Effects of Mechanical Turbo Compounding on a Turbocharged Diesel Engine

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ABSTRACT

This paper presents the simulation study on the effects of mechanical turbo-compounding on a turbocharged diesel engine. A downstream power-turbine has been coupled to the exhaust manifold after the main turbocharger, in the aim to recover waste heat energy. The engine in the current study is Scania DC13-06, which 6 cylinders and 13 litre in capacity. The possibilities, effectiveness and working range of the turbo compounded system were analyzed in this study. The system was modeled in AVL BOOST, which is a one dimensional (1D) engine code. The current study found that turbo compounding could possibly recover on average 11.4% more exhaust energy or extra 3.7kW of power. If the system is mechanically coupled to the engine, it could increase the average engine power by up to 1.2% and improve average BSFC by 1.9%.

INTRODUCTION

As shown in Figure 1, generally about 22-46% of the fuel energy in an internal combustion engine is expelled to the exhaust. Thus, efforts could be invested to harvest parts of this otherwise wasted source of energy.

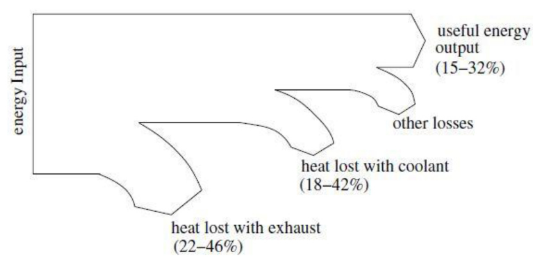

Figure 1. A Sankey diagram showing the energy balance of an internal combustion engine. [1]

Fuel prices have also increased drastically over the past years. As shown in Figure 2, both gasoline and diesel prices has increased tremendously. Diesel fuel for example experience an increase from 1.20 dollars per gallon in year 1997 to 2.80 dollars per gallon in year 2007.

The emission of diesel engine is gaining more attention as well due to the rising awareness of the preservation of Earth's environment. In 2009, the emission limit set by the European Emission Standards for passenger cars was 0.18 g/km for NOx and 0.005 g/km for particulate matter. [3] This can be seen in Figure 3. The emission limit is expected to be lower in the future.

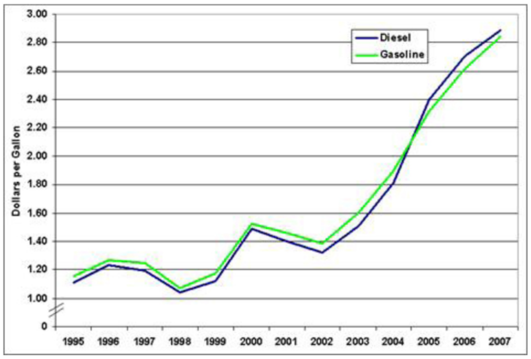

Figure 2. Average Annual Retail Sales Price for Diesel and Gasoline [2]

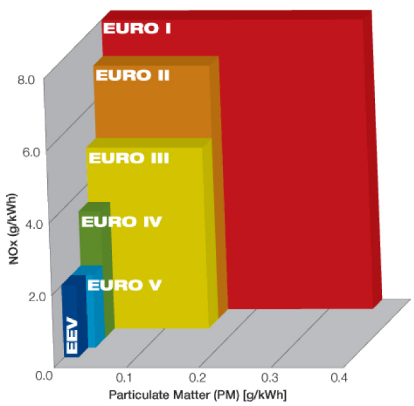

Figure 3. European Emission Standards [3]

Hence, having a more efficient engine system is indeed crucial as fuel prices are skyrocketing and emissions standard and regulations are getting more stringent. Exhaust energy recovery is very promising in this aspect. The energy recovered from the exhaust could be used to power the engine directly or be used to power other auxiliaries such as lighting, air conditioner or audio system, thus reducing parasitic loads and improve fuel economy.

LITERATURE REVIEW

Many fruitful efforts have been carried out to recover energy from exhaust gasses. Figure 4 shows the main methods that have been practiced and applied to recover energy from exhaust gasses.

The most dominating technologies for exhaust energy recovery are thermoelectric generators to convert heat directly to electricity, implementation of Rankine cycle through an expander, Stirling engine, mechanical turbo compounding and electrical turbo compounding. [4]

The study presented in this paper will focus specifically on the mechanical turbo compounding. Nevertheless, some generic overview of the turbo-compounding methodology will be provided.

