# SIMULATION OF EXHAUST WASTE ENERGY RECOVERY POTENTIALS USING ELECTRIC TURBO COMPOUND IN A TURBOCHARGED GASOLINE ENGINE

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To my late father Hj Che Puteh bin Hj Abdull Rahman and
my mother Hjh Aishah binti Salleh,
my wife Mrs Normaliza binti Mohamad Yusof and
to my beautiful daughters Nur Khaireen Ayeesha and Nur Khayra AzZahra

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# ABSTRACT

Thermal efficiency of a spark-ignited engine is normally in the range of 25 % to 35% and reciprocating engines represent a very large source of waste heat with most of the losses are from the exhaust, through coolant, by direct convection and radiation to the environment. There is a significant potential to expand waste heat recovery usage by tapping the large volumes of unused exhaust heat into useful energy such as electricity. The methodology involved in the thesis includes assessment of each waste heat recovery technology based on current developments, research trends and its future in an automotive application. It also looked into the potential energy recoveries, performances of each technology, other factors affecting the implementation and comparison for each technology. Finally, simulation of an Electric Turbo Compounding (ETC) was presented using a Ford EcoBoost as a baseline engine with modification using HyBoost setup modeled with the 1-Dimensional AVL Boost engine performance software. A validated 1-D engine model was used to investigate the impact on the Brake Specific Fuel Consumption (BSFC) and Brake Mean Effective Pressure (BMEP) and was run at full load conditions. The results showed a maximum reduction of 3.0% BSFC and a maximum increment of BMEP of 0.5 bar achieved at an engine speed of 2500 rpm, during the full load condition. The setup was also able to achieve 1 kW of power and up to 3.75 kW recovered from the exhaust heat. A comparison between the engine testing and 1-D engine model showed a good agreement at the full load conditions with a minimum BSFC Standard Deviation of 0.0206 at the engine speed of 3000 rpm.

# ABSTRAK

Kecekapan haba bagi enjin nyalaan pencucuh biasanya dalam lingkungan 25% hingga 35% dan enjin salingan merupakan sumber haba buangan yang sangat besar dengan kehilangan haba kebanyakannya adalah daripada ekzos, melalui penyejuk, dengan haba perolakan dan haba sinaran kepada persekitaran. Terdapat potensi yang besar untuk menggunakan semula sisa haba dengan menukar sejumlah besar haba ekzos yang tidak digunakan kepada tenaga yang berguna seperti elektrik. Metodologi yang terlibat dalam tesis ini termasuk penilaian setiap teknologi penggunaan semula sisa haba berdasarkan perkembangan semasa, kecenderungan penyelidikan dan masa depan dalam aplikasi automotif. Selain itu, tesis juga melihat potensi tenaga guna semula, prestasi setiap teknologi, faktor-faktor lain yang mempengaruhi pelaksanaan dan perbandingan bagi setiap teknologi. Akhir sekali, simulasi ke atas Elektrik Turbo Kompaun (ETC) dibentangkan menggunakan enjin asas Ford EcoBoost yang diubahsuai menyerupai model HyBoost melalui perisian prestasi enjin 1-Dimensi AVL Boost. Enjin model 1-D model yang telah disahkan telah digunakan bagi mengkaji kesan terhadap Brek Penggunaan Bahan Api Khusus (BPBAK) dan Tekanan Brek Min Berkesan (TBMB) dan dijalankan pada keadaan beban penuh. Keputusan menunjukkan di dalam keadaan beban penuh, pengurangan maksima 3.0% BPBAK serta kenaikan maksima TBMB sebanyak 0.5 bar dicapai pada kelajuan enjin 2500 ppm. Konfigurasi ini juga dapat mencapai kuasa elektrik sebanyak 1 kW sehingga 3.75 kW yang dijana semula daripada haba ekzos. Perbandingan antara ujian jentera dan 1-D model jentera menunjukkan kesamaan yang baik pada keadaan beban penuh dengan sisihan piawai BPBAK minima, 0.0206 diperolehi pada kelajuan enjin 3000 ppm.

