2011 NDIA Ground Vehicle Systems Engineering & Technology Symposium (GVSETS)
Power and Mobility (P&M) Mini-Symposium
2011 August 9-11; Dearborn, Michigan

Ultra-High Power Density Hybrid Power Systems and APUs

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Abstract

Military vehicles need prime power and auxiliary power systems with ever-increasing power density and specific power, as well as greater fuel economy, lower noise, lower exhaust emissions and greater stealth. D-STAR technologies, funded by the Army, DARPA, Marine Corps / Navy and others, are enabling a new generation of modified-HCCI (homogenous charge compression ignition) engines that simultaneously offer power density and specific power of racing-quality gasoline engines, operation on JP-8 and other heavy fuels, as well as the other desirable qualities mentioned above. D-STAR Engineering has recently developed a prototype for a 1 kW man-portable heavy-fuel hybrid power system, that has been successfully tested by the ONR / USMC, and has demonstrated the power core for a 2 kW hybrid power system (for Army TARDEC). D-STAR is also developing, based on funding from the Army, a 500 Watt hybrid power system, and has designs for hybrid heavy fuel power systems and APUs for 10 and 30 kW. These hybrid power systems and APUs offer 2x to 3x greater power density and specific power compared to power systems with conventional diesel engines.

The views presented in this paper are strictly that of the author, and do not necessarily represented the view of the various sponsors of R&D at D-STAR, such as the Army, ONR, USMC or other US government agencies.

1. Introduction

The U.S. armed forces have a large diversity of needs for energy on the battlefield, from radios and sensors to personal cooling systems or personal equipment transport. Whereas electronic systems are becoming more efficient, there is now a much greater variety of equipment that can help the soldier's mission, most of which needs electrical power and energy.

D-STAR has been developing devices that uses JP-8, JP-5, Jet-A, diesel / kerosene and other logistics compatible fuels to provide fully conditioned 28 V DC power. The Office of Naval Research (ONR) has provided support to D-STAR, under a Phase 1 (feasibility) and Phase 2 (Alpha Prototype), for a 500 Watt – 1000 Watt heavy fuel power system, for potential use by the Marine Corps and other agencies of the US Government.

The D-STAR Hybrid Power System uses a high-speed heavy fuel engine coupled to a permanent-magnet generator and an electronic power conditioning system. The systems also use internal sensors and electronics, to match the power needed to the power produced, by variable-speed operation of the engine to minimize noise and wear, using an internal battery for load buffering, and also iteratively optimize internal operating parameters to maintain safe internal temperatures and minimize fuel consumption. The hybrid power system uses logistics fuels to provide power for battery charging for soldiers, sensors, Unmanned Ground Vehicles and other applications.

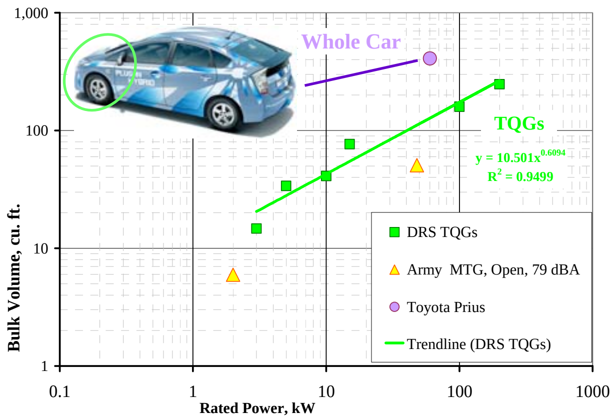
A TRL=5 ('Alpha' / lab-use) prototype has been developed, delivered to the government, and successfully tested by the government. Based on these tests, D-STAR ha been invited to submit a proposal to develop and deliver multiple TRL=6 ('Beta' / field use) prototypes.

