Challenges in Adapting State-of-the-Art On-Highway Diesel Engine Technologies To Meet Military Specifications

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ABSTRACT

State-of-the-art Diesel engines used for on-highway operation are integrated systems containing multiple subsystems for performance and emissions enhancements. The drive to lower tailpipe emissions on on-highway engines drives system complexity which is both undesired and unnecessary for military ground vehicles. There are, however, on-highway technologies such as high pressure fuel injection systems and advanced turbocharger systems that allow improving the engines' efficiency and therefore lowering its fuel consumption. The aforementioned technologies are currently available and present possible near term opportunities for military ground vehicles. The adaptation to allow reliable operation in military vehicles will be discussed as part of this near term view. The authors will also discuss the electronic controls architecture requirements that come along with these sophisticated technologies and discuss the advantages and opportunities that present themselves using advanced electronic controls for condition based maintenance and diagnostics.

INTRODUCTION

Lighter, more compact propulsion systems with higher power density without any negative robustness or maintenance consequence are sought after solutions for military vehicles.

Each of the three main levels of combat (strategic, operational and tactical) has its own distinct requirements, but share certain common denominators.

On the strategic level, equipment must be moved to the theater of operation via sea, air, rail or highway. In all described cases, the weight of the vehicles is considered a critical parameter as weight limitations are present for all four forms of movement. Specifically, the air and sea transport have placed additional constraints on footprint of the equipment to be transported.

On the operational aspect, the success of any combat mission hinges on the velocity of movement of the chosen maneuver. The speed is typically defined by the supply train as the main combat vehicles have the ability to move significantly faster through various terrains as compared to supply vehicles. The supply, of fuel, often becomes the bottleneck limiting the speed with which such maneuvers can be executed. This drives the desire for fuel efficient powertrains.

On the tactical level, the actual combat is executed and the propulsion system requirements vary depending on the location where the combat is executed. This can range from rough rocky terrain to sandy conditions to urban environment with concrete or asphalt roads. In all cases compactness of the combat vehicle and therefore the required powertrain can be defined as advantageous.

In summary, the ideal military powertrains for combat missions and peacetime operation are small, lightweight and fuel efficient.

COMMERCIAL VERSUS MILITARY DEMANDS

Functional requirements for military engines differ sharply from those of commercially available on-highway engines. While both applications require high reliability and fuel economy, there are the following differences:

- The overhaul frequency for military vehicles is set to 10,000 miles while the overhaul interval for a Class 8 truck is typically every 250,000 miles.
- Military vehicles average 1,000 miles per year in peacetime while commercial trucks can travel 250,000 miles per year.
- Military engines must have the ability to operate on JP8 as well as Diesel fuel. For emergency operation, short-term gasoline operation (albeit with limited performance and durability) is advantageous.
- Emissions compliance for military vehicles is typically limited to visible smoke, while commercial vehicles are subject to stringent emission regulations for all gaseous as well as PM emissions
- Maintenance and operation under extreme conditions is a firm requirement for military powerplants. Filtration for fuel and air have to endure significantly more severe boundary conditions than the commercial counterparts

(e.g. 200 hour maintenance free operation under zero visibility dust conditions with up to rated conditions)

- Cold start ability on JP8 as well as Diesel fuel needs to be ensured on military vehicles down to -50°C (with starting aids)
- Many military vehicles must be capable of fording up to 1.5 m depth with engine shutdown and restart.
- Shock and vibration under gun firing conditions can result in up to 60 g shock pulses which have to be endured by all components in the vehicle
- A military powertrain has to allow up to 60% sustained load operation at 40% side inclination

These demands pose a significant challenge on the design and packaging of these powertrains in military vehicles. In addition, the commercial platform's prime focus of reducing tailpipe emissions needs to be addressed.

AIR HANDLING SYSTEM

Figure 1 shows the layout of a conventional high pressure EGR system for an on-highway engine that is designed to assist the in-cylinder reduction of NOx emissions. These systems were introduced to comply with the 2004 heavy-duty emission standards which limited NOx emissions to 2.4 g/BHPhr.

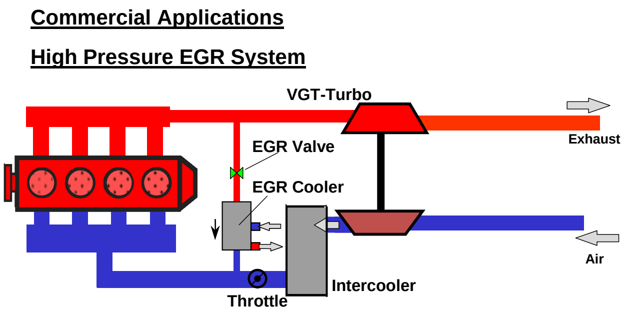


Figure 1: Commercial high pressure EGR system

Additional efforts to lower the engine-out emission levels, which in turn reduce the task of the aftertreatment system, result in the introduction of combined high- and low-pressure EGR systems. Such systems, which are currently in production on light-duty applications, have exhibited significant advantages in the heavy-duty area as well.