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# NOMENCLATURE

## Latin Symbols

| | |
|---|---|
| $A$ | Area |
| $a$ | Weibe Parameter |
| $C_m$ | Mean Piston Speed |
| $C_u$ | Circumferential Velocity |
| $D$ | Cylinder Bore |
| $h$ | Spesific Stagnation Enthalpy |
| $J/mol\ K$ | Entropy |
| $K$ | Specific Heats Ratio |
| $kW$ | Power |
| $m$ | Shape Parameter |
| $m_T$ | Turbine Mass Flow Rate |
| $n_{cycle}$ | Number of Cycles Per Second |
| $p_{c,1}$ | Pressure in the Cylinder |
| $P_{c,o}$ | Cylinder Pressure of the Motored Engine |
| $P_{amb}$ | Ambient Pressure |
| $P_{atm}$ | Atmospheric Pressure |
| $P_{engine}$ | Engine Power |

| | |
|---|---|
| $P_{ex}$ | Exhaust Pressure |
| $P_{in}$ | Induced Pressure |
| $P_T$ | Turbine Power |
| $Q$ | Total Fuel Heat Input |
| $T_{c,1}$ | Temperature in the Cylinder at Intake Valve Closing |
| $V_D$ | Engine Displacement |
| $Z$ | Thermoelectric Figure of Merit |

**Greek Symbols**

| | |
|---|---|
| $\alpha$ | Crank Angle |
| $\alpha_o$ | Start of Combustion |
| $\Delta\alpha$ | Combustion Duration |
| $\eta_m$ | Adiabatic Effficiency |
| $\sigma_{BSFC}$ | Standard Deviation of BSFC |

**Abbreviations and Subscripts**

| | |
|---|---|
| BDC | Bottom Dead Centre |
| BiTe | Bismuth Telluride |
| BMEP | Brake Mean Effective Pressure |
| BSFC | Brake Specific Fuel Consumption |
| CeFeSb | Skutterudite |

| | |
|---|---|
| DOE | US Department of Energy |
| EGR | Exhaust Gas Recirculation |
| ETC | Electric Turbo Compounding |
| FGT | Fixed Geometry Turbine |
| GDI | Gasoline Direct Injection |
| GDI | Gasoline Direct Injection |
| ICE | Internal Combustion Engine |
| IMEP | Indicated Mean Effective Pressure |
| LPT | Low Pressure Turbine |
| ORC | Organic Rankine Cycle |
| PFI | Port Fuel Injection |
| SiGe | Silicon Germanium |
| SnTe | Stanum Telluride |
| TDC | Top Dead Centre |
| TEG | Thermoelectric Generator |
| T-S | Temperature Entropy |
| VNT | Variable Nozzle Turbine |
| VTES | Variable Torque Enhancement System |
| WHRS | Waste Heat Recovery System |
| ZnBe | Zinc Beryllium |

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# CHAPTER 1

# INTRODUCTION

Since the start of the Industrial Age, industrialization has played an important role in rapid reduction of natural energy resources availability. Hence, in the beginning of the twenty-first century, using lesser energy has become a primary interest in most of the industrialised countries. Conserving energy by waste heat recovery suddenly become popular and majority of industrial sector plays an important role in venturing the recovery technology. In the 1970s, waste heat recovery systems (WHRS) were used mainly in power generation and energy industries (Reiter, 1983). Various types of heat recovery systems and equipment were invented since then (Reay, 1979). Apart from reducing energy consumption, it also resulted in significant cost savings and reduction in air pollutants (Reiter, 1983 and US Department of Energy, 2005).

The strategy of recovering the waste heat lies on the temperature of the stream of waste heat gases, methods to recover and reusing it and finally the economics involved therein (Reay, 1979). The importance of WHRS have caught the attention of engine manufacturers such as Detroit Diesel, Scania and Volvo to integrate exhaust heat recovery system (EHRS) especially for their long haul diesel engine used in land transportation sector. Over the years with the improvement of materials, engine simulation programmes and system innovation, the examples of the automotive WHRS have been expanded from previous mechanical turbo-compounding to electric turbo compounding, thermoelectric generator, organic Rankine cycle, steam Rankine cycle and Brayton cycle (Mohd Noor *et al.* 2014 and Saidur *et al.* 2012).