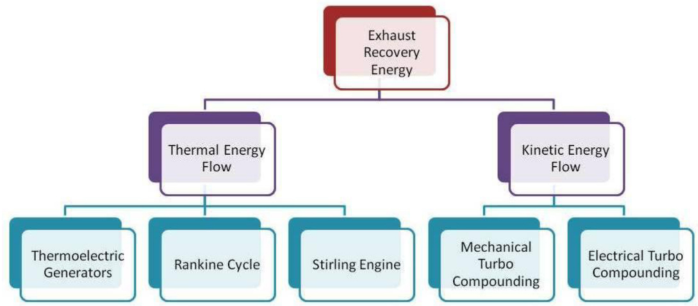

Figure 4. Main Methods of Exhaust Energy Recovery

Turbo Compounding

A turbo compound engine is an internal combustion engine that has a power-turbine to recover energy from the exhaust gases. The turbine could either be mechanically coupled to a gear& crankshaft that can provide additional power to the engine or be connected to a generator and produces electricity, which can power on board auxiliaries or stored in a battery.

Mechanical Turbo Compounding

Exhaust gases which have passed through the conventional turbocharger turbine are directed to a power-turbine, to further extract available energy. In a mechanical turbo-compounding system the power-turbine will then provide more torque, hence more power to the engine's crankshaft through a gear system. Figure 5 shows the schematic diagram of a mechanical turbo compounding system.

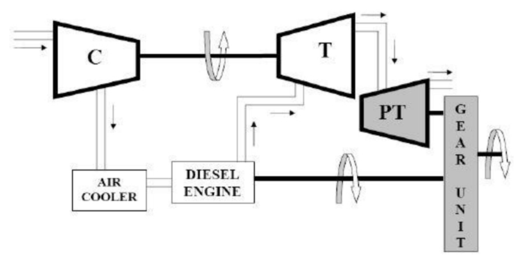

Figure 5. Schematic view of Mechanical Turbo Compounding [4]

Study shows that mechanical turbo compounding can reduce the brake specific fuel consumption (BSFC) by 5.7%. [4] However, this value depends strongly on the efficiency of the power-turbine.

By adding a power-turbine in the exhaust flow, up to 20% of exhaust energy recovery is possible which equals to about 5% of total fuel energy. [5] Besides that, engine peak power output can also be increased by up to 10% and overall thermal efficiency improvement by 3-5%.

These studies show that mechanical turbo compounding has some very desirable properties and advantages, such as high

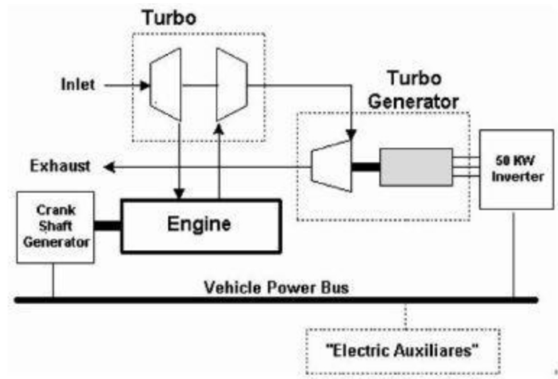

Figure 6. Schematic view of Electrical Turbo Compounding [6]

power density, good fuel consumption in heavy loading application, good engine response and well facilitated exhaust gas recirculation (EGR) due to high exhaust manifold pressure.

However, implementing mechanical turbo compounding in an internal combustion engine does have its challenges. Reliability and cost are some of the biggest concerns which create huge challenges in the design of gear train, coupling system and the power-turbine itself. The mechanical turbo-compounding system also adds complexity and weight to the original engine configuration, which has to be weighted carefully for positive improvements.

Another issue is that under low engine loading, there might be very little or negative gain from the turbo-compounding system. Additional space for the packaging of the system must also be considered. Besides, the cooled exhaust stream downstream the power-turbine might reduce the effectiveness of exhaust after-treatment systems. Thus the positioning of the power-turbine either before or after the after-treatment system has to be analyzed.

Electrical Turbo Compounding

Electrical turbo compounding is quite similar to its mechanical counterpart, especially on the energy recovery aspect. However, instead of being mechanically coupled to the engine, the power-turbine drives a generator. The generator produces electricity that can be fed into the vehicle electrical demand or stored in batteries. The electricity produced by the generator can be used to drive various auxiliary power needs such as air compressors and power steering system. Figure 6 shows the schematic diagram of an electrical turbo compounding system.