Figure 2 shows the schematic of such a system. Alterations on the EGR cooler design and the location of the valves are possible. Production examples show the EGR cooler removed from the high-pressure system and valve locations up- or downstream of the cooler.

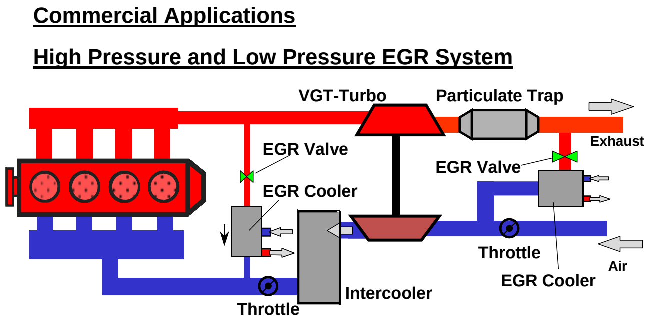


Figure 2: Combined high- and low-pressure EGR system

EGR AND BOOST PRESSURE CONTROLS

The systems described above have one challenge in common which is the simultaneous control of boost pressure and EGR. These two parameters counteract each other and result in an instable system if not governed with robust algorithms and calibrations.

Figure 3 illustrates one example of the EGR systems interaction with the EGR control and the resulting instability of the system if no countermeasures are taken.

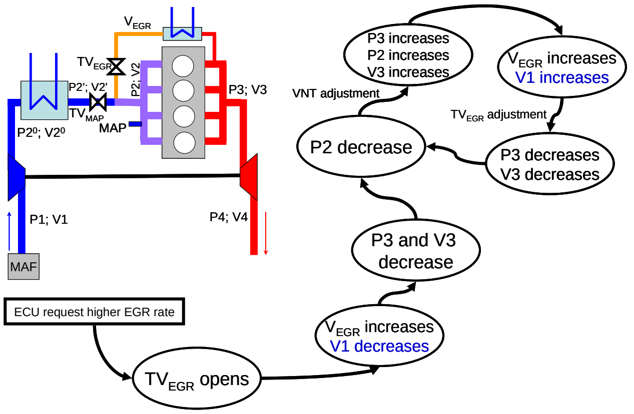


Figure 3: EGR and boost control

TURBO-MACHINERY MATCHING

The intuitive step to convert an on-highway engine to military use would be to remove the EGR system hardware from the engine. Unfortunately, it is not that easy as the turbo-machinery has to be matched to the overall system design. All subcomponents have to be matched to the pressure and flow characteristics of the complete system.

Figure 4 shows the comparison of two engines with comparable specific power outputs. Illustrated on the left side is the non-EGR version while the right side shows the EGR version of the engine. The overall pressure ratios increased with the introduction of EGR, this is due to the fact that the aim is to maintain the relative air fuel ratio at similar levels which in turn requires more air as a portion of the charge is displaced by exhaust gas. The pressure ratio on the compressor side is higher than the turbine side indicating the high efficiency of both components combined. The generation of boost pressure can be performed with lower resulting backpressure. This efficient characteristic complicates the introduction of EGR, which relies on a pressure drop between exhaust and intake manifold. The exhaust manifold pressure has to be higher than the intake manifold pressure to ensure that exhaust can be routed into the intake without the need for an intake air throttle. This reversal of pressure ratios results in efficiency losses of the turbo-machinery and consequently in an overall loss in engine efficiency.

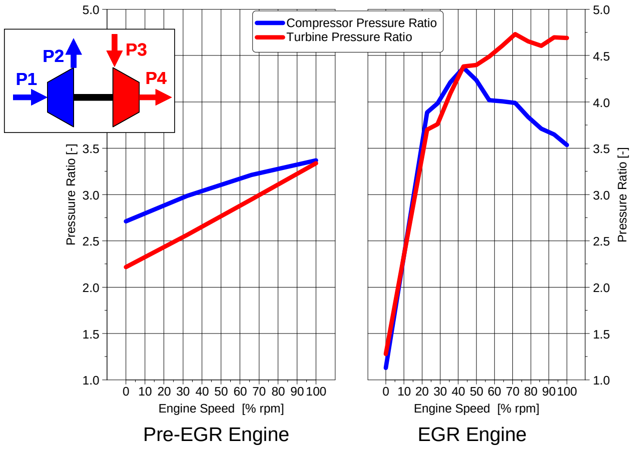


Figure 4: Boost and backpressure comparison

Figures 5 and 6 show how the turbine and the compressor were changed in order to allow EGR operation. In the transition towards EGR operation, the turbine size was reduced as indicated by the lower mass flow rate at the same pressure ratio.

