PREDICTION OF AN ELECTRICALLY TURBOCHARGED ENGINE AND PERFORMANCE PREDICTION IN AN ACTUAL DRIVE CYCLE

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ABSTRACT

The study involves the evaluation of the energy recovery potential of turboshaft separated (decoupled) electric turbocharger and its boosting capability in a spark-ignition engine through simulation-based work and comparing it to a conventional turbocharged engine over an actual drive cycle. The main objective of this study is to develop a 1-D numerical model and evaluate the amount of energy that can be recovered over a steady state full-load operating conditions, part-load conditions, and actual, transient drive cycle conditions besides investigating the capabilities of an electric turbocharger. The electric turbocharged system includes two motors and a battery pack to store the recovered electrical energy. GT-Power engine simulation software was used to model both engines and utilizes each of the components described earlier. The conventional turbocharged engine model is first simulated to obtain its performance characteristics. An electric turbocharger is then modelled by separating the turbine from the compressor. The turbine is connected to an electric generator and battery, whereas the compressor is connected to a separate motor. This electrically turbocharged engine was modelled at full load and controlled to produce the same brake power and brake torque characteristics as the similarly sized conventional turbocharged engine. The evaluation of energy recovered from the electrically turbocharged engine from the analysis can assessed in full-load steady state conditions that can be useful for research in part-load and transient studies involving the decoupled electrical turbocharger. At 2500 and 3000 rpm, the energy recovery was 0.57 kW and 0.5 kW respectively at steady state. The maximum electrical energy that was recovered was 5.25 kW at 6500 rpm. Both engines had the same fuel consumption over a drive cycle while no energy recovered for the entire duration of the drive cycle simulation.

ABSTRAK

Kajian ini melibatkan penilaian potensi pemulihan tenaga oleh pengecas turbo elektrik yang dipisahkan acinya dan keupayaan galakan (boost) dalam enjin pencucuh spark melalui kaedah berasaskan simulasi dan membandingkannya dengan enjin turbo konvensional di dalam kitaran pemanduan sebenar. Objektif utama kajian ini adalah untuk membangunkan model 1-D dan menilai jumlah tenaga yang boleh dipulihkan dalam keadaan stabil operasi beban penuh, keadaan beban separa, dan di dalam keadaan kitaran pemanduan sebenar selain menyiasat keupayaan turbo elektrik. Sistem turbo elektrik merangkumi dua motor dan pek bateri untuk menyimpan tenaga elektrik yang dipulihkan. Perisian simulasi enjin GT-Power digunakan untuk memodelkan kedua-dua enjin dan menggunakan setiap komponen yang terlibat. Model enjin turbo konvensional disimulasi terlebih dahulu untuk mendapatkan ciri-ciri prestasinya. Turbo elektrik kemudiannya dimodelkan dengan memisahkan turbin dari pemampat. Turbin disambungkan ke penjana elektrik dan bateri, manakala pemampat disambungkan ke motor yang berasingan. Enjin turbo elektrik ini disimulasi pada beban penuh dan dihad untuk menghasilkan kuasa dan tork yang sama seperti enjin turbo konvensional bersaiz sama. Penilaian tenaga yang dipulih dari enjin turbo elektrik berdasarkan analisis pada keadaan mantap semasa beban penuh digunakan untuk penyelidikan dalam kajian sebahagian beban dan kitaran pemanduan yang melibatkan engin turbo elektrik yang berasingan aci. Pada 2500 dan 3000 rpm, pemulihan tenaga adalah 0.57 kW dan 0.5 kW masing-masing pada keadaan mantap. Tenaga elektrik yang paling banyak dipulih ialah 5.25 kW pada 6500 rpm. Kedua-dua enjin mempunyai penggunaan bahan api yang sama sepanjang kitaran pemanduan manakala tiada tenaga dapat dipulih untuk keseluruhan tempoh simulasi kitaran pemanduan.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols		**Definitions**
(ΔX)	-	Actuator input
ɿ	-	Total fuel consumed
η	-	Compressor efficiency
P_{em}	-	Electric machine power
p_{exh}	-	Exhaust pressure
τ	-	Time constant
ω	-	Angular velocity
1-D	-	One dimensional
BMEP	-	Brake mean effective pressure
BSFC	-	Brake-specific fuel consumption
BSG	-	Belt-driven starter generator
CamPro	-	Cam profiling
CDA	-	Cylinder deactivation
CFE	-	Charged fuel efficiency
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
DC	-	Direct current
EAT	-	Electrically assisted turbocharger
eC	-	Electric supercharger
EGR	-	Exhaust Gas Recirculation
EST	-	Electrically split turbocharger
ETA	-	Electrical turbocharged assistance
ETC	-	Electric turbo-compounding
e-turbo	-	Electric turbocharger

