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COMMON BORE ENGINE PHILOSOPHY FOR FUTURE POWER-PACK CONFIGURATIONS

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ABSTRACT

This paper discusses the packaging characteristics of a family of power-packs for military land vehicles in the 21st century. 3 classes of vehicles are considered: light vehicles (300 - 600 Hp), medium weight vehicles (600-1000 Hp) and heavy vehicles (1000-1500 Hp).

The paper highlights that a common bore engine approach provides both very good performance and a very compact power-pack. 2 different engine styles are examined. The results are expected to be applicable for a spectrum of modernized engine platforms that would employ a common bore engine approach.

The approach offers many product development and production advantages, including lower development and tooling costs, and reduced product inventory needs, lead times, development costs, in addition to reduced product development risk. Various trade study parameters are considered in addition to engine power.

Power-pack configurations based on a common bore approach shows significant commonality advantages and manufacturing efficiencies across the future family of engines horsepower classes. The common bore engine approach also demonstrates that a significant reduction in power-pack space claim can be achieved, while still retaining all of the development, production, and, maintenance advantages
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INTRODUCTION

The US Army Tank Automotive Research, Development, and Engineering Center (TARDEC) has expressed the desire to develop an engine 'family' that would be suitable across the range of tracked military vehicles, ranging from 300 – 1500+ Hp regime[1].

The perceived advantages of a common engine family are reduced product development cost and time. A common engine family would also have reduced life cycle costs after production owing to commonality in spare parts, maintenance and repair tools, training and repair procedures.

A challenge with executing the concept is identifying the critical features of an engine that would optimize the advantages of a common engine family without significantly compromising the potential disadvantage of instituting a common engine family philosophy – performance and packaging.

In this investigation, a review of the performance characteristics of a common bore engine for military applications is presented, along with identifying packaging sensitivities and other critical parameters. The investigation was performed with 2 different engine types for exemplary purposes, but would be applicable for any engine type.

For investigative purposes, the application of the family of engines for military vehicle applications was divided into 3 different categories:

- Light vehicles in the approximate range of a 300-600 Hp engine class.
- Medium weight vehicles in the approximate range of a 600 – 1000 Hp engine class
- Heavy weight vehicles in the approximate range of a 1000-1500 Hp engine classification

In this analysis of a common family of engines, various considerations are necessary in order to determine the relative merit of the concept. These are:

- Resultant Power-pack Density Using a Common Engine Bore Approach. This is a critical consideration for military vehicle applications. Certainly, independently designed engines offer the promise of higher performance – the issue is the extent of the advantage and the added life cycle cost burden associated with an independently designed engine
- Engine Life Cycle Cost, including:
    - Development Advantages
    - Production Advantages
    - Maintenance and Repair Advantages

These items are addressed in detail in this investigation. Variables in the investigation include engine type, engine bore size, and vehicle size. For consistency, the predictive techniques used to determine performance were consistent with prior investigations [2].

ANALYSIS

Analytic calculations were performed for estimation of power-pack density and life cycle cost differences. Each will be discussed in detail in the section to follow.

Power-pack Density

Power-pack density (Hp/Volume) is a critical parameter in military vehicle applications. In order to determine power-pack density, the following items are needed:

- Engine volume
- Transmission volume
- Fuel tank and delivery system volume
- Exhaust system volume
- Cooling system volume
- Air induction and filtration system volume
- Battery volume
- Final drive volume
- Miscellaneous volumes
- Control System Volume
- Unused space

For the purposes of this analysis, the following assumptions are made regarding the power-pack components, as outlined in Table 1. The reference document identified in Table 1 was cited previously [2].