1 kW Hybrid Power System

2. Problems with Conventional Diesel Gen-Sets

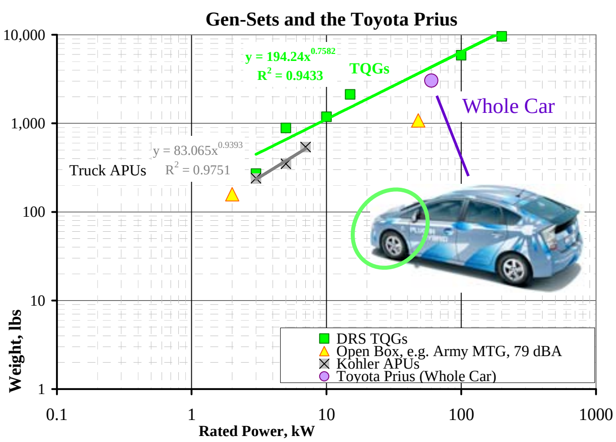
2.1 Size : Military Generator Sets are Too Large

The graph below shows the volume of typical military generator sets, and compares it with the bulk volume of a commercial hybrid power system, a well known car in the same power class.

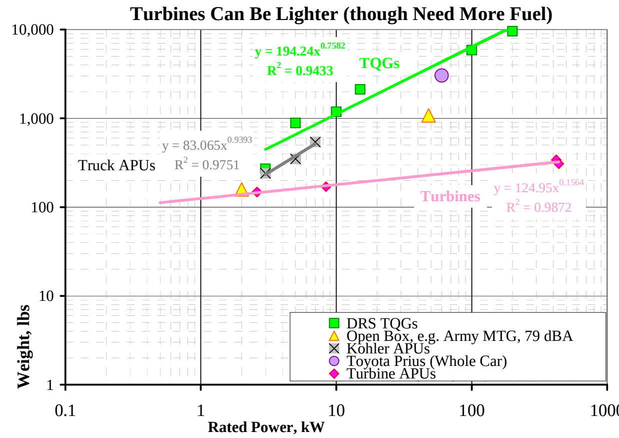


2.2 Weight : Military Gen-Sets are Too Heavy

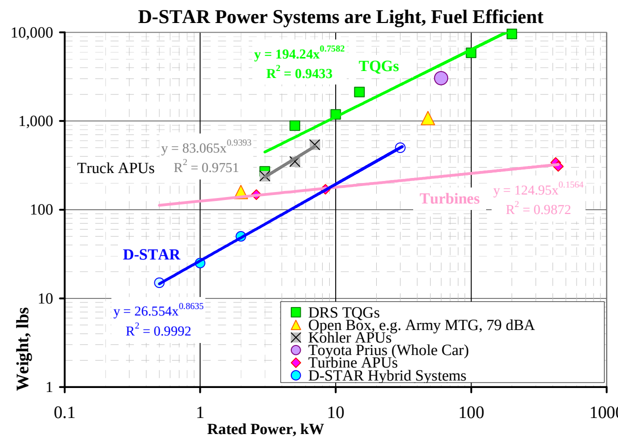
The graph below shows that the weight of typical military heavy fuel generator sets is greater than a hybrid-electric whole car of the same power, albeit that operates on gasoline, not diesel.



The graph below shows that generator sets based on turbine engines can be light-weight, especially in the large power categories. However, turbine engines become less competitive in the smaller power categories. Turbine engines also have increasingly poor fuel consumption at smaller rated power levels, and at part-load conditions. Further, turbine engines are an order of magnitude more expensive than typical diesel engines, as indicated in the next section.



The graph below provides an indication of the weight of the heavy fuel generator sets that can be achieved by D-STAR technologies (the blue trend line). The weights (blue lines) are projections based on actual hardware built and tested by D-STAR and what is achievable when the prototypes evolve from TRL=5 at present to TRL = 6 in the near future.



2.3 Noise : The Enemy of Stealth

The 2 kW Military Tactical Generator (MTG) makes 79 dB(A) of noise at 7 meters (25 ft) distance, whereas the ONR / USMC goal for the 1 kW generator is < 70 dB.

Considering that half the power would reduce noise by about 3 dB, the 79 dB noise of the 2 kW MTG is equivalent to 76 dB for a 1 kW generator at 7 m. It is thus desirable to reduce the noise of the 1 kW class generator by > 6 dB, which implies a 4x reduction in noise power output.

Noise can be reduced by encapsulation. However, that increases weight, which is contrary to USMC needs for a 1 kW generator that weighs 15 lbs, rather than the 138 – 158 lbs for the 2 kW MTG, or 10x lower weight, for only 2x lower power, while simultaneously reducing noise by 4x.

