Deploying Variable Valve Timing System in 'OM457' Diesel Engine to Reduce Specific Fuel Consumption and Its Impact on Emissions

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Deploying Variable Valve Timing System in 'OM457' Diesel Engine to Reduce Specific Fuel Consumption and Its Impact on Emissions

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Abstract
Applying Variable Valve Actuation systems is one of the most effective ways to improve Brake Specific Fuel Consumption in an engine, which largely affect the pumping work. In this article determination of optimum valve timing angels, using Approximation of Discrete Data by a Curve is investigated for a HD diesel engine to minimize BSFC. In the first part of this study a model of Compression Ignition engine (OM457) in GT-SUITE software are applied for optimization. Then the indicated best angels for EVO, IVO, EVC and IVC were added to the model as lookup tables to shape the VVT system. Eventually, results indicated that using VVT angles the BSFC parameter decreases more than 2% in average. Furthermore in order to compare differences in emissions rate, the European Stationary Cycle (ESC) was applied and generated NOx pollutant was reduced to 92.6%.

Keywords: OM457 Diesel Engine, Variable Valve Timing, Optimization, Specific Fuel Consumption, Specific Emissions.

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1. INTRODUCTION:

DIESEL engines are favored in heavy-duty commercial and military applications as they have high performance in terms of fuel economy, torque at low speed, and power density [1]. For that purpose the intake and exhaust valve timing of an engine greatly influence the fuel economy, emissions, and performance of an engine. Conventional valve train systems can only optimize the intake and exhaust valve timing for one given operational condition. That is, the optimized valve timing can either improve fuel economy and reduce emissions at low engine speeds or maximize engine power and torque outputs at high speeds. However, with the development of continuously variable valve timing (VVT) systems, the intake and exhaust valve timing can be modified as a function of engine speed and load to obtain both improved fuel economy and reduced emissions at low engine speeds and increased power and torque at high engine speeds [2]. VVT is computer-controlled and typically uses oil pressure to change the position of a phaser mechanism on the end of the camshaft to advance or retard cam timing [3].

The first VVT systems came into existence in the nineteenth century on early steam locomotives, supported variable cutoff. In early 1920s, VVT was developed on some airplane radial engines with high compression ratios to enhance their performance [4] and in automotive applications, the VVT was first developed by Fiat in late 1960 [5]. Considering the ability of the system it was soon used by other companies like Honda [6] General motors, Ford and other automobile manufacturers [7].

The aim of this paper is to find the optimum angels for EVO, EVC, IVO and IVC regardless of any specific mechanism to operate VVT system and offering a suitable method to benefiting from the least of generated pollutions or from maximum fuel efficiency at the appropriate place.

In order to evaluation of the optimum angels, a one dimensional model of 'OM457' engine will be used. To summarize the calculation, EVC and IVO angels

are linked together as overlap of valves. Consequently only EVO, overlap and IVC are three independent parameters to calculate.
Unfortunately the best angels to achieve the least of BSFC and pollutants are different, so two sets of angels will be evaluated. The first set is to reach minimum BSFC and it is named Economic-VVT (E-VVT) along with the second set which is to obtain minimum generated pollution and it is named Green-VVT (G-VVT). Both of these modes can be considered in the engines in such a way that driver changes the function of engine to G-VVT in urban roads or changes it to the E-VVT mode outside of the cities. The command of switching engine mode can also be submitted to the vehicle without driver's authorization. It is possible to use wireless systems to send the instruction to the vehicle at certain distance of the city.
At the second phase of this paper, a control unit will be adding to the 1-D model of engine to change the optimum angels in different revolutionary speeds and finally, at third phase the ESC test will be operate to compare the engine emissions with and without VVT system.

۲. METHODOLOGY:

In order to find the best EVO, IVC and overlap degrees, GT-suite software was applied to study and calculate the optimum parameters related to BSFC and pollutions. A one dimensional model of 'OM457' engine was used for optimization of proposed parameters and Figure 1 is representing this model.
'OM457' is a Diesel engine with maximum Torque of 1598 [Nm] in 1200 [rpm] and maximum Power of 350 [HP] in 2000 [rpm]. Some characteristics of this engine are listed in Table 1.

Table 1: Characteristics of 'OM457'

No. of cylinders / Location	6 / In-line
Engine Displacement [Liter]	12
Bore [mm]	128
Stroke [mm]	155
Connecting rod length [mm]	247
Compression ratio	17.5:1
Aspiration	Single Turbocharger
Dry weight [Kg]	1045