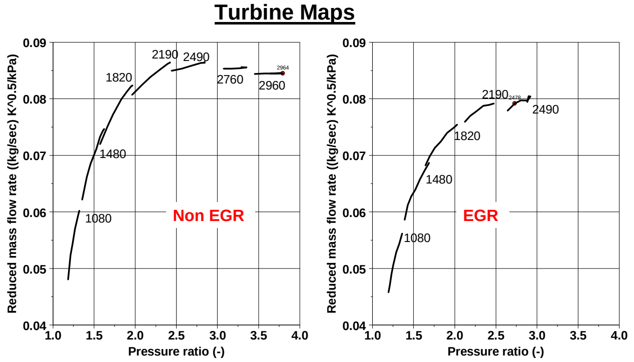


Figure 5: Turbine comparison

Concurrently, the compressor has to be adjusted for operation with EGR. The overall width of the map has to be increased in order to allow operation in a wider mass-flow-rate area. The surge line is moved to lower, the choke line to higher mass flow rates. This results in the consequence that the area of highest efficiency moves to lower compression ratios, resulting in comparably lower compressor effectiveness at higher compression ratios.

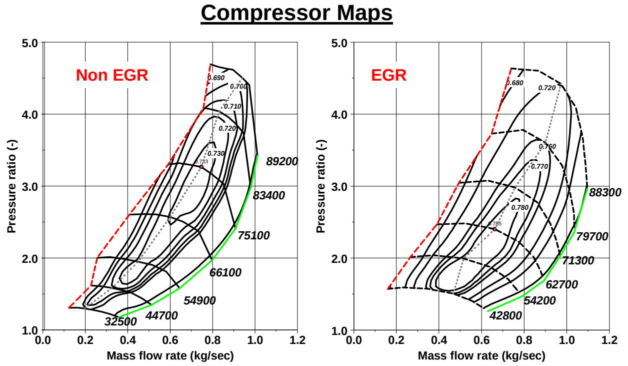


Figure 6: Compressor comparison

FUEL HANDLING SYSTEM

As previously described, the military requirements on the fuel injection system side are vastly different from commercial applications. The operation of varying grades of Diesel fuel, as well as the operation on JP8 has to be accounted for. The following table shows a comparison of these two fuels and highlights the differences which have some significance on the operation of the engine.

Table 1: Fuel property comparison

Properties	Unit	US Diesel	JP 8
Density @ 15°C	kg/l	~840	<800
Viscosity @ 40°C	mm²/s (cSt)	1.9 … 2.3	1.2 … 1.4
Cetane Number		42	53
Distillation			
10% Recovery	°C	180 max.	190
50% Recovery	°C	255 max.	200
90% Recovery	°C	315 max.	230
Heat of combustion	kJ/kg	42600	43100
Sulfur content	ppm	<15 ppm Ø<8 ppm	<3000 ppm Ø ~ 100 ppm
Cloud point	°C	-35	-49
Flash point	°C	38	63
Lubricity (HFRR)	µm	~500	>700

When choosing the fuel injection system for JP-8 operation, there are four significant differences from Diesel fuel that must be accounted for, including: density, viscosity, heating values, and lubricity. These differences can harm the high pressure generating part of a fuel injection system as these components are typically subject to the highest hertzian stress.

Figure 7 shows three commercially available fuel injection systems.

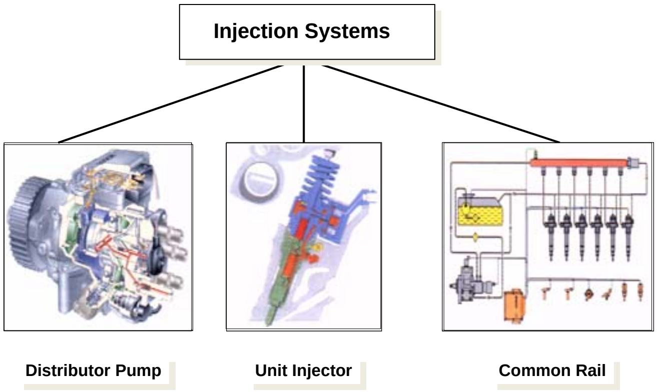


Figure 7: Fuel injection systems

The currently predominant fuel delivery system is the common-rail system. Many heavy-duty engines have migrated to this more flexible system from their originally mainstream unit pump systems. Common rail high pressure pumps, as well as the rail pressure control valve, are typically designed for operation with Diesel fuel. The corresponding materials as well as heat treatment choices typically do not consider the operation with low lubricity fuels such as JP8 or gasoline. Therefore, hardening of these components in a military JP-8 based engine becomes mandatory. This can be accomplished by redesigning of the subcomponents such as the high pressure fuel pump which can be integrated into the engine lubrication system. This however can result in oil to fuel introduction and the corresponding consequences on combustion such as higher sulfate emissions (H2SO4 formation) and higher PM. The authors of this paper have researched the impact of high lubrication levels (up to 30%) in the fuel on the combustion process and no military relevant negative impact was identified.

For on-road trucks, for all types of fuel injection system, the desire to increase fuel injection pressures remains strong. This is primarily motivated by the desire to reduce engine-out emissions with exhaust gas recirculation (EGR). The introduction of EGR results in the undesired increase in soot formation which can to some extent be reversed through the increase in injection pressure. Figure 8 shows the evolution of injection pressures over the past two decades. The trend to increase these fuel injection pressures remains unchanged.