One distinct advantage of electrical turbo compounding is that it offers better output flexibility. The power can be used to directly power auxiliary equipment or be stored in a battery and be used to power the auxiliaries when necessary to avoid engine idling for driver needs in hybrid application. This can increase fuel savings up to 10% depending on the idling reduction. [5]

The turbine power output and speed can also be controlled independently regardless of engine speed and load thus opens up potential for better performance and emissions control. Simulations show that in an electrical turbo compounding system, a reduction of 8-9% overall BSFC is possible for turbocharger with relatively high efficiencies. [4]

Recent Studies in Turbo Compounding

The power-turbine can be installed in two arrangements. One is in series with the turbocharger the other in parallel with the turbocharger. [7,8] Both arrangement adopts a bypass valve that regulates the distribution of the exhaust gases. Studies have shown that arranging the power-turbine in series with the turbocharger provides more improvements in terms of power output and fuel consumption. [7]During partial loads, the inclusion of the power-turbine downstream might give negative effect to the engine. This is because of the back pressure imposed due to insufficient exhaust gas flow that allows the power-turbine to work efficiently. [7,9]

The reason for this is because most turbines that are available on the market work on higher pressure ratio whereas the amount of exhaust pressure after the turbocharger is significantly very low. Research has been done on design and developing a low pressure turbine that can work effectively for turbo compounding. [10]

Another aspect of turbo compounding that is crucial is the gear train that transfer the rotational power of the power-turbine that can then be converted or stored. One method is to employ a continuously variable transmission (CVT) to provide better control and efficiency. [11]

Indeed turbo compounding does give improvements however, there are many other exhaust energy recovery method that has proven to give more improvement such as the Rankine cycle. [12,13]. Although so, turbo compounding has its own benefits and advantages mainly in its attractive cost and wide

Table 1. Benefits & Disadvantages of Exhaust Heat Recovery Techniques [13]

Technology	bsfc benefit	Effect on Engine	Volume Weight	Cost	Applicability
Mechanical Turbocompounding	**	****	**	*	*****
Electrical Turbocompounding	***	***	**	**	****
Rankine With Steam	****	*****	*****	****	**
Rankine with Organic	*****	*****	****	*****	***

applicability. Table 1 shows the turbo compounding system compared to widely researched Rankine cycle. [13] Turbo compounding system also has the advantage of having a relatively lower weight. Table 2 show the weight comparison of some turbo compounding system and heat recovery power cycle. [12]

Table 2. Added weight comparison of turbo-compounding and heat recovery fluid power cycles [12]

Scania - electric turbo compound		Caterpillar turbo compound		Heat recovery fluid power cycle	
Component	Weight (kg)	Component	Weight (kg)	Component	Weight (kg)
Turbine	20.0	Turbine	20.0	Expander	6.0
Compressor	20.0	Compressor	20.0	Pump	5.0
Electric motor	30.0	Gear train	30.0	Gear train	20.0
Clutch	5.0	Clutch	10.0	Working fluid	25.0
				Condenser	10.0
				Heat exchanger	30.0
Auxiliaries	10.0	Auxiliaries	10.0	Auxiliaries	10.0
Total	85.0	Total	90.0	Total	106.0

METHODOLOGY

For turbo compounding method, which works on the Brayton cycle, the exhaust gas that is expelled by the internal combustion engine first reaches the main turbocharger system. The turbocharger turbine will extract of the exhaust energy to drive the compressor, which in turn produces boost for the engine.

The exhaust gas leaving the turbine will then be directed to a second turbine known as the power-turbine. The power-turbine will then recover parts of the remaining energy from the exhaust gas. Figure 7 shows the schematics diagram of the mechanical turbo-compounding system used in this study.

The system shown in Figure 7 was modeled using AVL BOOST, which is part of AVL SIMULATION TOOLS [14]. The purpose of modeling the mechanical turbo-compounding system is not only to see how much exhaust energy that can be possibly recovered by the turbine, but also to see the effects of the system on the engine performances. The effects considered in this study are the engine BSFC, net power produce by the engine and also total power obtained from the whole system.

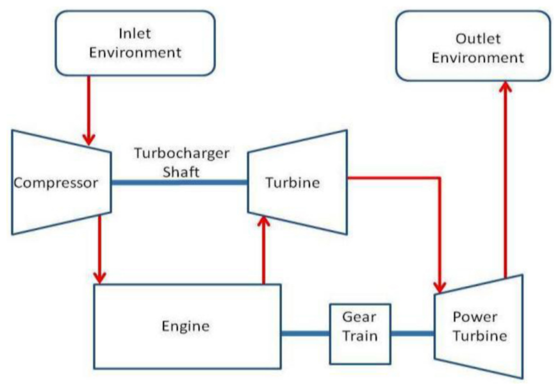

Figure 7. Schematic Diagram of the Exhaust Energy Recovery System (mechanical turbo-compounding)

Installation of a power-turbine downstream the main turbocharger would inevitably create backpressure. Thus it is expected that the performance of the engine will be affected. Nevertheless, careful system integration could result in the power extracted by the power-turbine more than offset the power loss from the engine, hence positive overall power gain. This might not be the case for all operating range of the engine, thus bypassing the power-turbine might be required at some instances. Through analysis of the overall possibilities, the range where the mechanical turbo compounding can potentially work to improve the engine system could be determined.