Table 1. Technique Used to Predict Power-pack Volume

Power-pack Item	Volume Prediction Method	Comments
Engine	Computer Aided Design	. Shrink wrap or estimate of height, width, length technique used for calculating volumes (instead of dunk volume)
Transmission	Curve fit (from 20 to 60 tons)	Similar to reasoning applied in reference document
Cooling System	Based off of fielded engine performance in a military platform.	120 F cooling requirement. Includes volume for fan drive system.
Air filtration system volume	2.6 ft3/ (lbm/sec) of combustion air intake flow	Similar to reasoning applied in reference document. Installed power loss assumed to be 3.3 % of engine gross power
Inlet and exhaust System volume	0.546 ft3/(lbm/sec) of combustion air intake flow	Procedure as recommended in reference document
Battery volume	0.12 ft3 battery/ft3 of engine	Rounded up to nearest 2 ft3 in final analysis to represent discrete battery numbers.
Control System Volume	1 ft3	Common family will likely use identical controllers. Consistent with reasoning used in reference document
Powerpack wiring volume	1 ft3	Consistent with reasoning in reference document
Fuel tanks and fuel delivery system	60 sprocket horsepower hours per ton of vehicle weight	Other variables and procedures as described in reference document
Misc. Volume	0 ft3	Typically small number. Also, very application specific
Final Drive Volume	0.065 ft3/ton of vehicle weight	Similar to procedure applied in reference document.
Clearance and Unusable Volume	9 % of total volume	Very application specific. Similar percentages obtained in reference document.

Efficiencies and Power requirements were determined as follows:

- Transmission Efficiency = 80 %
- Final Drive Efficiency: 98.5 %
- Fan Power Requirements: As required to meet 120 F cooling point. Internal and exhaust grille pressure drops based on experience with military platforms.

An additional assumption performed in the packaging analysis is that the engine power design point is equal to 25 Hp/ton of vehicle weight.

Using the above techniques, the methodology was compared to the results using the AIPS engine[2]. Predicted power-pack volume, sprocket power, and power-pack density were all within 0.4 % of published values (using published engine and cooling system volumes), indicating that the model was accurately created.

The model was then compared to a 7L 2 stroke engine examined in the same investigation. In this case, the predictions were within 1.6 % of published values. This indicates the accuracy of the model in being extended to other platforms.

Engine Variants:

Multiple engine configurations were reviewed and considered for the analysis. For this initial investigation, two different basic engine configurations were down-selected and examined in this study (an OPOC and a Boxer style engine). It is expected that many of the conclusions of the investigation would be largely insensitive to the engine style used (e.g., OPOC, OP, Boxer, V, I, etc.), as discussed later. Configurations examined were:

1.) An opposed piston opposed cylinder (OPOC) engine. For this configuration, various engine bore diameters (116 and 146 mm) were examined to determine the sensitivity of bore size to overall packaging size.The following engine design items were held constant:
    - Peak cylinder pressure: 210 bar
    - Mean piston speed: 13 m/sec
2.) A conventional boxer (Boxer) style engine with a 146 mm bore. In this configuration, the following parameters were fixed:
    - Bore/stroke ratio: 1:1
    - Maximum Power/cylinder: 150 Hp

    It should be noted that in this investigation the engine configuration was set to be ‘Boxer’ style in nature. Depending on the particular application, a V-style engine may be more efficient at reducing the ‘unusable volume’ and have other development and performance advantages.

A review of the cylinder heat transfer characteristics indicated that oil combined with air cooling was expected to be adequate for all configurations, allowing one to take advantage of the added increased temperature capabilities of the cooling medium and the resultant increased power density. While the ultimate cooling scheme may involve water cooled cylinders instead, the important aspect for this investigation was to maintain consistency – the optimal cylinder cooling scheme is not expected to be vehicle size dependant but rather dependant on the engine design and packaging characteristics.

The following engine trade study cases were analyzed:

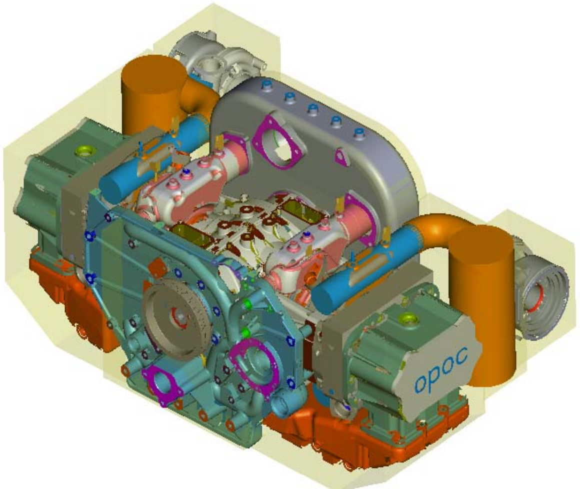
Table 2. Engine Configurations Examined

Case #	Engine Hp	Engine style	Engine Bore Size
1a	500	OPOC	116
1b	600	Boxer	146
2a	1000	OPOC	116
2c	900	Boxer	146
3a	1500	OPOC	116
3b	1500	OPOC	146
3c	1500	Boxer	146