2.4 Wet Stacking

This occurs when a constant speed conventional diesel engine is running at part load. Because of un-throttled operation, it has the maximum rated air flow but, because of low power needs, it has very little fuel flow. The resulting exhaust gas temperatures are low enough that oxides of sulfur in the exhaust (from burning of sulfur in fuel) mix with water vapor in the exhaust to form dilute sulfuric acid, which condenses in the cool exhaust system and thus begins corrosion of the metal components in the exhaust system. A variable speed, load-following system would largely eliminate wet-stacking by reducing both fuel and air flows at part load settings.

The Source of Most Problems of Conventional Generator Sets is the Engine

This is indicated by the following observations :

Large size : Large low-speed engine ⇒ large generator ⇒ large gen-set

Heavy weight : Large size of engine + generator ⇒ heavy generator set

High cost : Large size & weight of subsystems ⇒ greater system cost

High noise : Combustion shock noise of conventional diesel engines. Low frequency noise of low-speed engines is difficult to attenuate.

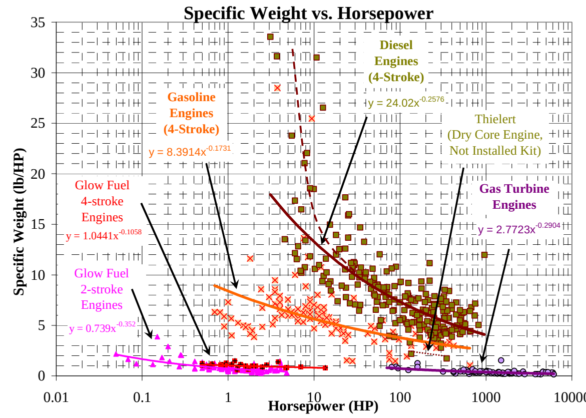
Exhaust emissions : Stratified charge produces smoke

High peak combustion temperature produces NOx.

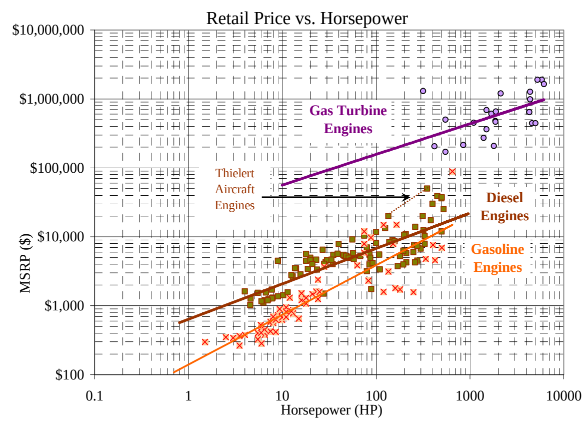
3. Problems with Conventional Heavy Fuel Engines and Their Resolution

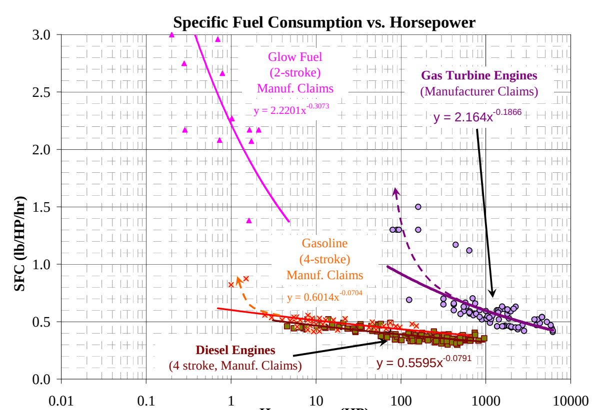
The large size and weight of conventional heavy fuel generator sets is caused primarily by the engines, indicating a primary need for engines.

3.1 Conventional Diesel Engine Handicaps : Weight and Cost, as depicted below



There is a trade-off between weight and cost : gas turbine engines are lighter, but cost more. Gas turbines are also notoriously inefficient in small sizes and low (part-load) power settings.





It is desirable to have small heavy fuel engines that have the size and weight of gas turbine engines, the fuel economy of diesel engines, and the cost of gasoline engines. Such an engine can be developed, for power in the range needed by the Army, using D-STAR technologies demonstrated under various programs.