Governing Equations

AVL BOOST is a one dimensional engine code. The governing equations are energy, momentum and mass conservation, solved along mean path-line of the flow. Equations of mass and energy are solved for each volume and the momentum equation solved for each boundary between volumes. The equations are written in an explicitly conservative form in (1), (2), (3).

Equation (1): Mass continuity equation

$$\frac{dm}{dt} = \sum\nolimits_{boundaries} m_{flux} \tag{1}$$

Equation (2): Conservation of momentum equation

$$\frac{d(m_{flux})}{dt} = \frac{dpA + \sum_{boundaries}(m_{flux}u)}{dx} - \frac{4C_f \frac{\rho u^2 dxA}{2D} - C_p\left(\frac{1}{2}\rho u^2\right)A}{dx} \tag{2}$$

Equation (3): Conservation of energy equation

$$\frac{d(me)}{dt} = p\frac{dV}{dt} + \sum\nolimits_{bound.} m_{flux}H - h_g A(T_{gas} - T_{wall}) \tag{3}$$

Engine Power

The engine power is govern by the equation

$$P_{engine} = BMEP.V_D.n_{cycle} \tag{1}$$

Where n_{cycle} is number of cycles per second

Turbine Power

For turbine simulation, the performance characteristics along a line of constant turbine speed were used. The power provided by the turbine is determined by the turbine mass flow rate and the enthalpy difference over the turbine.

$$P_T = \dot{m}_T.\eta_m.(h_3 - h_4) \tag{2}$$

$$h_3 - h_4 = \eta_{s,T}.c_p.T_3.\left[1 - \left(\frac{p_4}{p_3}\right)^{\frac{\kappa-1}{\kappa}}\right] \tag{3}$$

where κ is ratio of specific heats. Subscripts T, 3 and 4 represent total condition, inlet and outlet of control volume respectively.

Selection of Engine

An engine from Scania was chosen for the current study [15]. The engine is a 13 litre six cylinder in-line turbocharged intercooled diesel. Table 3 shows the engine's specifications and Figure 8 show its performance characteristics [15].

Table 3. SCANIA Engine Specification [15]

Scania Engine, DC13-06	
Capacity	12.74 litre
Bore	130mm
Stroke	160mm
Compression Ratio	17.1
Maximum Power	265kW @ 1900rpm
Maximum Torque	1850Nm @ 1300rpm

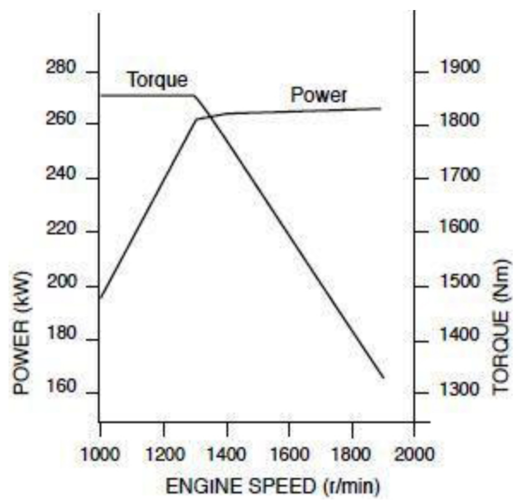

Figure 8. Engine's Torque and Power Curve [15]

The engine already has an integrated turbo charging system and this setup will be the benchmark in the current study. The performance of the proposed mechanical turbo-compounding system will be compared against the original setup. Two models are produced in the current study, one replicating the original engine setup (Table 1 & Figure 8) and another using the original engine but coupled with a secondary turbine downstream the main turbocharger.

Modeling of Original Engine

Figure 9 shows the AVL BOOST model of the original engine system. The main objective of modeling the original engine is so that a benchmark performance can be obtained which will then be compared to the turbo-compounded engine.

All of the crucial parameters are set according to the manufacturer's specification sheet [15].