Power-pack Packaging Results

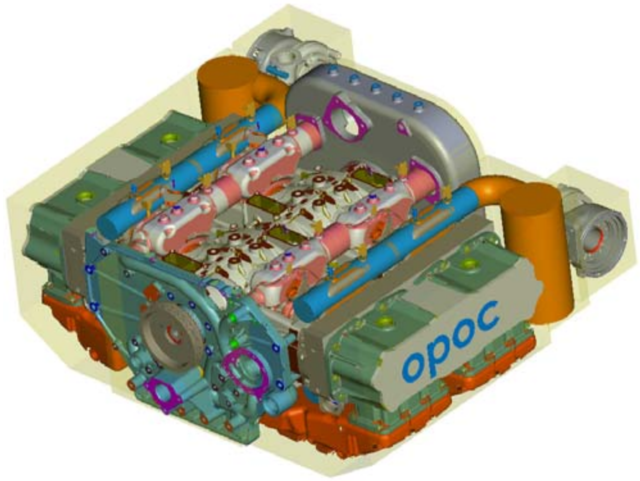
A pictorial summary of several conceptual engine solutions is shown in Figures 1 – 7 below, including a applied packaging concept for use in a military vehicle.

For the purposes of this investigation, engine volumes were predicted using the shrink-wrapped region technique for the Boxer engine. In the case of the OPOC engine, volume calculations were predicted using approximate length width and height calculations. A sample check indicated that the 2 differing procedures were within 7 % of each other.