Apart from energy recovery from waste heat more stringent standards are being imposed on automotive emissions and in the same time there is a requirement to improve fuel economy due to increase of world fuel prices. Mandating the reduction of $CO_2$ exhausts emissions is becoming global trend with European Union (EU) leading the way with substantial standards improvement over the past 25 years. The use of highly boosted downsized engines is a feasible option in reducing $CO_2$ emission. Reduction of displacement by means of downsizing; either by producing a much smaller specific cylinder displacement or by reducing the number of cylinders with the usage of supercharger or turbocharger with similar output of a much larger engine. Reduction in engine capacity and size will also reduces the weight of the vehicle and contribute to the increased fuel economy as shown in **Figure 1.1** (Fraser *et al.* 2009). This phenomena have resulted in numerous downsized engines already being brought to production.

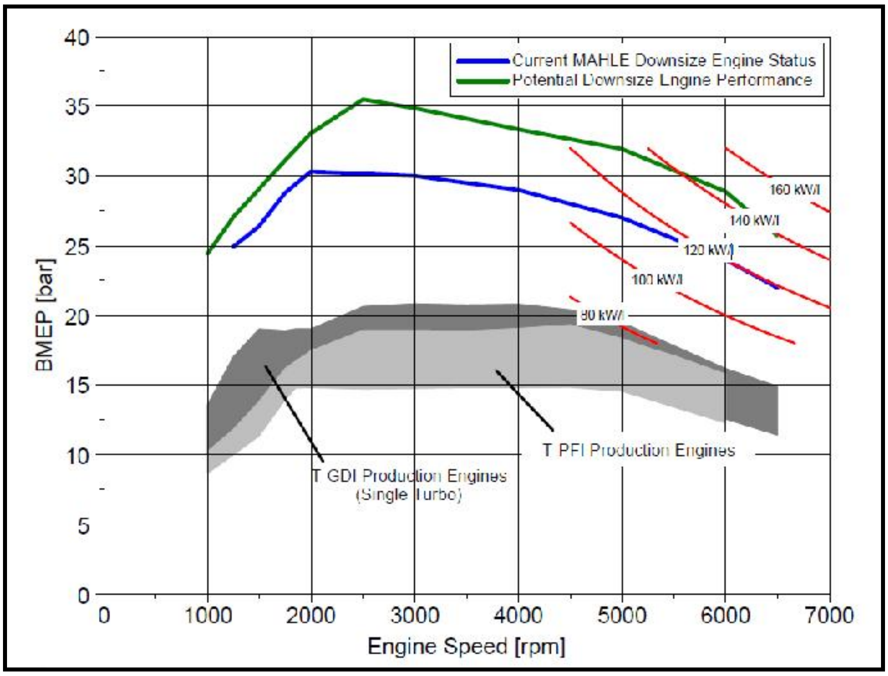


**Figure 1.1**. Gasoline downsize engine full load performance (Fraser *et al.* 2009)

At present, waste heat recovery systems for Internal Combustion Engines (ICE) can be categorized into 3 methods; (1) Bottoming Cycles, (2) Turbo Compounding and (3) Thermoelectric Generator. Electric Turbo Compounding (ETC) concept have been pioneered by Caterpillar in 2002 using integrated turbo compound downstream power turbine to recover exhaust heat and producing electricity from unexploited waste heat.