For military applications the need for increased high pressure systems can result in increased specific power output. Such fuel delivery systems can provide increased amounts of fuel for the same pulse width of the injector. Higher fuel injection pressures also result in lower exhaust gas temperatures especially under full load operation, therefore protecting the components such as the turbocharger, but also reducing the thermal signature of the vehicle.

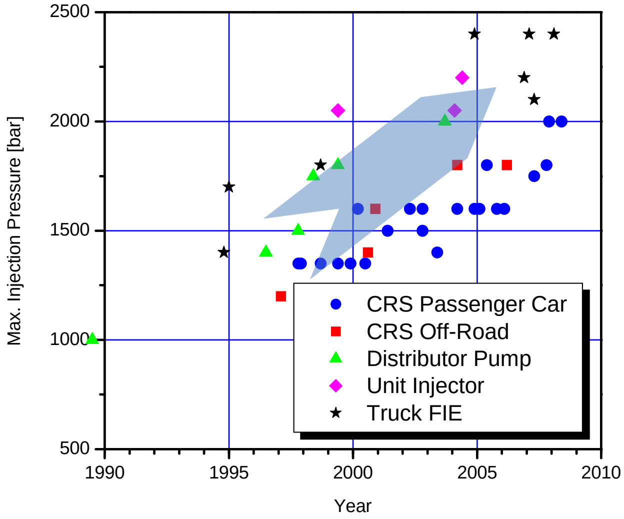


Figure 8: Injection pressure development

Considering the physical and chemical properties of JP8, the following conclusions can be made:

- Density as well as viscosity of JP8 is lower compared to Diesel
    - Injected volume is higher (higher flow velocity in the spray hole)
    - Friction in the spray hole is lower
    - Lubrication is poor (especially in the pump drive)
- The amount of Cyclo-paraffines and Aromatics in JP8 is relatively high
    - Cyclo-paraffines and aromatics have a higher density compared to paraffines, the viscosity is comparable
    - Cyclo-paraffines and aromatics have a low cetane number
- The self ignition behavior of aromatics and cyclo-paraffines is worse compared to iso-paraffines or n-paraffines
- The cloud point of n-paraffines (especially with a high number of carbons) is significantly higher compared to aromatics and poly-paraffines

Figure 9 shows two full load runs on the same engine, one with DF-2 and one with JP8. The engine calibration remained unchanged for both tests. Please note from the full load plot that the torque is similar and over the largest portion of the engine speed noticeably higher despite the lower injected fuel mass (as function of JP8's lower density). The combination of lower injected fuel quantity and equal or slightly higher torque results in improved specific fuel consumption which accounts for approximately 4% advantage operating on JP8 over DF-2. The performance and emissions calibration was not altered, therefore the pulse width for the fuel injectors remained the same for both tests. The conclusion can be made that other properties such as the 10 points higher cetane number contributed to higher combustion efficiency, resulting in higher torque output. This fact is corroborated by the continuously lower smoke numbers when operating the engine on JP8.

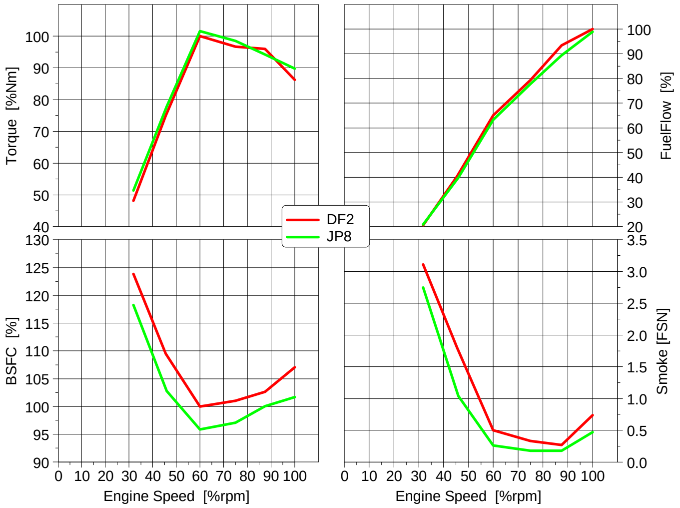


Figure 9: Full load comparison DF and JP8

EMISSION CONTROL SYSTEMS

The use of advanced emission control systems, including highly efficient exhaust gas aftertreatment systems, becomes mandatory with the introduction of MY 2010 heavy-duty engines. Figure 10 shows the schematic of a DPF SCR system designed for heavy-duty applications. In addition to the hardware complexity, these systems require significant effort in calibrating each of the aftertreatment components to allow the highest possible effectiveness and robust operation over the vehicles' lifetime.