hp	-	horsepower
ICE	-	Internal combustion engine
IMEP	-	Indicated Mean Effective Pressure
K	-	Output ratio
kW	-	Kilowatt
kWh	-	Kilowatt per hour
NEDC	-	New european driving cycle
Nm	-	Torque
NOx	-	Nitrogen oxide
ODE	-	Ordinary differential equation
ORC	-	Organic rankine cycle
P	-	Motor power
PID	-	Proportional integral derivative
rpm	-	Revolutions per minute
SI	-	Spark-ignition
T	-	Torque
TEG	-	Thermoelectric generator
VFD	-	Variable-frequency drive
VVT	-	Variable Valve Timing
W	-	Power
WLTC	-	Worldwide harmonized light vehicles test cycle
Y	-	System response
$Y_{initial}$	-	Initial response

LIST OF APPENDICES

LIST OF PUBLICATIONS

I. K. Subramaniam., W. S-I. Wan Salim., (2021) Part-Load Simulation and Energy Recovery Evaluation of An Electrically Turbocharged Engine Low Engine Speeds, Journal of The Society of Automotive Engineers Malaysia, SOCIETY OF AUTOMOTIVE ENGINEERS MALAYSIA

II. K. Subramaniam., W. S-I. Wan Salim., (2021) Modelling an Electrically Turbocharged Engine and Predicting the Performance Under Steady-State Engine, International Journal of Automotive and Mechanical Engineering, Universiti Malaysia Pahang Publisher

CHAPTER 1

INTRODUCTION

1.1 Background study

The automotive industry has been identified as a key source of greenhouse gases which causes climate change around the world. This has led to major legislations put upon the automotive industry to reduce and eventually negate the negative impact to the environment. Carbon monoxide (CO) and nitrogen oxide (NOx) emissions are limited to 1g/km and 0.08 g/km respectively under Euro 6 requirements while carbon dioxide (CO_2) emissions are limited to 98 g/km [1]. Figure 1.1 shows the CO_2 emissions per transported passengers for the European Union member nations for the year 2019 [2].

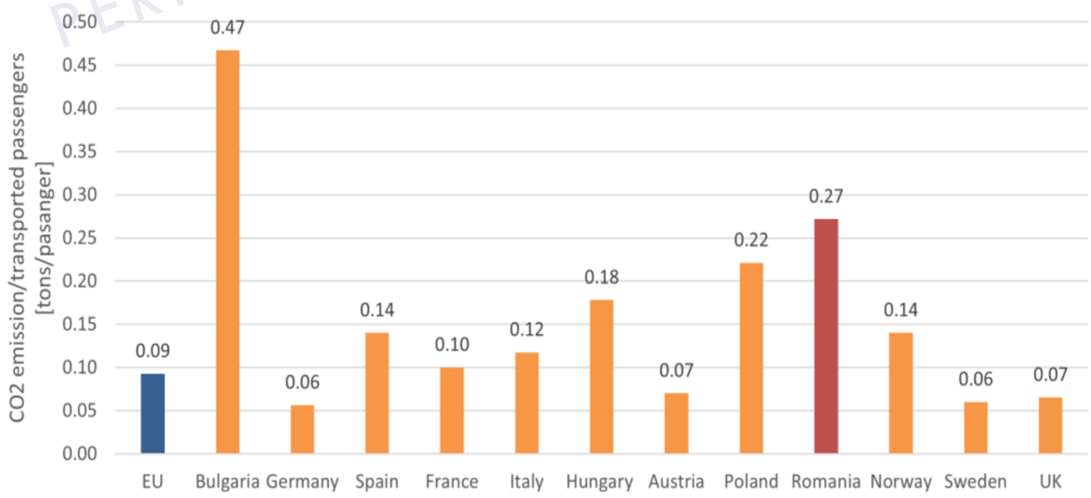

Figure 1.1: CO_2 emissions per transported passengers for the European Union member nations for the year 2019 [2].