## 1.1. Exhaust Energy

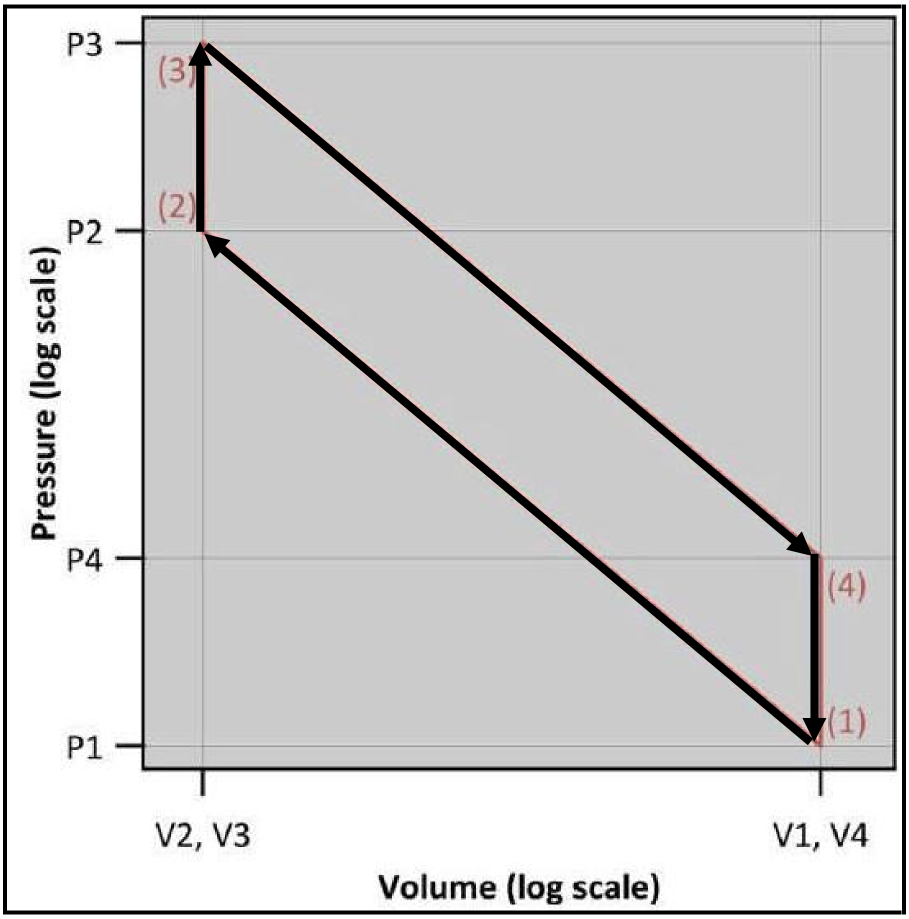


**Figure 1.2**. Ideal Otto Cycle (Heywood, 1988)

**Figure 1.2** explains the PV Diagram in an ideal Otto engine cycle. Maximum possible closed-cycle efficiency (ideal efficiency) is represented by the state of (1) to (2) with isentropic (adiabatic and reversible) compression from max (V1) to min cylinder volume (V2). Compression ratio is represented by $r_c$, which is the value of V1 over V2. The state (2) to (3) is the adiabatic and isochoric (at constant volume) combustion. The state (3) to (4) represents isentropic expansion. Whilst the state (4) to (1) exhaust process which the available energy is rejected which can be converted to mechanical or electrical work for later use.

Algrain (2005) in his work mentioned when the power produced by the turbocharger turbine exceeds the power requirement of the compressor, the surplus mechanical power is converted into electrical power by a generator mounted on the turbocharger shaft. **Figure 1.3** shows the surplus power of the system as a function of engine power. The power surplus is then converted into electricity to power an electric motor mounted on the crankshaft, which also used to assists the engine. This results to an increase in the system efficiency. The electrical machine also can be used as a motor to accelerate the turbocharger shaft if the power requirement of the compressor was lower than expected.