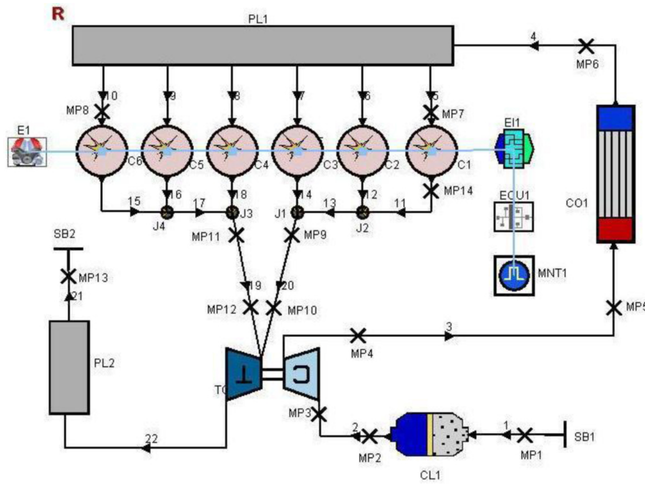

Figure 9. 1D Model of the Original Engine

Validation of the Engine Model

The engine model is validated with the power curve of the SCANIA engine, as shown in Figure 8. Figure 10 shows the comparison between the power curve of the model and the real engine while Figure 11 shows the comparison between the torque curve of the model and the real engine.

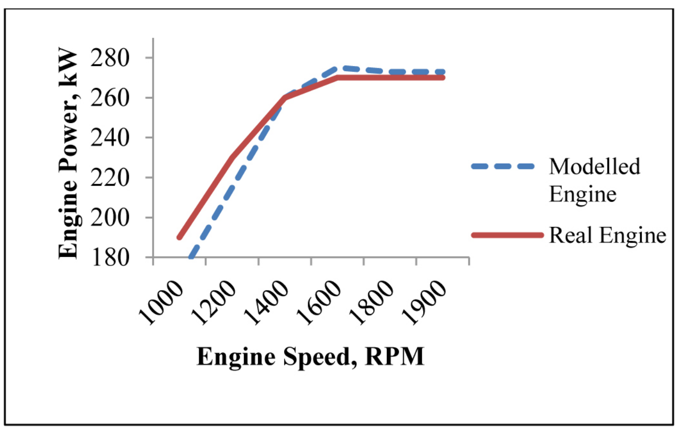

Figure 10. Comparison of the Model and Real Engine Power Curve

At the lower range around 1000-1400rpm, the difference between the modeled engine and the real engine is on average 5.6%. At the higher end, the average differences are smaller. The modeled engine deviates from the real engine by about 1.4% of the original engine from 1400 to 1900rpm. Overall, the average difference between the modeled engine and the real engine is about 3.5%.

At the lower range around 1000-1400rpm, the difference between the modeled engine and the real engine is on average 1.5%. At the higher end, the average differences are larger. The modeled engine deviates from the real engine by about 5% of the original engine from 1400 to 1900rpm.Overall, the average difference between the modeled engine and the real engine is about 1.2%.As a physical engine is not available for testing, the engine specifications and performance figures used are taken from the manufacturer's sheet [8]. Nevertheless, this paper aims to show that a power turbine can be beneficial with little to no alteration to the current engine system and components.

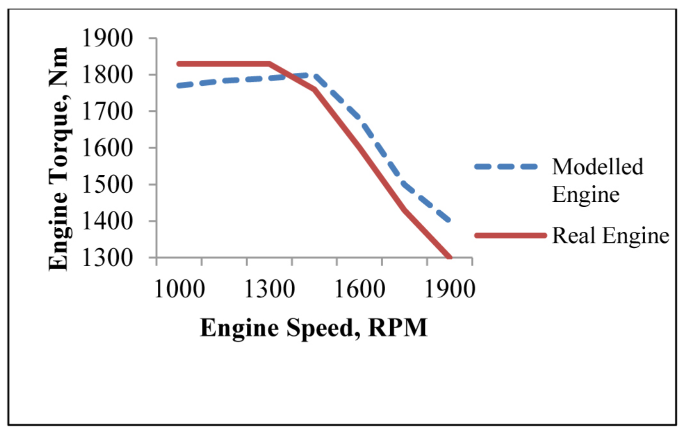

Figure 11. Comparison of the Model and Real Engine Torque Curve

Selection of Power-Turbine

From the simulation of original engine, it was found that the exhaust pressure downstream the main turbocharger is in the range of 120 to 160kPa. The possibility to extract energy out of these conditions will need a turbine working efficiently at low pressure ratio. In reality, there is very limited choice of off-the-shelves turbine which could fit the purpose. As for this initial study, a standard turbocharger turbine was chosen as the downstream power-turbine. The chosen model is a Garrett GT4508R turbine, with housing size of 85 Trim, and area-to-radius ratio of 1.44 [16].

Future improvement in the proposed system will essentially require higher efficiency turbine, and this probably need to be specifically designed, similar to reference [10].

Modeling of Turbo Compounded Engine

Figure 12 shows the 1D model of the turbo compounded engine. The difference one can notice compared to Figure 9 is the inclusion of a power-turbine downstream the main turbocharger.