The figure reflects the urgent need to reduce emissions further to safeguard the environment and also making the automotive industry more sustainable. Major automotive manufacturers have had to heed to calls by the regulators around the globe in reducing carbon emissions. This has led to more efficient engines being produced for the commercial and passenger car market. The efficiency of an engine is translated upon by the amount of fuel consumed which is indicated by the CO_2 emissions produced by the engine. Hybrid plug ins and boosting have been viable routes taken by manufactures to improve upon the emissions levels of the vehicles they produce. Boosting can be implemented on an internal combustion engine via the process of downsizing which requires forced induction process.

1.1.1 Engine downsizing

One of the technologies that has gain traction due to this is downsizing via turbochargers. Downsizing reduces the friction and throttling losses due to the decrease in the size of the engine. This is achieved by improving the combustion process in the combustion chambers by forced- induction using turbochargers. Turbochargers act as a waste heat recovery system in recuperating the otherwise lost exhaust gases through a turbine which turns the compressor connected by a turboshaft. The compressor facilitates in increasing the intake pressure to improve the efficiency of the engine.

While the advantages of the turbocharged engine make it a popular choice for auto manufacturer to comply to emission standards, the driveability of the vehicle suffers due to the bad transient response commonly associated with turbocharged engines. The time taken for the energy transfer to take place causes a delay in power and torque output. Besides, not all the energy from the exhaust gases is recovered. Most of them are still lost through the wastegate which prevents the turbocharger from over speeding and being inefficient. Turbocharged engines also face challenges in being efficient at low engine speeds. Past studies have shown that turbocharged engine’s BSFC worsens in a drive cycle compared to naturally aspirated engines due to high back pressure build up at the turbine and the operation of the turbocharger at low efficiency points.

The use of an electric turbocharger eliminates the delay in transient response and enables the possibility of recovering the exhaust gasses lost through the wastegate. Electric turbocharger is a forced-induction system where an electrical machine commonly a motor generator is mated to the shaft between the turbine and the compressor whereby it assists the compressor when power is needed during a drive cycle and recovers energy from the turbine and stores in a storage component, usually a battery when otherwise. The assisting of the compressor by an electrically motor essentially eliminates the transient delay as power is instantly provided by the battery pack where electrical energy is stored. The electrical turbocharger can also be used as replacement for the wastegate therefore enabling all the exhaust gasses to pass through the turbocharger. The electrical turbocharger can also make sure the compressor always operates at high efficiency points over the whole drive cycle by providing enough energy from the motor generator. This will further increase the intake pressure causing more efficient combustion to take place in the combustion chamber, improving the performance of the engine.

Further studies need to be done to make electrical turbocharger system more feasible in the automotive industry by researching more on the issues concerning it. One of the main issues are that of fuel economy and energy recovery capabilities of the system at low engine speeds. The system needs to be investigated on an actual urban drive cycle as the engine speed range of urban drive cycles are usually of low engine speeds and most common among passenger vehicles in Malaysia nowadays. Another area of interest should be on the different configuration of the electrical turbocharger. Studies need to be made of the performance of the engine in correlation to the different arrangement of the electrical turbocharger system.

1.2 Problem statement

A waste heat recovery system enhances the efficiency of an engine by way of recuperating waste heat energy from the exhaust system and mechanical energy from the vehicle braking system. In high performance and motor-sport applications, full-load engine operations are ever-present. As opposed to this, engines on normal passenger vehicles operate mostly at low loads and speeds. Therefore, the amount of energy that can be recuperated during operation can be a lot less compared to their motorsport counterpart. It is therefore very crucial to characterize and estimate the amount of energy available for extraction from the combustion engine over normal driving conditions if such a system is to be introduced in normal road vehicles such as passenger cars.

On top of this, another aspect that need to be investigated is what effect does the electrical turbocharger have to the boosting process at the intake manifold and performance of the engine in a driving cycle. This is necessary as the separation of the turboshaft from the turbine and compressor would provide the flexibility to control the energy recovery process at the turbine and the boosting process at the compressor.

1.3 Research objectives

This study aims at achieving the following objectives:

i. To develop a numerical model of electric turbocharging system for both energy recovery and boosting system.
ii. To compare the performance of the electrical turbocharger to the conventional turbocharger over a drive cycle.
iii. To estimate amount of energy that can be recovered by the electrical turbocharger over steady-state, part- load and drive cycle.