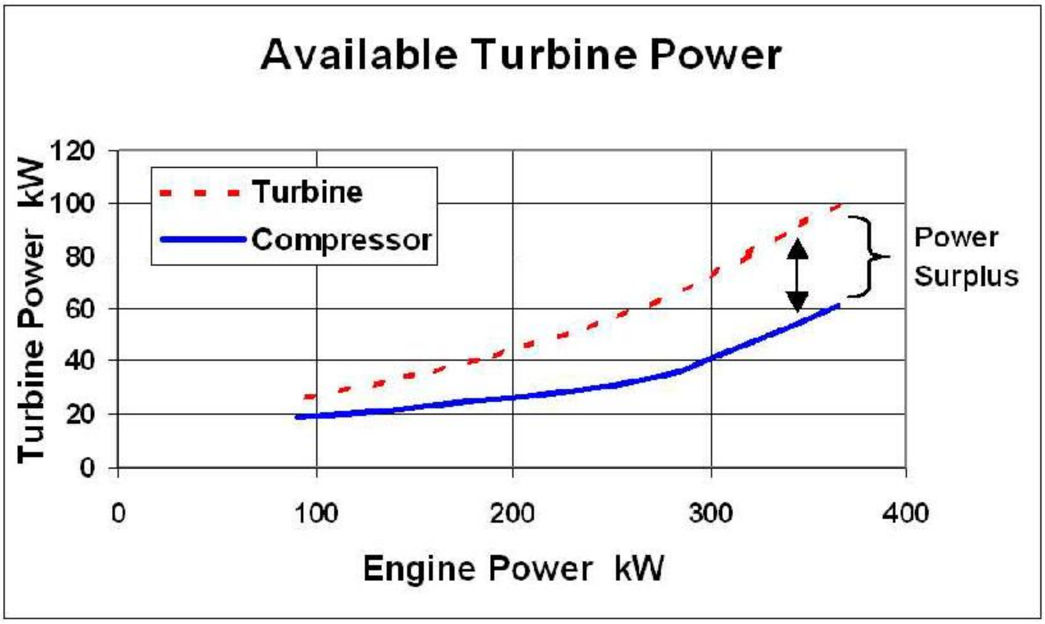


**Figure 1.3**. Compressor and Turbine Power in Engine (Algrain, 2005)

## 1.2 Electric Turbo Compounding as a Waste Heat Recovery System Option for Gasoline Engine

In a gasoline powered internal combustion engines, about 40% of the fuel energy is wasted in exhaust gases, and another 30% losses in engine coolant (Stabler, 2002). The increasing demand in improving the efficiency of the engine requires extensive research and technology development by most of the engine manufacturers. Exhaust gas heat utilization in the form of WHRS has attracted a major interest due to substantial potential of the amount of heat that can be recovered (Stobart and Weerasinghe, 2006 and Jianqin *et al.* 2011). Recovering useful energy, in the form of electrical power from engine exhaust waste heat would directly reduce system fuel consumption, increase available electric power and improve overall system efficiency by adding the power produced by the engine (Millo *et al.* (2006) and Hoppman and Algrain, (2003)).