3.2 High Power Density Diesel Engines :

The Need for a New Approach

As indicated by the first graph in section 3.1 (Specific Weight vs. Rated Power), large diesel engines gradually approach the Specific Weight of gasoline engines. The smallest diesel engines, on the other hand, get progressively worse as the engines are scaled down below 10 hp, and do not exist for rated power levels less than 1 hp.

There are two key technologies that allow large diesel engines to be competitive : turbocharging, and extremely high fuel injection pressures.

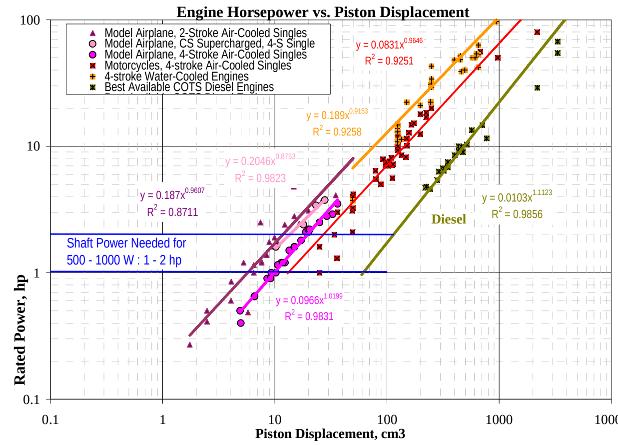
Due to the square-cube laws of physics (Reynolds numbers, leakages, roughness ratios, tip gap ratios, etc.), very small turbochargers are generally not feasible, especially for engines of < 3 hp.

As for fuel injection pressures, these have increased, over time, from 1500 psi a few decades ago, to 30,000 – 40,000 psi at present. Maybe, in the near future, we can develop 50,000 psi fuel injectors needed for operation at the high speeds optimal for small engines, but these fuel systems would be very large and prone to internal leaks.

Comparison of Small Engine Performance

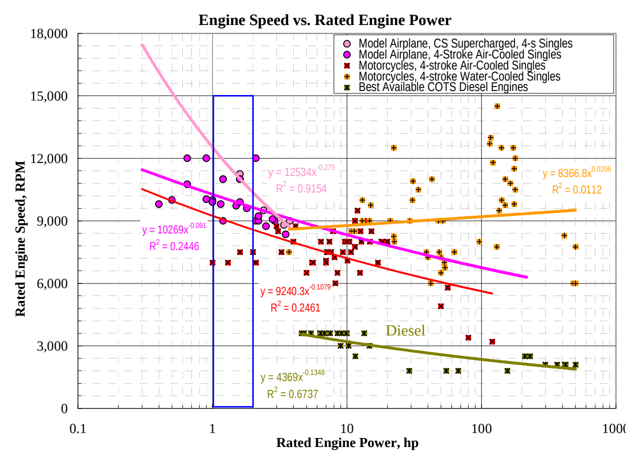
The graph below shows the power vs. size (displacement volume) of small engines. The R^2 values are fairly close to the maximum attainable of 1, indicating a very strong correlation of data and its usefulness for prediction purposes.

The graph below shows that, to produce 1 – 2 hp, a typical glow or gasoline engine would need to be of about 15 – 30 cc, but even a hypothetical, extrapolated diesel engine would need to be of about 60 – 120 cc for the same power, or about 4x larger. Why is that so?



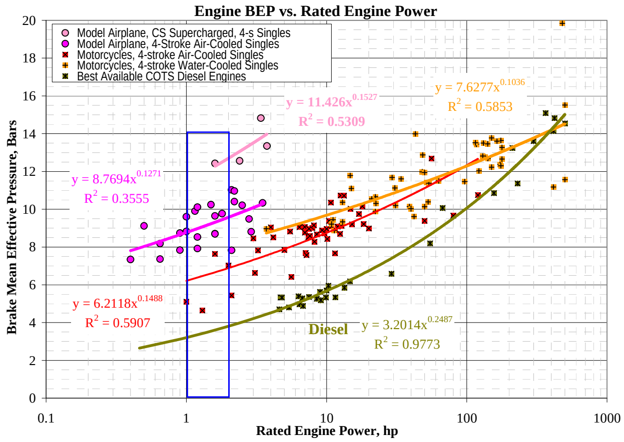
Power produced by an engine is the product of Size (Displacement), Speed (RPM) and Brake Mean Effective Pressure (BMEP). The graph below is a comparison of the speed of various small engines.