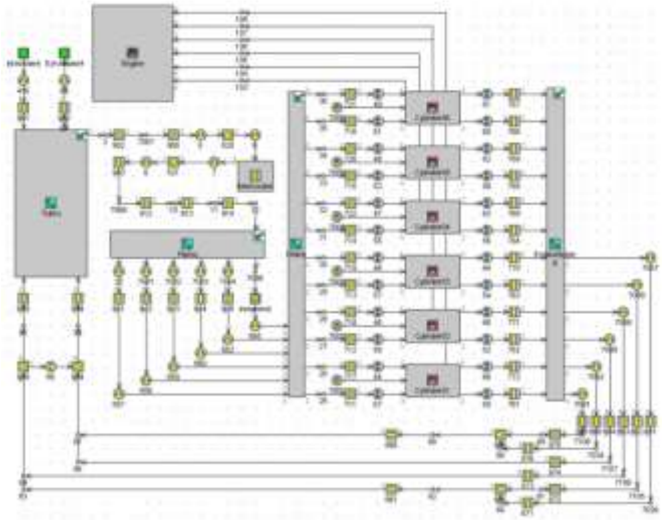
Figure 1: 1-D model of OM457

In order to achieve a reliable model, with reducing the error between the models output and experimental results, some parameters were achieved in DESA Company and they were added to software model. The software also performs the calculation several times to achieve converged results. For this problem, the work will be followed in four stages:

Stage 1: Optimization of EVO, IVC and overlap degrees to achieve optimum values for BSFC and NSP parameters.

Stage 2: Adding a control unit to the valves in order to change timing and shape the VVT system.

Stage 3: Operating the ESC test to illustrate the difference between engine emissions with and without VVT system.

2.1. Stage one: For these type of optimization problems, different methods like sensitivity analysis [8] or variation methods, genetic algorithm [9] Neural Networks [10] and the cascade model [11] have been applied. In this paper, the EVO, IVC and overlap degrees considered as input variables and the BSFC and Normalized Specific Pollution (NSP) is the output.
In some cases due to the decoupled response of parameters based on the EVO, IVC and overlap degrees, it is possible to find the best value for EVO, IVC and valves overlap as follow:

1. Find the best EVO, considering a fixed value for IVC and overlap. (The IVC could be equal to IVC of based engine.)
2. Find the best amount for IVC, considering the best amount of EVO but maintaining the overlap value.
3. Find the best value for the engine overlap, considering the optimum amounts of EVO and IVC.
4. After choosing the best values for EVO, IVC and overlap values, it is necessary to shift them in order to check the authenticity of the results.

For 'OM457', the DOE method used to shape the standardized effects and check the dependency of elements in responses. By utilizing with Minitab software, it was specified that the EVO, IVC and valves overlap degrees do not have any interaction in the proposed range.

2.2. Stage two: The obtained values for the best EVO, IVC and overlap degrees in each revolutionary speed have been collected in four lookup tables as showed in Figure 2. In this scheme, VVT system uses the feedback of revolutionary speed of engine and changes the EVO, IVC and overlap degrees to achieve the optimum values.

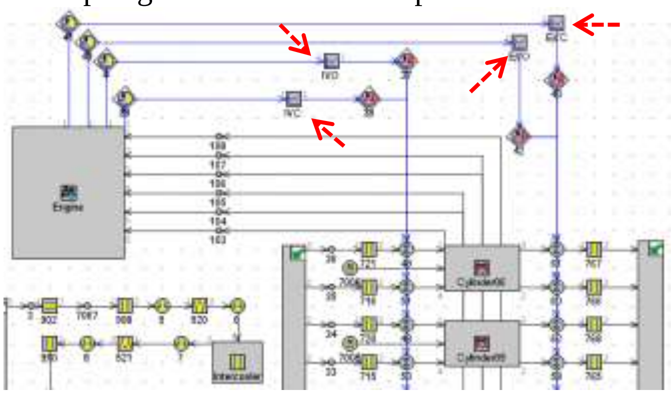

Figure 2: lookup tables of VVT system

In this stage, after deploying VVT system which causes additional MEP and reduction of wasted power in pumping cycles, it is possible to modify the injected fuel in each cycle. Respecting to other features of engine such as maximum MEP, the injected fuel into the cylinder in each cycle could be modified. After fuel modification, another alternation in emission rate is expected.

2.3. Stage three: The following table includes a summary of the emission standards and their implementation dates for HD diesel engines. [12]

Table 2: EU Emission Standards for Heavy-Duty Diesel Engines [12]

Stage	**Date**	**Test**	CO [g/kWh]	**HC** [g/kWh]	**NOx** [g/kWh]
Euro I	1992, ≤ 85 kW	ECE R-49	4.5	1.1	8.0
	1992, > 85 kW		4.5	1.1	8.0
Euro II	1996.10		4.0	1.1	7.0
	1998.10		4.0	1.1	7.0
Euro III	1999.10	ESC & ELR	1.5	0.25	2.0
	2000.10		2.1	0.66	5.0
Euro IV	2005.10		1.5	0.46	3.5
Euro V	2008.10		1.5	0.46	2.0
Euro VI	2013.01	WHSC	1.5	0.13	0.40

The proposed model of engine in this paper comply the Euro IV standard, so in order to realize engine emissions, the ESC and ELR standards could be executed. Since only software analysis is considered in this paper, the ESC test will be implemented to assess emissions.