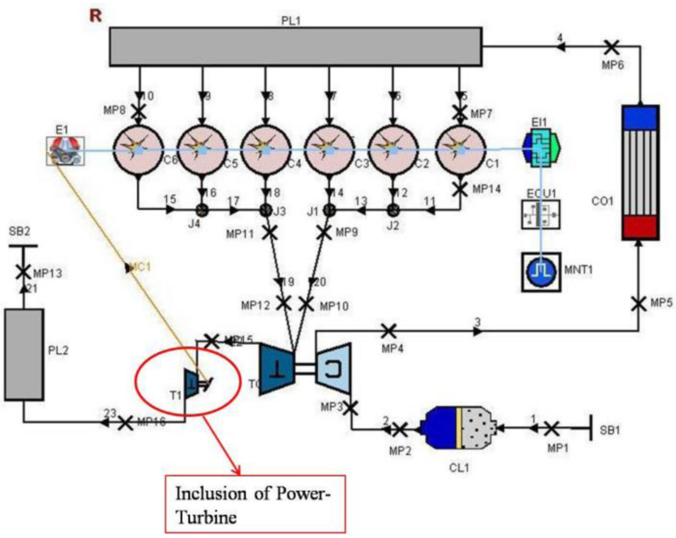

Figure 12. 1D Model of the Turbo Compounded engine

Results and Discussions

When a power-turbine is installed downstream the turbocharger, the performance of the engine will be affected. This is due to the restriction by the power-turbine that imposed a certain degree of backpressure in the exhaust system. This is evident in Figure 13 where the pressure ratio across the turbocharger turbine of the compounded engine is lesser on all operating engine speed.

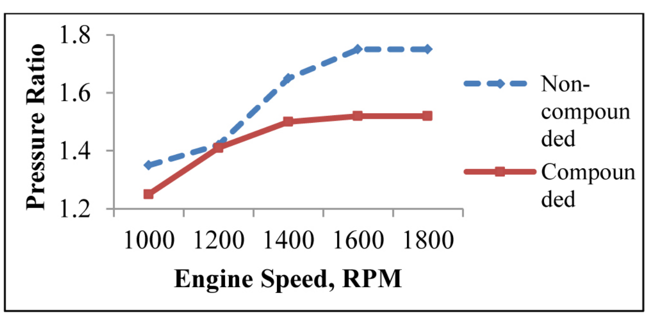

Figure 13. Turbine Pressure Ratio vs. Engine Speed

However, the drop has to be judged against the power generated by the power-turbine downstream the turbocharger. In Figure14, it can be seen that the power of the engine actually increase at higher engine speeds. The compounded engine only produces more power compared to the original engine only when it reaches engine speed of more than 1400 rpm.

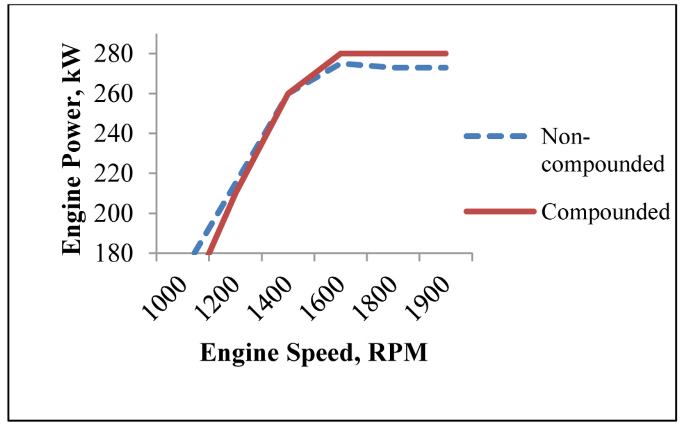

Figure 14. Total Power vs. Engine Speed

The power extracted by the power-turbine increases with increasing engine speed as can be seen in Figure 15. This is because the pressure ratio across the power-turbine gets higher as the engine's speed increase as shown in Figure 16.

At low engine speed (less than 1400rpm) the engine power decreased by about 4.7% on average. This is mainly due to the restriction that the power-turbine imposed. However, at high engine speed (more than 1400rpm) a maximum increase of 7% and an average increase of about 2.3% in engine power are possible.

It is important to note that although at high engine speed the engine power shows improvement, when taking into consideration the whole operating range, the engine power actually decreases by about 1.2%. This is where the inclusion of a by-pass system might prove beneficial.