The graph below shows that the fastest single-cylinder COTS diesel engines, rated at 3600 RPM, are 2x – 3x slower than the 8000 – 10,000 RPM expected for a high power density glow or gasoline engine to make the 1 – 2 hp needed to meet the USMC requirement. Lower speed explains half the difference.



One primary reason the COTS diesel engines are 2x – 3x slower is because of their need for high pressure fuel injection directly into the cylinder, with its intrinsic limitations on charging the injectors and firing them at such speeds while maintaining low leakage through tight clearances with their attendant friction. The other primary reason for the slow speed of COTS diesel engines is their high compression ratios and peak combustion pressures, and the resulting heavier components, inertias and forces including friction.

The graph below shows the third parameter, Brake Mean Effective Pressure, for various engines.



The above graph shows that small glow and gasoline engines in the 1 – 2 hp range can have a Brake Mean Effective Pressure (BMEP) of about 6 – 10 Bars, whereas a small diesel engine for the same 1 – 2 hp, if feasible, would have a BMEP of only about 3 – 4 bars. The COTS Diesel BMEP is 2x smaller than COTS glow and gasoline engines. This explains the other 2x lower power density of diesel engines.

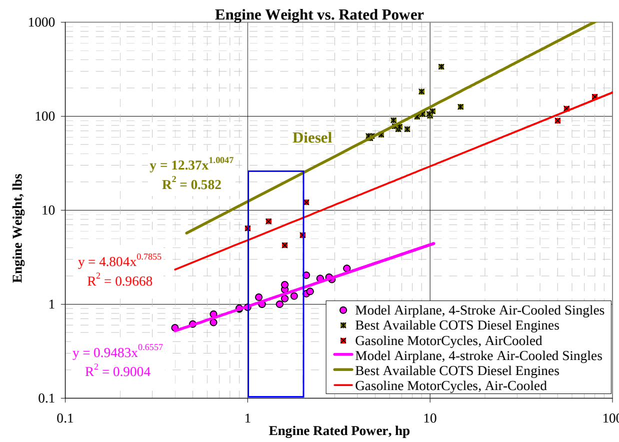
Why do COTS diesel engines have lower BMEP? This is mainly due to two reasons :

- COTS diesel engines rely on highly stratified charge of fuel in air, due to late in-cylinder injection just before top dead center. This prevents complete use of air in the cylinder. Any efforts to increase fuel injection quantity only cause an increase in smoke. Conventional diesel engines are often smoke limited to about 0.6 Equivalence Ratio, i.e., can use only about 60% of the air in the engine, before a dramatic rise in smoke produced by the engine.
- COTS diesel engines have higher compression ratios and thus higher average air and gas pressures, causing an increase in air and gas leaks past the pistons. This is aggravated further by the slow mean piston speeds of the engines, giving the air and gases more time, on a per cycle basis, for them to leak past the pistons. This may cause another 10% loss in BMEP.

So, the combined effects of lower speed, lower air utilization, greater gas leakage and greater friction explain the 5x lower power per unit displacement volume for the COTS diesel engines.

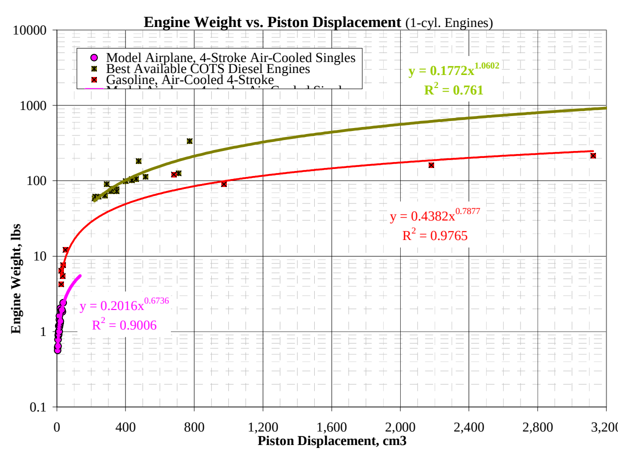
But, that is only half the story.

The graph below shows the weight of COTS diesel and other small engines.



While very small diesel engines are not feasible, and the Diesel engine curve should not be extrapolated (low value of R^2), the graph does show that small diesel engines weigh up to an order of magnitude (about 5x – 10x) more than small gasoline and glow engines of about the same power.