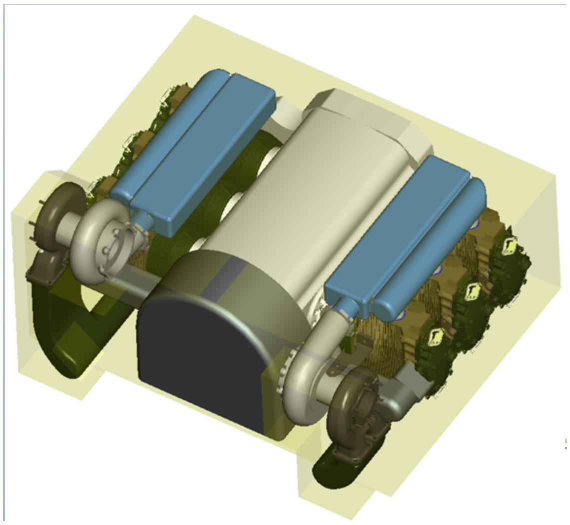
Engine Volume (L/ft3)
416 / 14.69

Figure 1. Case #1a. OPOC Engine (116 mm bore) 1 module - 500 Hp



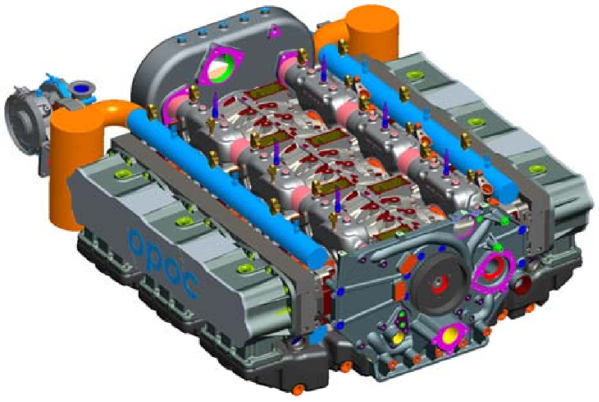
Engine Volume (L/ft3)
688 / 24.30

Figure 2. Case #2a. OPOC Engine (116 mm bore). 2 modules - 1000 Hp



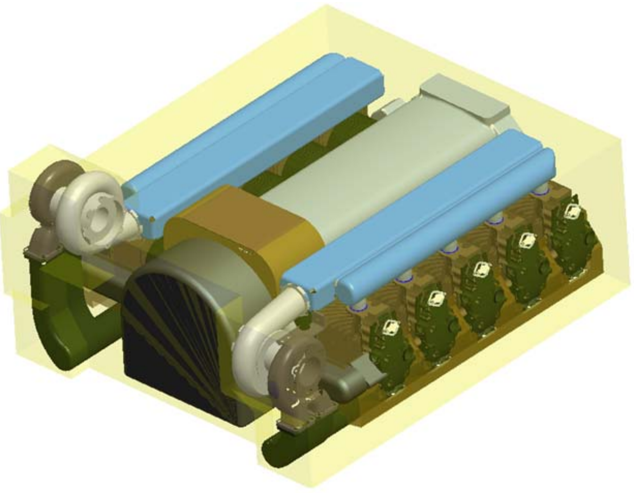
Engine Volume (L/ft3)
1036 / 36.6

Figure 3. Case #2c. Boxer Engine 146 mm bore. 900 Hp



Engine Volume (L/ft3)
961 / 33.9

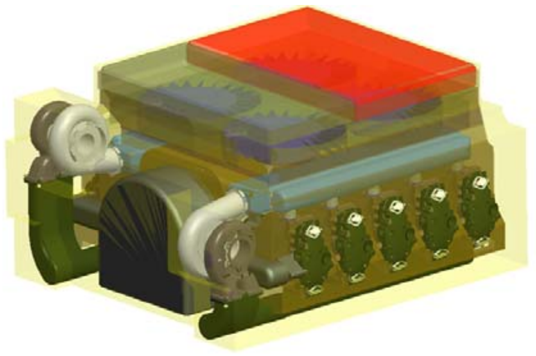
Figure 4. Case #3a. OPOC Engine (116 mm bore). 1500 Hp



Engine Volume (L / ft3)
1450 / 51.2

Figure 5. Case #3c. Boxer Engine (146 mm bore). 1500 Hp

An example of an engine with an adequately designed cooling system (packaged within a ‘typical’ engine bay volume) is illustrated in Figure 6 and 7 below. As described previously, cooling system sizing was based on prior experience with military platforms. The system was packaged with 4 direct drive fans. Depending on packaging and performance constraints and requirements, alternative cooling systems may be advantageous.



Engine + Cooling System Volume (L/ft3)
1652 / 58.3

Figure 6. Ten Cylinder Boxer Engine with Complete Cooling Package (except cooling air exhaust ducting).

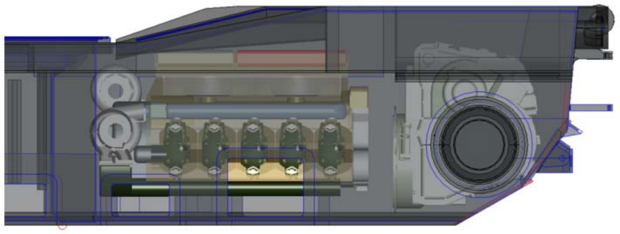


Figure 7. Boxer engine packaged inside a representative heavy weight vehicle platform.

Power-pack Density Results Summary

Using the methodology described above, power-pack densities were predicted for the 3 different vehicle weight classes and 2 different engine styles. OPOC engine performance was predicted at 2 different bore sizes for the heavy vehicle application.

Detailed results are presented in Tables 3-5 below. In order to enable ease of comparison, engine power and volume requirement values were standardized into 500, 1000, and 1500 Hp categories. Volumes and Hp Losses were based on the standardized values.

Table 3. Volume and Power Calculations for a Light Weight Vehicle (20 tons)

Engine Style	**OPOC**	**Boxer**
Engine Bore Size (mm)	116.0	146.0
Engine Power (Gross Hp)	500.0	600.0
Standardized Power (Hp)	500.0	500.0
Fan Power (Hp)	23.0	45.8
Transmission/Final Drive Train Efficiency	0.785	0.785
Intake and Exit Losses (Hp)	16.7	16.7
Engine Volume (ft3)	14.7	21.2
Transmission Volume (ft3)	13.0	13.0
Cooling System Volume (ft3)	8.6	7.1
Air Induction System Volume (ft3)	2.6	3.6
Inlet & Exhaust System Volume (ft3)	0.5	0.8
Battery Volume (ft3)	2.0	4.0
Control System Volume (ft3)	1.0	1.0
Powerpack Wiring Volume (ft3)	1.0	1.0
Fuel System (ft3)	13.2	17.9
Final Drive Volume (ft3)	1.3	1.3
Clearance and Unusable Volume (ft3)	5.5	5.6
Total Volume (ft3)	63.4	77.6
Sprocket Horsepower	361.4	343.5
Power Density { sprocket Hp/volume(ft3) }	**5.7**	**4.4**