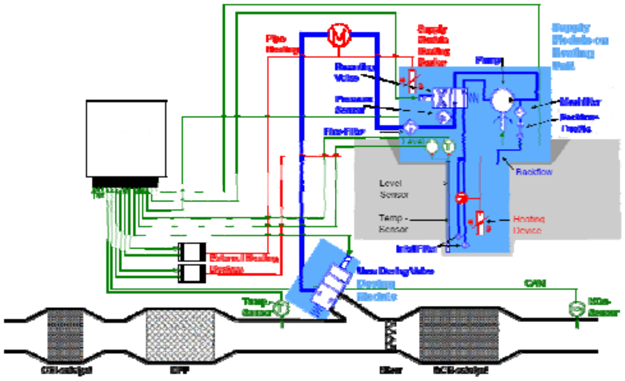


Figure 10: DPF / SCR emission control system

In the military world, this additional complexity is not only undesirable, but can potentially endanger the vehicle and its occupants due to some required intervention necessary to maintain the aftertreatment systems integrity (e.g. DPF regeneration). The removal process of such integrated emission control system is another challenge as the controls are typically deeply integrated in the engine management system and do not allow easy and fast removal through calibration.

ELECTRONIC CONTROLS

Electronic controls have become an integral part of modern powertrain systems. What originated as an enabler for faster actuation and reaction to changes in boundary conditions has evolved into a highly complex integrated system. Electronic controls are not only responsible for the engine operating functions, but also must serve as data interface to other vehicle subsystems such as vehicle and transmission, diagnostic handler, and the control of the exhaust aftertreatment devices. The exhaust aftertreatment system alone is quite complex, ranging from Diesel Particle Filters (DPF), through NOx treatment systems, such as SCR or NOx adsorber.

Further complicating matters, the electronic controls are integrated in the base engine management system and cannot be removed or 'dead-calibrated' in an easy way. The removal process for any subsystems usually causes undesired system reactions such as limp-home operation of the engine. With the introduction of government mandated on board diagnostics, the diagnostic portion of the software now represents the largest portion in terms of overall software size as well as calibration effort specifically with the introduction of diagnostic systems with increased level of stringency such as the HD-OBD.

In addition to the already complex engine controls, the overall vehicle controller architecture as it is designed in current vehicles allows each controller to use the diagnostic port for reporting, as shown in Figure 11.

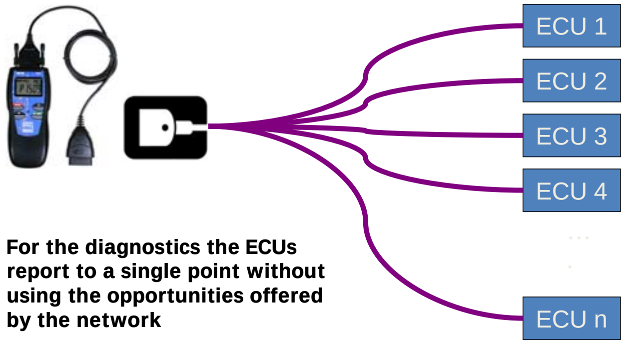


Figure 11: State-of-the-art diagnostic system layout

CAN and other bus networks allow the transfer of information and other data amongst multiple ECU's. This allows the efficient use of sensors within this network. The disadvantage of such a system is the spread of fault codes within the network once a sensor fails or starts broadcasting false information. In Figure 12 an example with a fault detection in one ECU is shown. The sensor or actuator which is used by four other control units but has its primary function in ECU #8 will cause failure messages to be generated by all ECU's that utilize this signal (example: vehicle speed sensor used by ABS system, suspension controller, cruise control, and entertainment system).

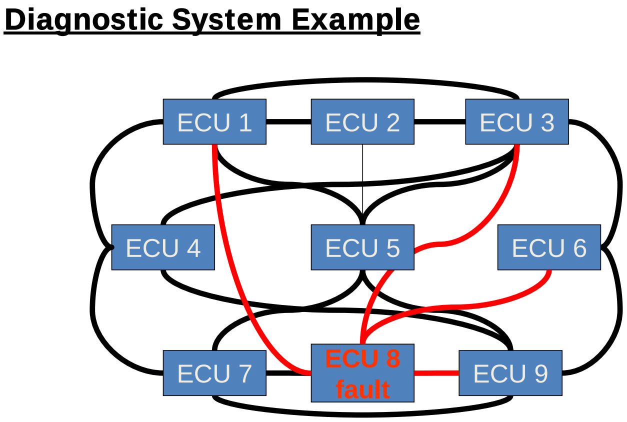
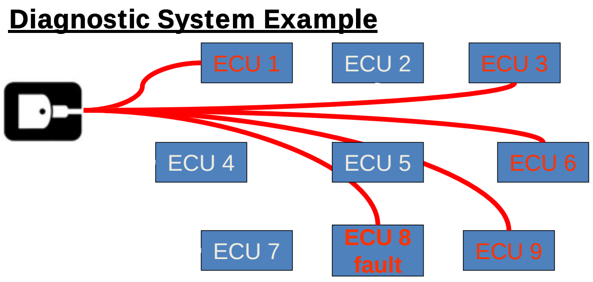


Figure 12: ECU network with fault 1

The result is that the diagnostic tool receives five messages reporting the same fault code as shown in Figure 13.



When e.g. the wheel speed sensor doesn't work, also the functions which need its output as an input, will report a fault.

Thereby multiple errors are reported and as result it might get even difficult to recognize where the fault results from.