That COTS diesels have more weight even for the same displacement volume is also confirmed by the graph below.



Why do COTS diesel engines weigh more? In fact, because they have lower operating speeds, one would expect lower inertial forces and stresses that would enable the use of lighter materials.

The only culprits here seem to be :

- Higher compression ratios, causing higher post-compression pressures. These are needed to ensure compression ignition during cold weather, but cause a higher pressure even before combustion begins.

- Higher peak combustion pressures intrinsic to the diesel combustion process, which begins with ‘diesel knock’ (spontaneous combustion of all fuel accumulated prior to start of combustion). This uncontrolled simultaneous combustion can be mitigated by split injection schemes, but that aggravates the problems of tiny fuel injectors, as discussed earlier.

Is there no solution to the large size, heavy weight and slow speed of diesel engines (making them not well suited for driving propellers or modern Permanent Magnet generators), their undesirable Noise, Vibration and Harshness (NVH), their need for an expensive high pressure fuel injection and the greater cost of their larger heavier engine components?

Can we make small heavy fuel engines that are as light as equivalent glow fuel engines, or at least as light as widely available gasoline engines?

The answer lies <u>not</u> in trying to eliminate the fairly light-weight, very efficient and highly developed mechanical (piston-rod-crank) system of conventional engines. That can, at best, yield very marginal gains in power density and specific power.

The answer lies in solving the real problems : low air utilization, high peak pressures and low operating speeds of conventional diesel engines.

4. Small ‘Heavy Fuel’ Engines

the D-STAR Approach

- **Greater Operating Speed.** This can only be achieved if the engines have :

  - <u>Light-weight components</u> (by use of lower compression ratios and limited peak combustion pressures), and

  - <u>Abandonment of direct high-pressure injection</u> of fuel into the cylinders. Achieving direct fuel injection within the short time span available for truly high speed engines can only be achieved by extreme fuel injection pressures (50,000 psi? 100,000 psi?), that are an increasing challenge for small engines due to the square-cube laws of scaling.

- **Greater Air Utilization.** This requires :

  - <u>Abandonment of direct in-cylinder fuel injection.</u> Stratified charge engines can never achieve the same air utilization, and the same power density, as otherwise equivalent homogenous charge engines such as gasoline engines.

  - <u>Adoption of external fuel injection</u> and mixing of air and fuel prior to introduction of the charge into the engine. This does create the problem of uncontrolled combustion of the fuel-air mixture at the high compression ratios used in COTS diesel engines. But, this problem can be solved by the following steps :

  - <u>Dramatic reduction in compression ratios</u> used for heavy fuel engines. This will not only eliminate the uncontrolled ignition of fuel, but will also offer a reduction in the air leaking past the piston (‘blow-by’), offer the use of lower forces between the rings and the cylinder walls for reduced friction and wear, enable the use of lighter, lower-inertia flywheels, and form the basis for lower peak combustion pressures in the engine.

- <u>Abandonment of ‘Compression Ignition’</u>. CI requires high compression ratios for cold starting, and has large variation in the onset of combustion. This causes an increase in the peak pressures that occur rarely but the engine must be made strong enough to withstand, and causes an increase in the perceived NVH for the engine. Turbine engines use ‘heavy’ fuels but do not use compression ignition; they use an ignitor.

- <u>Adoption of spark-assisted ignition</u>. Spark ignition systems, with modern ‘solid state’ electronic components, are extremely reliable and used on millions of gasoline engines world wide. Spark-assisted diesel combustion has been successfully demonstrated by D-STAR Engineering on several of its engines.

- **Active Management of Peak Combustion Pressures.** By limiting the peak pressures in the engine, components can be made lighter, operating speeds can be increased, and NVH can be reduced. A Pressure Management System (PMS) has been developed by D-STAR, and used successfully on several of its 2 – 10 hp ‘heavy fuel’ engines.

The combined synergy between the above features has enabled the development of heavy fuel engines that have the power density of gasoline engines.

The engines do have the extra cost of the PMS, but avoid the cost of high pressure fuel injection systems and the extra cost of the larger, heavier engine components of COTS diesel engines. Engines with D-STAR technologies can thus be actually <u>less expensive than COTS diesel engines</u>.