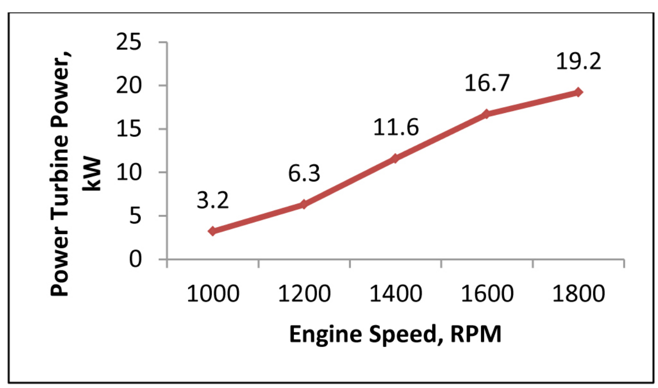

Figure 15. Power-Turbine Power vs. Engine Speed

Another thing worth noting is that the total power extracted by both the main turbine and the power-turbine in the compounded engine is higher than the main turbine alone for in the original engine, as can be seen in Figure 17. This means that the combination of both turbines can actually extract more power from the system thus resulting in a more efficient system.

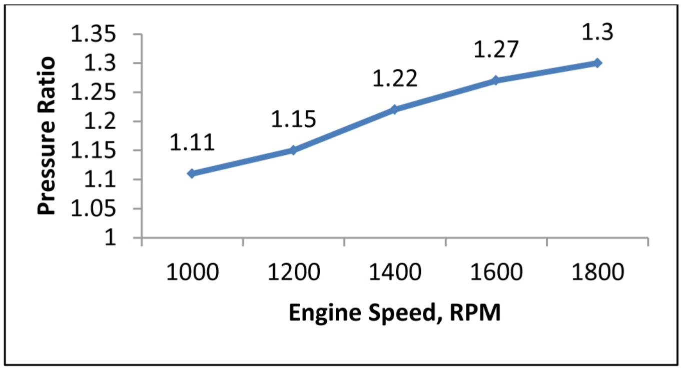

Figure 16. Power-Turbine Pressure Ratio vs. Engine Speed

From Figure 17, the compounded system can actually extract an average of 11.4% and a maximum of 25.7% of energy from the exhaust which is otherwise wasted. This translates to an average increase of 3.7kW of recovered energy from the exhaust flow. The extra power can actually be used to power the auxiliaries on the vehicle if coupled to an electric generator. To put this into perspective, the average electrical power consumption of common vehicle is about 1.7kW.

This means the extra power generated from the compounded system is more than enough to power the vehicles auxiliaries such as lights, air-conditioning and entertainment system. This could potentially mean that the vehicle's alternator, which supplies power to the auxiliaries, that is parasitic to engine could be omitted.

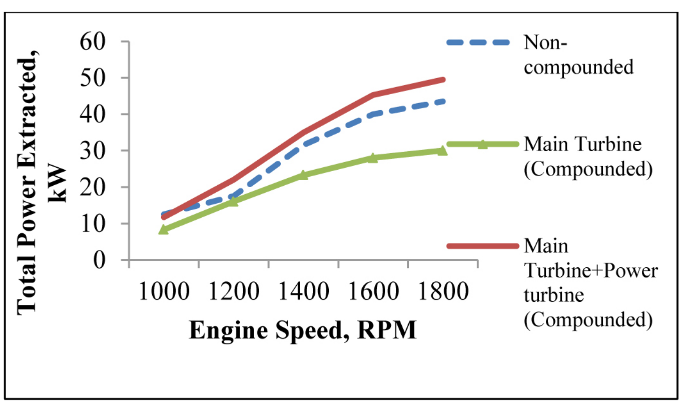

Figure 17. Total Power Extracted vs. Engine Speed

Figure 18 shows the main turbine efficiency at various engine speeds. For the compounded system, the model used the same turbocharger setup as the original engine. From Figure 18, by using the same turbocharger setup, the efficiency of the turbine drops but the drop is still acceptable as the efficiency of the main turbine is around 70%. For this study, the same turbine and compressor setup were used as the non-compounded engine. It is possible to use different turbocharger for further improvements. Even with the exact same setup, overall improvement is recorded despite the drop in turbocharger efficiency.