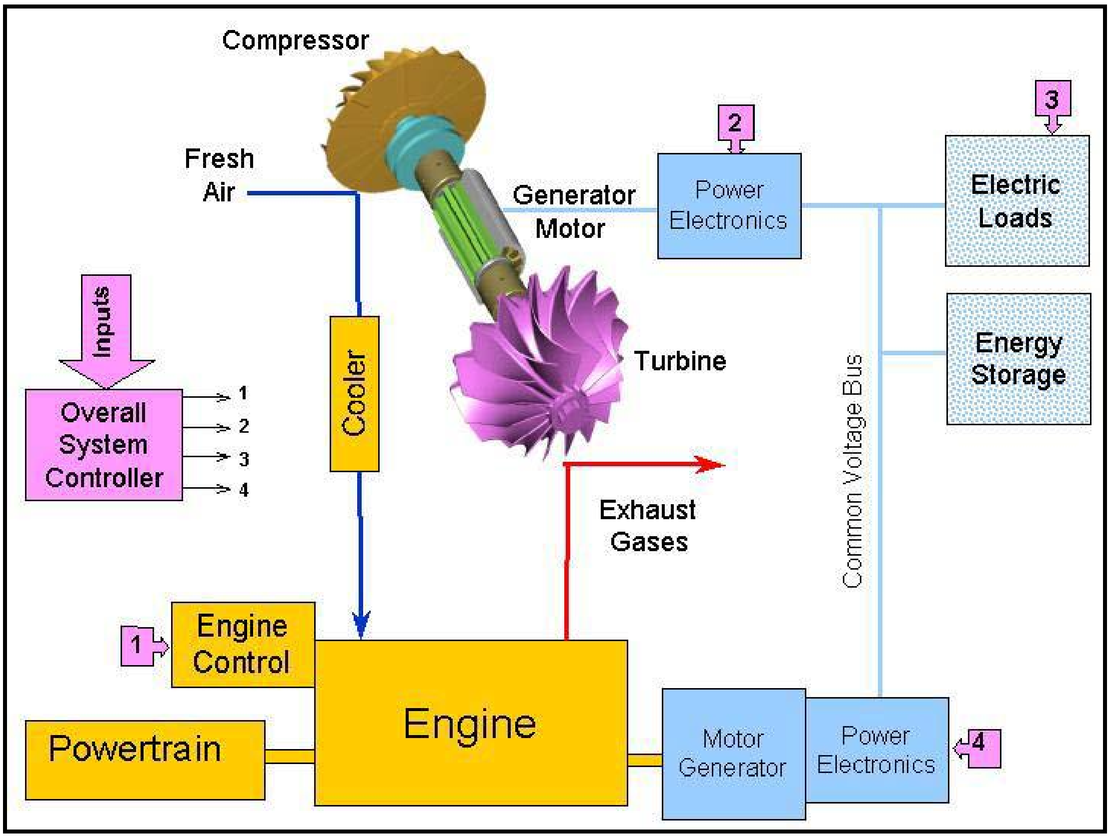


**Figure 1.4**. Electric turbo compound schematic by Caterpillar (Hoppman and Algrain, 2003)

Electric Turbo Compounding (ETC) prototype (**Figure 1.4**) was first developed by Caterpillar for diesel engines in 2003 (Hoppman and Algrain 2003). The system consists of an electric machine integrated into the turbocharger shaft. The electric machine can work as a motor to improve transient response or work as a generator to recover energy. In another design by John Deere, an extra downstream power turbine with electric machine was designed for diesel engine (Vuk, 2005). Controlled Power Technologies Ltd UK also has developed a system called Turbo-generator Integrated Gas Energy Recovery System (TIGERS); in which a turbo-generator was used in a naturally aspirated gasoline engine exhaust line. Caterpillar and John Deere both claimed that they were able to achieve fuel economy improvement between 3 to 5% (Hoppman and Algrain, 2003 and Vuk, 2005).

In a recent work by Zhuge *et al.* (2011), an electric turbo compound gasoline engine with Fixed Geometry Turbine (FGT) and Variable Nozzle Turbine (VNT) was tested using engine performance software GT-Drive was able to achieve improvement of fuel economy by 4.74% and 1.86% under US06 and FTP75 simulation of high loading and low loading driving cycles respectively (**Table 1.1**).

**Table 1.1**. Performance of ETC systems under driving cycles (Zhuge *et al*. 2011)

| | ETC with FGT | | ETC with FGT (Turbine Speed Control) | | ETC with VNT | |
|---|---|---|---|---|---|---|
| Driving cycles | US06 | FTP75 | US06 | FTP75 | US06 | FTP75 |
| Average power (kW) | 15.1 | 4.76 | 15.1 | 4.76 | 15.1 | 4.76 |
| Electric power (kW) | 1.01 | 0.266 | 0.969 | 0.286 | 1.05 | 0.297 |
| Fuel consumption (g) | 812 | 1243 | 803 | 1214 | 810 | 1220 |
| Fuel consumption of original engine (g) | 844 | 1234 | 843 | 1237 | 848 | 1240 |
| Improvement of fuel efficiency | 3.8% | -0.73% | 4.74% | 1.86% | 4.48% | 1.61% |

*The Federal Test Procedure 75 (FTP-75) simulation cycle has been used for emission certification and fuel economy testing of light-duty vehicles in the United States, while US06 was the supplemental test to FTP75 which is more towards aggressive acceleration and rapid fluctuation driving behaviour.*

The design of a downstream power turbine eliminates the integration complexity of electric machine into the engine turbocharger. However, the design also has implication to the system architecture. As the exhaust pressure at the exit of the main turbocharger turbine is relatively low, the additional turbine installed must be able to recover the exhaust energy at low pressure. Conventional and of the shelf turbine performance in meeting the low pressure requirement was very poor, so a patented high performance Low Pressure Turbine (LPT) design was developed to mitigate this issue (Aman *et al.* 2011). The LPT design work was in conjunction with HyBoost low carbon vehicle project for exploratory waste heat recovery system in a heavily downsized GDI engine.

## 1.3 Motivation

The thesis work is based on various electric turbo compounding project. However, it is focused on previous HyBoost project which is the acronym for the Hybridised Boosted Optimised System with the turbo compounding unit. A heavily downsized Ford three-cylinder 1.0 liter turbo GDI EcoBoost engine was used against a naturally aspirated 2L four-cylinder port-injected gasoline engine as its baseline comparison. Variable Torque Enhancement System (VTES) or electric supercharger has been used to eliminate the turbo lag. In the system, the function of electric turbo-compound unit in the project was to supply continuous charge to battery charger or energy storage and controller for the use of VTES (Refer **Figure 1.5**).