Figure 13: ECU network with fault 2

In order to reduce the necessary trouble-shooting time, an alternative is proposed that combine the subsystems in meaningful groups with a master unit coordinating and reporting trouble codes. This alternative system is displayed in Figure 14. As the complexity of powertrain and its subsystems increases, the consolidation of control systems to subgroups will allow faster maintenance and troubleshooting, thus increasing uptime of the vehicle. The relevance of grouping systems has to be evaluated very carefully with specific view on the overall system architecture. Combining modules that are using the same signals may not always be the ideal combination and result in a similarly fragmented system.

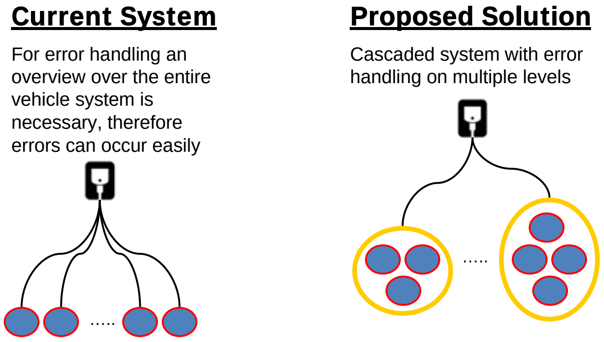


Figure 14: Proposed alternative network

In addition to the diagnostic system clean-up, an advanced variant handler can enable one base software and calibration to handle numerous hardware configurations. Each hardware configuration is directly tied to a variant calibration within the software and can be selected through a switch after start of the controller. Such a setup is more demanding on the controller hardware as it requires more memory and processing power, but it limits the overall amount of different electronic hardware components and corresponding part-numbers, diagnostic devices, etc. An example is shown in Figure 15.

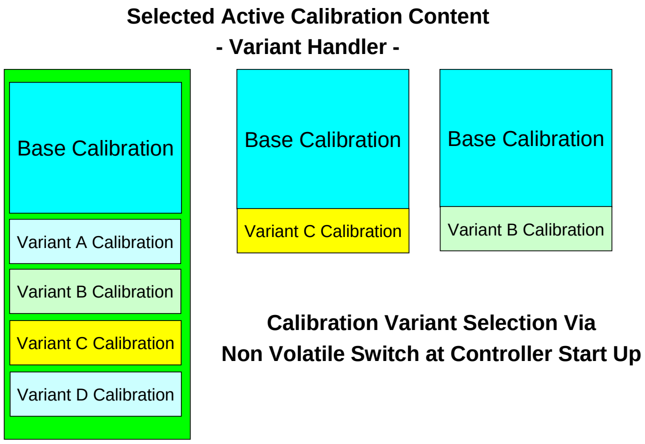


Figure 15: Variant handler 1

The variant handler also has to contain software configurations that allow the enabling or disabling of certain sub modules. Figure 16 shows this setup with four sub-modules (the amount of sub-modules is not limited by the software). Software switches allow the activation or deactivation of certain modules. In the example of an advanced heavy-duty engine, such software would facilitate faster and safe disablement of the aftertreatment software, including its diagnostics, than with the current state-of-the-art software architectures which are defined by highly integrated sub-systems.

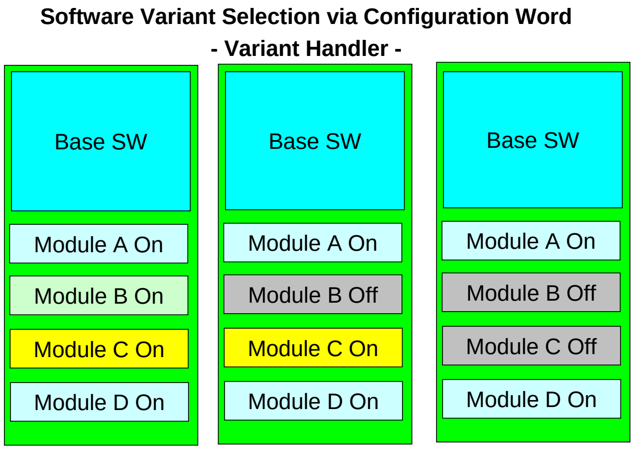


Figure 16: Variant handler 2

In the effort to realize the aforementioned software functions, FEV developed a flexible controller system that contains the described functions. This controller originated as an exhaust aftertreatment controller, but was continuously developed to a more versatile tool that allows performing significantly more actions to be performed beyond the aftertreatment portion itself. Figure 17 shows the high level functions of the controller.

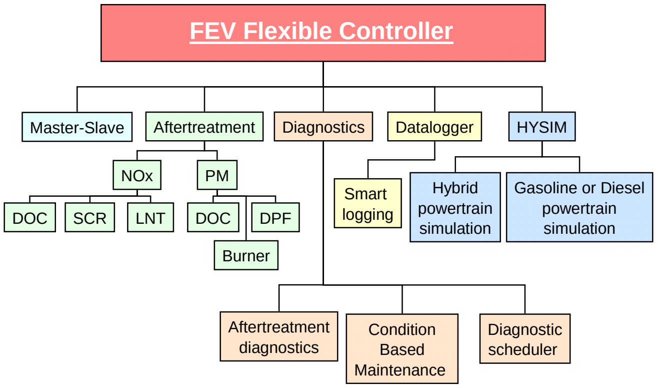


Figure 17: FEV flexible controller

All displayed functions were tested in various applications on Infineon's TriCore 1796 as well as Motorola's MPC5554 processors and control boards.