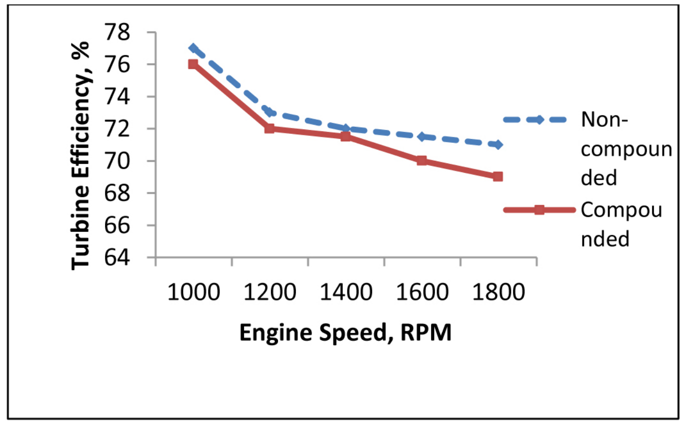

Figure 18. Efficiency of Main Turbine vs. Engine Speed

Figure 19 shows the brake specific fuel consumption (BSFC) of both the engines. From the Figure 19, one can see that the BSFC for the compounded engine is lower compared to the original only at engine speed higher than 1400 rpm. Lower BSFC means that the engine consumes less fuel to produce work. BSFC of the turbo-compounding engine is 12.6% higher than the original engine at 1000rpm, eventually becomes equal for engine speeds of 1200 - 1400rpm, before showing improvements. A maximum reduction of 3.3% in BSFC is possible at 1800rpm engine speed. The weak BSFC of the turbo-compounding engine at low speed is mainly due to the exhaust backpressure created by the power-turbine.

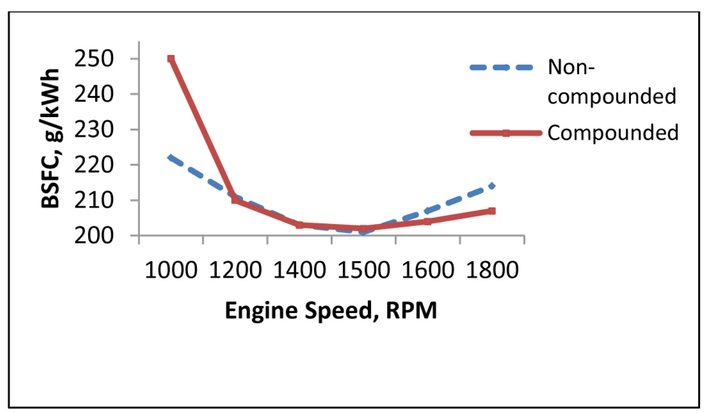

Figure 19. BSFC vs. Engine Speed

Looking back at Figure 14, it could be seen that at speed more than 1400 rpm, the turbo compounding engine produced more power compared to the original engine by about 2.3% average. However, the average power of the engine actually decreases. This is where a by-pass system that eliminates the power decrease during low engine speed could lead to positive improvement overall. If a by-pass system is integrated, then an average increase of 1.2% in engine power is possible which will also result in a decrease in BSFC of about 1.9% average.

A by-pass system is beneficial in a turbo compounding engine, as the exhaust flow can be directed away from the power-turbine during low speed. This allows the power-turbine to work only when a positive power gain is possible.

Although the increase of 1.2% in engine power and 1.9% in BSFC might seem small, this is just to show that turbo compounding system can actually produce more energy compared to a non-compounded system.

CONCLUSION

This paper presents some review on the turbo compounding method and also the modeling efforts and results of a mechanical turbo compounding system. The turbo-compounding system uses a power-turbine downstream the turbocharger and it is mechanical connected to the engine crankshaft. The engine used for the current study is a SCANIA Diesel 13 litre engine.

Modeling showed that the turbo compounding setup can be more beneficial than turbo-charging alone. An average increase of 1.2% of total engine power and average BSFC improvement of 1.9% is possible using mechanical turbo-compounding when a by-pass system is implemented. Improvement in engine performance however could only be seen at higher RPM. Poor performance at low engine RPM is recorded due to exhaust backpressure by the power-turbine. This further exemplifies the importance of a by-pass system in turbo-compounding engine.

Turbo-compounding system can also extract up to 25.7% extra exhaust energy and on average 11.4% more compared to a non-compounded system. This translates to an extra 3.7kW of power obtained from otherwise wasted exhaust energy. That amount of power is more than enough to power the auxiliaries in the vehicle and could potentially lead to the exclusion of the parasitic alternator. This potential could only be realized by efficient system integration, such as using by-pass to avoid power-turbine back pressure, and selection of high efficiency power-turbines.

Due to the physical engine being unavailable for testing and experiment, there is still much room to improve on the quality of the engine model. Nevertheless, this is just a preliminary study which shows that turbo compounding can be utilized as an exhaust energy recovery method without much modification on the current system.

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DEFINITIONS/ABBREVIATIONS

A *- area*

C_p *- specific heat*

H *- enthalpy*

M *- mass flow rate*

P/p *- pressure*

T *- temperature*

V_d *- displacement volume*

ρ *- density*

η *- efficiency*

BMEP *- brake mean effective pressure*

BSFC *- brake specific fuel consumption*

rpm *- revolution per minute*

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