Table 4. Volume and Power Calculations for a Medium Weight Vehicle (40 tons)

Engine Style	**OPOC**	**Boxer**
Engine Bore Size (mm)	116	146
Engine Horse Power (Gross)	1000	900
Standardized Engine Power (Hp)	1000	1000
Fan Power (Hp)	45.0	113.3
Transmission/Final Drive Train Efficiency	0.785	0.785
Intake and Exit Losses (Hp)	33.3	33.3
Engine Volume (ft3)	24.3	36.6
Transmission Volume (ft3)	24.6	24.6
Cooling System Volume (ft3)	13.8	13.6
Air Induction System Volume (ft3)	6.4	7.3
Inlet and Exhaust System Volume (ft3)	1.3	1.7
Battery Volume (ft3)	4.0	6.0
Control System Volume (ft3)	1.0	1.0
Powerpack Wiring Volume (ft3)	1.0	1.0

Fuel System Volume (ft3)	26.0	28.2
Final Drive Volume (ft3)	2.6	2.6
Clearance and Unusable Volume (ft3)	10.0	11.7

Total Volume (ft3)	115.1	134.4
Sprocket Horsepower	723.5	669.9

Power Density{sprocket Hp/volume(ft3)}	**6.3**	**5.0**

Table 5. Volume and Power Calculations for a Heavy Weight Vehicle (60 tons)

Engine Style	**OPOC**	**OPOC**	**Boxer**
Engine Bore Size (mm)	116	146	146
Engine Horse Power (Gross)	1500	1500	1500
Fan Power (Hp)	90.0	90.0	176.0
Transmission/Final Drive Train Efficiency	0.785	0.785	0.785
Intake and Exit Losses (Hp)	50.0	50.0	50.0
Engine Volume (ft3)	33.9	51.8	51.2
Transmission Volume (ft3)	34.9	34.9	34.9
Cooling System Volume (ft3)	21.6	21.6	18.5
Air Induction System Volume (ft3)	7.8	7.8	11.0
Inlet and Exhaust System Volume (ft3)	1.6	1.6	2.3
Battery Volume (ft3)	6.0	8.0	8.0
Control System Volume (ft3)	1.0	1.0	1.0
Powerpack Wiring Volume (ft3)	1.0	1.0	1.0
Fuel System Volume (ft3)	39.4	39.4	46.3
Final Drive Volume (ft3)	3.9	3.9	3.9
Clearance and Unusable Volume (ft3)	14.4	16.3	17.0

Total Volume (ft3)	165.6	187.4	195.1
Sprocket Horsepower	1068	1068	1000

Power Density{sprocket Hp/volume(ft3)}	**6.4**	**5.7**	**5.1**

A comparison of power-pack density with respect to engine size (vehicle weight) is shown in Figure 7 below. In Figure 8, the same data is translated and presented with respect to engine bore diameter.

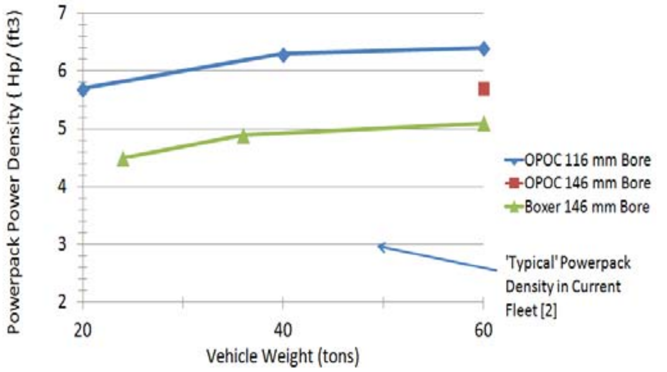


Figure 7. Comparison of power-pack density for various vehicle weights and engine configurations.