ADAPTATIONS TO MILITARY SPECIFICATIONS

Figure 18 compares the main aspects of the propulsion system for commercial and military applications. Two main categories are identified; the left side represents the cost of ownership, which defines the daily expenses subsequent to the procurement of the vehicle and the right side represents the development cost items. The nine sub-categories listed are weighted based on their importance for either of the applications, the closer to the periphery, the more important the corresponding criterion.

It becomes evident from this graph that for both main categories the demands deviate in virtually all points when comparing military and commercial requirements. While on the development side a lot of focus has to be spent to develop the militarized version, the items driving cost of ownership show trends towards greater importance for the commercial applications.

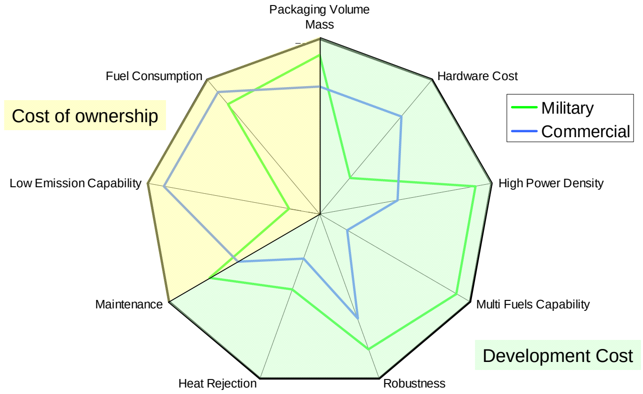


Figure 18: Weighing of military versus commercial specs

In order to adapt a heavy-duty on road engine to comply with military specifications and demands, changes to each of the discussed components have to be conducted.

The air handling system has to account for non-EGR operation which will require a complete redesign of the turbo-machinery. Both the turbine and the compressor will need to be adapted to the changed boundary conditions. This mandatory change will ultimately result in an increase in efficiency.

The fuel injection system has to account for low lubricity and high HFRR fuel operation. This can be accomplished with lubricity enhancing fuel additives, or alternatively, engine oil system lubricated high pressure pumps need to be considered in the system layout.

All changes made to the hardware on the air as well as the fuel handling side need to be accompanied by the corresponding redesign of the software as well as the necessary re-calibration of the systems. A variant handler as described in the Chapter ELECTONIC CONTOLS can accelerate this process significantly. All electronic controls software has to have a significant level of redundancy exceeding SIL 4, or possibly similar structures as in the aerospace industry which contain triple redundancies. Hardware commonality between control modules, as a result of the consequent use of the variant handler allows easier and faster system troubleshooting and has the potential to increase uptime of equipment.

Adapting a commercial engine through the measures described above may still not meet all the requirements such as highest possible power density. Figure 19 shows the limiting factors that define an engines peak power output level.

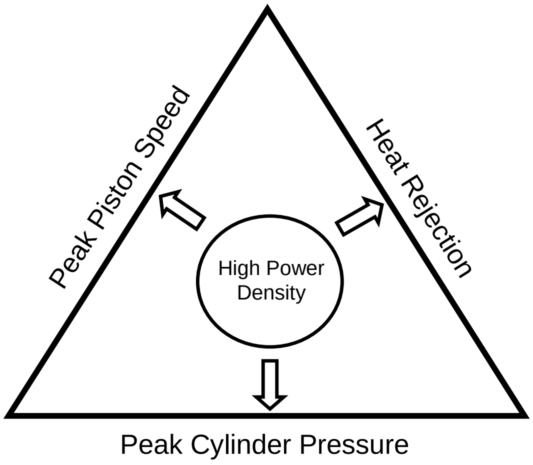


Figure 19: High power density limitations

In Figure 20 the limits are quantified and possible solutions are suggested. As the mean piston speed cannot exceed specific limits, which ultimately define the engine speed one possible solution is to increase the amount of working cycles generating power. Either two stroke engines or the concept of the 4 / 2 stroke engine could become feasible. This alternative concept will be discussed in the following chapter. The cylinder peak pressure is typically limited through the cylinder head, head gasket, piston, etc. The current state-of-the-art peak pressure maxima range up to 220 bar in mass production, with a few exceptions running higher numbers for performance applications. The heat rejection which is defined by the amount thermal energy that needs to be extracted from the coolant in order to operate the engine under safe and part protected conditions. In addition the overall heat rejection has to account for the thermal energy extracted out of the compressed air downstream the turbocharger and in the case of engines that use cooled EGR also the heat from the EGR cooler. The sum of these three heat sources can be up to 35% of the power at rated conditions. The elimination of the EGR allows a reduction in the radiated heat load through the cooler and also allows through the adaptation of the boosting system a reduction in heat rejection from the intercooler as the pressure ratios can be reduced. The only remaining option to reduce heat rejection is to allow higher operating temperatures of the engine. This can result in increased thermal stress of base engine components and must be evaluated carefully. Materials used for the cylinder-head, crank-case and piston will likely require modification to allow additional heat load.

