCLUSIONS

The demise of the internal combustion engine has been predicted for over half of its 100+ year dominance in and transformation of the global mobility terrain. While battery electric vehicles will remain a critical investment for the future of mobility, the efficiency, power and long-term future of the internal combustion engine cannot be overlooked. BEVs will show growth first in light applications, small vehicles, low load, and in short and predictable duty cycles. With current battery technology, over 30,000 pounds of batteries would be required to power a 50+ ton combat vehicle. It is simply not feasible with current technology.

The Army, after much study, has selected the Opposed-Piston Engine architecture as its platform for the future of combat vehicle mobility due to its superior power density, heat rejection, and efficiency, and we have only just begun to discover the vehicle optimization that will be possible when equipped with this leap-ahead mobility technology. Future platforms and segments will enjoy the benefits of a superior engine as well as the economies of scale that will come from the proliferation of the architecture.