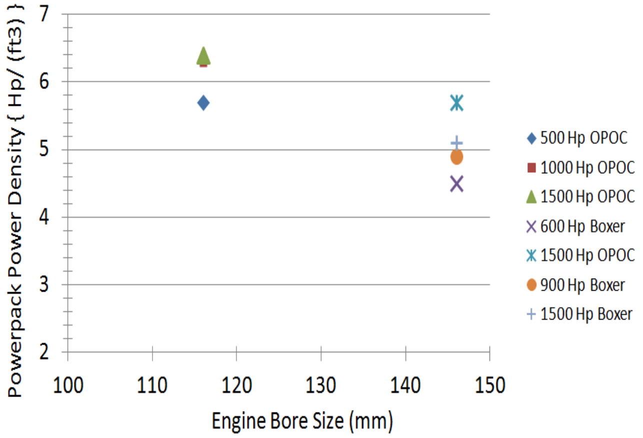


Figure 8. Impact of Bore Diameter to Power-pack Power Density

Review of Tables 3-5 and Figures 7 and 8 point out several key points:

- All engine concepts offer significantly higher power-pack densities than typically exists in the current military fleet (see Figure 7). The improvement in power density is in the range of 50 – 100 % + better than what currently exists.
- For the same size cylinder bore (146 mm), an OPOC engine has a modest advantage compared to a more conventional boxer engine (see Tables 4-5 and Figure 7). In order to take full advantage of the higher power densities of the OPOC engine in the horsepower regime of interest, bore size for the OPOC engine should be smaller.
- A smaller bore OPOC engine (116 mm) indicates a packaging advantage over the larger diameter

146 mm bore engines (see Figure 12), with an approximate increase in power-pack power density of more than 10 %.

- A review of the trends in Figure 7 suggest that the relative advantages of the 116 mm OPOC engine compared to the 146 mm Boxer style engine remain relatively constant throughout the vehicle weight class regime. This aspect is examined in more detail in Table 6 below. Here it is seen that the packaging benefits remain essentially constant throughout the regime of interest, suggesting that optimum engine bore and engine style, while being important considerations, they have little sensitivity to engine horsepower throughout the regime of interest.

Table 6. Comparison of Power-pack Densities for Different Engine Styles and Bore Sizes

Hp	OPOC 116 mm	Boxer 146 mm	Ratio
500	5.7	4.4	1.30
1000	6.3	5.0	1.26
1500	6.4	5.1	1.25

Common Bore Life Cycle Benefits

The major advantage of a common bore engine design philosophy is the life cycle cost advantage –

- Reduced development time and cost,
- Reduced production unit cost, and
- Reduced maintenance and repair costs.

In this section, a review of the advantages and a 'top-down' estimate of the potential cost savings of applying a common engine bore philosophy is made. Owing to the unknown nature of each platforms particular performance requirements, the estimates are very general in nature but serve to exemplify the advantages of a common engine development effort.

Common Bore Engine Development Advantages:

The application of a common bore engine concept offers significant development advantages, including the following:

- Reduced development of critical core cylinder components (cylinder, valves, piston, etc.)
- Reduced qualification expense and time
- Reduced tooling and prototype material expenses

A comparative example between independent and engine family development costs is identified below:

Table 7. Estimate of Engine (Core Plus Cooling System) Development Cost Savings Using a Common Bore Engine Approach (vs Independent Engine Design)

Vehicle Platform	Independently Designed Engine	Common Family Engine
Heavy (1000-1500 Hp Engine)	Baseline	Same as Baseline Costs
Medium (500-1000 Hp Engine)	15 % Less than Baseline Costs	55 % Less than Baseline Development Costs
Light (300-500 Hp Engine)	30 % Less than Baseline Costs	65 % Less than Baseline Costs
Total development Costs for a completely modernized engine fleet	2.55 X Baseline Engine Development Costs	1.8 X Baseline Development Costs
Approximate Cost Savings to Modernize an Engine Fleet Using a Common Bore Approach : 40 %		

As discussed previously, the estimates are very qualitative in nature ('top-down', based on experience with other engine development programs) but serve to point out the general aspect that significant cost savings can be realized by using a common engine family development approach. Another critical assumption made in developing the estimate is that the Technology Readiness Level of the engine is at 3 at the onset of the effort.