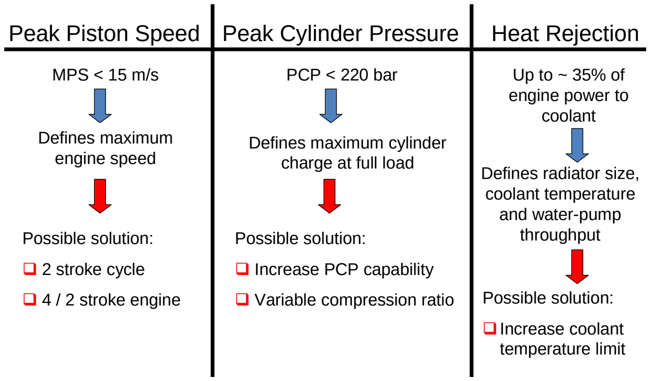


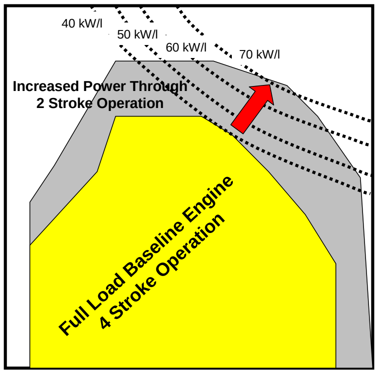
Figure 20: Possible high power density solutions

ENGINE DESIGN ALTERNATIVES

In the previous chapter solutions for increased power output were discussed. One solution that maintains superior fuel economy under part load conditions and provides superior power levels at full load is a concept that combines the 4 stroke and the 2 stroke concept. Figure 21 shows the engine operating range of conventional 4 stroke heavy duty Diesel engines and superimposes an area that can be achieved using the 2 stroke approach. Depending on the base engine power level, considerable increase in peak power can be achieved with this concept.

The requirements to successfully operate an engine under both combustion concepts heavily rely on several enabling technologies:

- A fully variable valvetrain that allows fast and seamless transition between conventional 4 stroke mode to 2 stroke operation. This valvetrain has to provide the ability to open both intake as well as exhaust valves simultaneously for scavenging.
- Multiple stage boosting system allowing highest possible scavenging efficiencies. As the scavenging relies on the pressure drop between intake and exhaust valve a supercharger that does not contribute to a pressure increase on the exhaust side should be the preferred solution.
- The fuel injection system has to be able to double the injection events in 2 stroke mode.
- A variable compression ratio mechanism allowing higher specific power outputs without violating peak cylinder pressure limitations.
- All of the aforementioned features have to be monitored and tightly controlled through sophisticated control algorithms allowing fast and seamless transitions between the two different operating modes.



Main Design features:

- ☐ Increased boost capability through 2 stages
- ☐ Combination turbo- and supercharger allowing 2 stroke operation
- ☐ Flexible injection system
- ☐ Hydraulically actuated variable valvetrain
- ☐ Variable compression ratio (fully variable or 2 step)

Figure 21: 2 / 4 stroke engine features

Figure 22 shows an example of a heavy-duty connecting rod that was tested on a 10 l class engine for an extended amount of time. This design features a switching mechanism that allows operation at two distinct compression ratios. The hardware example shown was designed to run at compression ratios of 14 or 17. The transition between these compression ratios takes on the order of 1.5 to 2.5 seconds and is dependent on the engine speed. Aside from the switching mechanism for the shuttle valve which is located at the bottom of the connecting rod no other base engine modifications are required to operate this device. The advantage of being able to switch between high and low compression ratio allows increased power output levels without violating peak-cylinder pressure limitations and retaining the fuel consumption benefits and cold start ability that are inherent with high compression ratios.

- ☐ Bore diameter: 125 mm
- ☐ Protected for peak firing pressure: 180 bar
- ☐ CR range: 14 – 17
- ☐ Eccentricity: 4 mm
- ☐ Piston and piston pin carry over from base engine
- ☐ Mechanical switch with 3/2 way valve integrated in conrod lower part

Figure 22: 2 step VCR

CONCLUSIONS

The authors of this paper presented possibilities to adapt commercial state-of-the-art heavy-duty Diesel engines to operate under military conditions. The changes that are required to transform an on-highway engine designed to meet stringent emission standards while retaining high fuel economy by far exceeds the effort required to remove the emission control components. The inherently integrated nature of commercial engine subsystems poses a significant but not insurmountable challenge when attempting to transfer to a military application. In order to obtain the best possible result it is however required to approach each subsystem individually and assess their interaction independently. Simply removing or adapting certain components without proper engineering will inevitably result in a package that will require compromises from the end-user.

The implementation of advanced technologies specifically targeted towards higher power output is best suited for a ground up development effort rather than a retrofit installation in an existing platform.

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