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*HyBoost project was funded by the United Kingdom Technology Strategy Board (TSB) with aim was to reduce the carbon emission from 169 g/km to 99.7 g/km. The research was led by Ricardo UK Ltd in partnership with Ford (UK), Valeo, Control Power Technologies, European Advanced Lead Acid Battery Consortium (EALABC) and Imperial College London.*

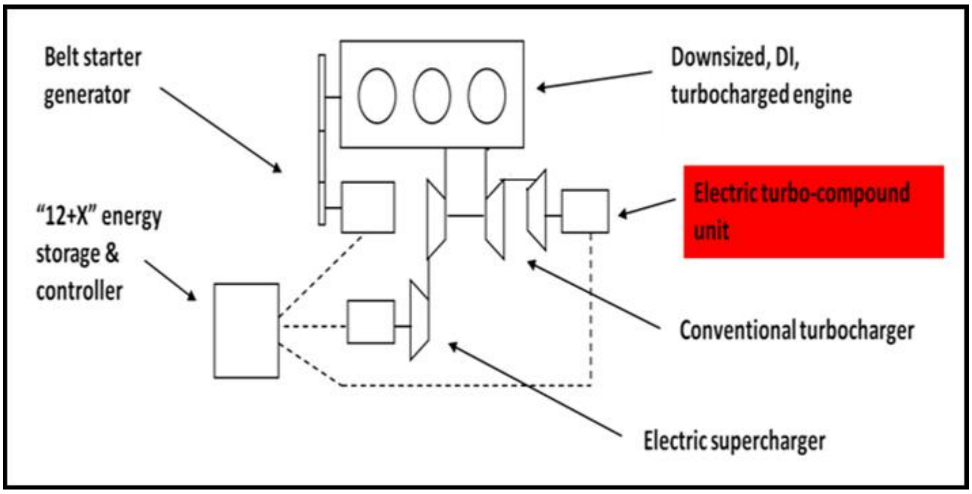


**Figure 1.5**. HyBoost Engine Architecture (Mamat *et al.* 2011).

The simulation results in 1-D Ricardo Wave dynamic code results have shown that an improvement in *BSFC* and *BMEP* of as much as 3 % can be achieved. In a test bed result, shows the use of LPT at the exhaust post catalyst location enable a maximum *BSFC* reduction of 2.6% and recovers exhaust energy of 1.3 kW. However, it was observed that the model channeled the recovered exhaust energy into the crankshaft of the engine and not to an electric generator; with the assumption of mechanical efficiency of 100%. Therefore, it is the intention of this research to simulate the energy recovered by introducing electric turbo compounding or electric generator into the engine model and aim to achieve the same amount of BSFC and BMEP improvement.

This research mainly focuses on two aspects; first to model and simulate a heavily downsized Ford three-cylinder 1.0 liter turbo GDI EcoBoost engine with downstream turbo-electric generator by integrating it into the 1-Dimensional AVL Boost gas dynamic engine model. Secondly, to validate the results with data provided by Imperial College London, Ricardo UK Ltd and previous work from Mamat, (2011) with aim of achieving BSFC reduction of 2% or higher percentage and energy recovery of 1kW.

## 1.4 Thesis Objective

The thesis presents the simulation and validation work of the Electric Turbo Compounding (ETC). The research objective is to analyse the performance of a turbocharged gasoline engine with ETC by using 1-D modeling and simulation against previous experimental result.

## 1.5 Thesis Scope

In the present research, a model of Electric Turbo Compound for a turbocharged gasoline engine is proposed. The model is inspired from a detailed and comprehensive investigation of previous research work. The simulation process was done through engine performance simulation software AVL Boost. The engine simulation was based on the ETC unit located after the engine turbocharger whereas in the HyBoost setup the location of ETC was after the catalyst (post catalyst). These simulations define the optimum dimensions and structure of the ETC to meet the performance requirements. For the validation purpose of simulation results, a comparison between such results and experimental results produced from PhD thesis by Dr Aman Mohamad Ihsan bin Mamat and other published papers is composed.

## 1.6 Thesis Outline

The content of this dissertation is basically divided into five main chapters. Chapter 1 introduces the reader to the background of engine downsizing and waste heat recovery. The research motivation is derived from the existing HyBoost project with the objective to prove and validate electric turbo-compounding simulation based on the data obtained from Imperial College London. Chapter 2 provides the literature reviews of this topic for the reader to recognize the present achievements of the researches concerning the field of GDI, engine downsizing and available waste heat recovery system. Chapter 3 involves the 1-D gas dynamic and mathematical modeling of the system. Chapter 4 displays the overall graphical and written results together with general discussions from the modeling, simulation and validation of the system. Finally, Chapter 5 covers conclusions drawn based on the results of the analysis and outlines some of the recommendations for possible future works on the similar subject.

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