Common Bore Production Unit Cost Advantages:

In addition to reduced maintenance costs, average unit production prices will also be significantly reduced using a common bore approach to engine design. Estimated cost reductions are contained in Table 8 below:

Table 8: Comparison of Average Unit Production Cost Savings Using a Common Bore Engine Design Philosophy

Vehicle Platform	**Independently designed diesel engine**	**OPOC Common Module Engine Design**	**Boxer or conventional diesel engine design**
Heavy (1000-1500 Hp Engine)	Baseline	91 % of Baseline Costs	91 % of Baseline Costs
Medium (500-1000 Hp Engine)	75 % of Baseline Costs	64 % of Baseline Costs	68 % of Baseline Costs
Light (300-500 Hp Engine)	68 % of Baseline Costs	38 % of Baseline Costs	58 % of Baseline Costs
Average Unit Production Cost Estimate	**75 % of Baseline Engine Cost**	**54 % of Engine Baseline Cost**	**66 % of Engine Baseline Cost**

The above calculations were made using the following model and considerations:

- All platforms are concurrently in production.
- Commonality savings is purely the result of decreased material costs and tooling expenses.
- Production rates are spread out over a 10 year time frame, totaling 3000 engines for the heavy vehicle application, 8000 medium weight vehicle applications, and 12000 light weight vehicle applications.

Common Bore Maintenance and Repair Cost Advantages:

Another very significant advantage of employing the common bore engine development philosophy is that field maintenance and repair aspect of product life cycle will also be significantly reduced. These benefits include:

- Reduced maintenance expenses
- Reduced repair procedures and tools
- Reduced engine repair costs

To illustrate the significance of the advantages of a common bore engine, the following table approximates the annual parts buy (95 % of near-total) for a particular military engine in current production and with extensive years of fielding experience (AVDS-1790 9AR and 5AR Engine Series):

Table 9: Comparison of Annual Parts Buy for Maintenance of an Engine Fleet

Replacement Parts Category	% Parts of Total Engine Part Number (includes kits)	% Parts of Total Engine Maintenance Cost (Annual)
Common Bore	8	53
Other Parts in Common Family	43	13
Unique	49	34

Common bore engine parts would include parts such as cylinders, pistons, rocker arms, oil squirts, etc. ‘Other parts in common family’ engine would include parts that would be common to the engine regardless of the engine horsepower and number of cylinders used. Examples of these would include switches, sensors, solenoid valves, starting aid components, filters, a high percentage of fuel and oil lines, etc.

Here it is clearly illustrated that while common bore parts only comprise 8 % of the total parts acquisition process, the cost of the parts is 50 % of the entire material maintenance expense. Clearly, an ‘economy of scale’ opportunity exists with a common bore philosophy that would not be available using an independent engine design philosophy. While it is expected that this number would be dependant on the customer maintainance philosophy, the engine type, etc., the magnitude of the importance of retaining a common bore philosophy is anticipated to remain.

CONCLUSIONS & RECOMMENDATIONS

A common family/common bore engine configuration approach was investigated from a technical and life cycle cost perspective for military vehicle platforms ranging from light (20 tons) to heavy weight (60 tons) vehicle platforms. It is shown that using modernized engine design philosophy, a common bore engine can be developed that will result in approximately a 50-100 % + increase in power-pack density than what currently exists in the military fleet throughout the vehicle size range examined. The results suggest that over the spectrum of military vehicle sizes of interest, using a common bore approach has nearly the same technical performance than would exist with the independent development, operating point optimized engine bore size. The results were based on comparison of an Opposed Piston Opposed Cylinder and a Boxer engine design that had different bore diameters.

While the common bore engine design approach is expected to be technically as good as an independent engine design, the life cycle cost advantages are significant. Development and production unit costs are expected to decrease in the vicinity of 30- 40 % and it is shown that material acquisition costs for maintenance and repair parts represent approximately 50 % common bore items, and approximately 2/3 of all material expenses would be similar with a common engine family approach – offering substantial opportunity for 'economy of scale' acquisition philosophy.

Future efforts in this area should consider alternative configurations, such as an Opposed Piston engine style. Also, a more refined analysis utilizing envisioned engine bays, requirements, and advanced thermal management along with development of a life cycle analysis model in line with the engine modernization plan. Additionally, the methodology and relationships exist that the optimum engine bore size for a particular engine configuration can be estimated apriori and would serve as an excellent guide for future propulsion system strategies.

REFERENCES

[1] TARDEC Broad Agency Announcement W56HZV-05-R-BAA1 Topic #27

[2] Raffa, C., Schwartz, E., Tasdemir, J., "Combat Vehicle Engine Selection Methodology Based on Vehicle Integration Considerations", SAE International Technical Paper 2005-01-1545, 2005, doi:10.4271/2005-01-1545.