1.4 Scope of study

The focus of this study is to model and simulate an engine model to determine the energy recovery of the electrical turbocharger over a real drive cycle and comparing its performance to a conventional turbocharger of similar engine displacement. A 1-D engine simulation software is used to model the engines and obtaining the performance data of the engines. The base engine used is a 1.6 litre turbocharged engine. The modelling process, comparison of the performance and estimation of energy recovered over a drive cycle are studied for the electrical turbocharger engine.

i. Modelling and simulation is done involving both conventional turbocharger engine and electrical turbocharger engine. The components involved are an Internal Combustion Engine, turbocharger for waste heat recovery, motor generator and a battery for the electrical turbocharger. A turbocharged engine comprising of components such as throttle, cylinder and exhaust runner is used as the primary engine model. This turbocharged engine is then connected with a motor generator to act as the power source supplied from the battery which is recharged when power demand is less. Selection of the electrical machines would be based on existing technologies. This includes the use of existing motor generator units and battery.

ii. The performance of the conventional turbocharged engine and electrical turbocharged engine over a drive cycle is compared in terms of engines parameters such as Brake Power, Brake Torque, BSFC and Cumulative fuel consumption. The drive cycle used is based on an actual road test done on specific routes around Kuala Lumpur. This drive cycle is an urban drive cycle which mainly consist of traffic congestion and short sprints.

iii. The estimation of energy recovered is done by obtaining the net energy produced by the system. This is done by subtracting the amount of electrical energy produced by the generator at the turbine with the amount supplied at the compressor. The energy recovered is represented in kW as the component used for recovery is an electrical component.

1.5 Significance of study

It is hoped that all the research questions can be answered after thorough investigation regarding the theories and hypothesis of this project. In general, the use of the 1-D software would classify the mechanics of the internal combustion engine. It would not only be useful in modelling of the real conditions of the engine but would be crucial in determining the performance of the engines. The results would be available at the end of the simulation in post processing.

By carrying out the simulation, we would be able to predict the amount of energy that would be generated or recovered from an electrical turbocharged engine. This would eventually enable us to compare with other kinds of engines or different setups of the system in terms of performance and fuel economy.

This project would propose an electrical turbocharger consisting of a separate turbo shaft between the turbine and the compressor. The outcome of this project would enable us to determine whether electrical turbocharger is efficient and viable in incorporating with the internal combustion engine of a passenger vehicle at real driving conditions.

The other ideal outcome that is expected from this study is the effect a compressor operating at optimum levels at all times would have on the boosting process of the engine and engine BSFC.

1.6 Outline of thesis

The overall outline of the thesis is elaborated and summarized in Table 1.1 with each part of the thesis discussed with detail.

Table 1.1: Outlines of thesis.

Chapter	**Title**	**Description**
Chapter 1	Introduction	Includes Background of study, Problem statement, Research objectives, Scopes of study, Significance of the study and outline of the thesis.
Chapter 2	Literature Review	Contents of this chapter will be about the previous studies concerning conventional turbocharging and electric turbocharging. The mode of simulation and type of components will be recognised, analysed, and correlated with other studies done previously.
Chapter 3	Methodology	For this study, the simulation procedure was divided into three parts. The first part was the steady-state full load simulation where both the base engine model and the electrical turbocharged engine was run at full throttle to determine the maximum Brake Torque (Nm) and Brake Power (hp). Next, part-load simulation was carried out on the electrical turbocharged engine where the engine model was simulated to run at a steady engine speed but varying engine torque loads. The simulation was repeated by increasing the engine speed. Lastly, both the base engine and the electrical turbocharged engine were run on a transient simulation based on an actual drive cycle.

Table 1.1: Outlines of thesis. (continued)

Chapter 4	Result and Discussion	
		In this chapter, the findings of the engine simulations of both engines were discussed extensively. To ensure clear presentation of the findings, the data was illustrated in figures, graphs and tables and discussed with numerical data and statistics supported by previous studies by other researchers. The steady state and transient analysis were discussed for both base CFE engine and the e-turbo CFE engine model while part-load was described for the e-turbo CFE model. The steady state and transient analysis were divided into two section, engine performance data and energy recovery data. Each section relates to the objectives of this research. The part-load analysis was done using compressor power demand and net electrical energy recovery.
Chapter 5	Conclusions and recommendations	This chapter explains the summary of the study accordance with the objectives of study and detail recommendations for future work.
	References	A list of references citing other researchers of their work.
	Appendices	A collection of relevant documents and raw data from the simulation. Copies of the papers published from this study was also included.

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