In order to evaluate the optimum angels to reach minimum emission rate a normalized parameter will utilize to find optimum angels and it is named Normalized Specific Pollution or NSP. The NSP parameter can be obtained according to equation 1:

$$NSP = a.NNOx + b.NHC + c.NCO \qquad (1)$$

Where label of N behind the pollutants indicate the normalized value between 0 to 1 and a, b, c are fixed weighting factors that for 'OM457' and they are selected respecting to primary engine emissions as shown in Table 3.

Table 3: weighting factors

sign	value
a	0.936908
b	0.007709
c	0.055383

The minimum values for BSFC and NSP occur in different angles as demonstrated in Figure 3 for EVO in 2000 [rpm]. Thus, in this paper one set of angles will be proposed to achieve optimum BSFC and another set of angles will be proposed to achieve optimum NSP.

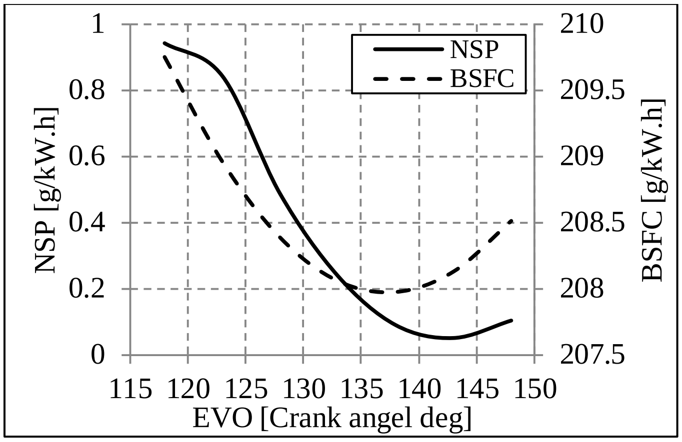

Figure 3: Variation of NSP & BSFC for different EVO angles at 2000 [rpm].

European Stationary Cycle (ESC): The test cycle consists of a number of speed and power modes which cover the typical operating range of diesel engines. It is determined by 13 steadies and modes.
The engine is tested on an engine dynamometer over a sequence of steady-state modes as illustrated in Table 4 and Figure 4. Emissions are measured during each mode and averaged over the cycle using a set of weighting factors. Particulate matter emissions are sampled on one filter over the 13 modes. The final emission results are expressed in [g/kWh]. [13]

Table 4: ESC Test Modes [13]

Mode	Engine Speed	Load [%]	Weight [%]	Duration [min]
1	Low idle	0	15	4
2	A	100	8	2
3	B	50	10	2
4	B	75	10	2
5	A	50	5	2
6	A	75	5	2
7	A	25	5	2
8	B	100	9	2
9	B	25	10	2
10	C	100	8	2
11	C	25	5	2
12	C	75	5	2
13	C	50	5	2

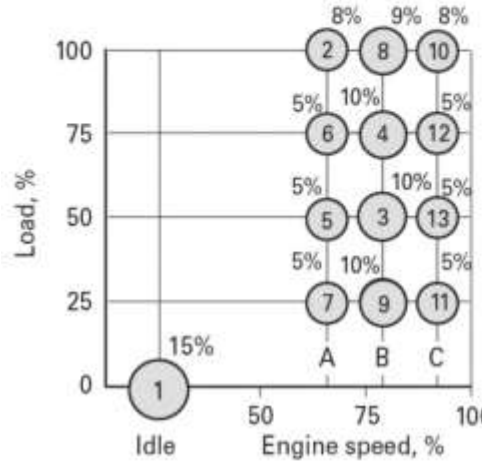

Figure 4: European Stationary Cycle (ESC)

In accordance with the ESC testing procedure, the summed average emission will be calculated in the following way:

$$e_{g/kWh} = \frac{\sum_{i=1}^{13} e_i * WF_i}{\sum_{i=1}^{13} P_i * WF_i} \tag{2}$$

Which e_i is emission in mode i [g/h], P_i is engine power in mode i [kW] and WF_i is weighting factor in mode i.

The catalysts used in the after-treatment system consist of catalytically active transition metal compounds, which are fixed onto ceramic carriers. The after-treatment system in modern Euro VI engines causes up to 96% reduction of NOx. Poor activity of the SCR[1] after-treatment system due to inactive catalysts may cause an increase in NOx emission and cause secondary damage in the engine itself due to an exhaust gas pressure increase.

۳. MODELLING RESULTS:

The OM457 has many applications, including Truck, marine, military, municipal, and agricultural vehicles, as well as stationary settings. The engine has differing trim and power levels [14]. Here are some of the features of this engine.

In this engine, the dedicated times for exhaust and intake valves are illustrated in Figure 5. Respect to crank angle degree, both exhaust valves open at 118 and close at 387. Moreover, both of the intake valves open at 336 and close at 576 degrees.

[1] Selective Catalytic Reduction

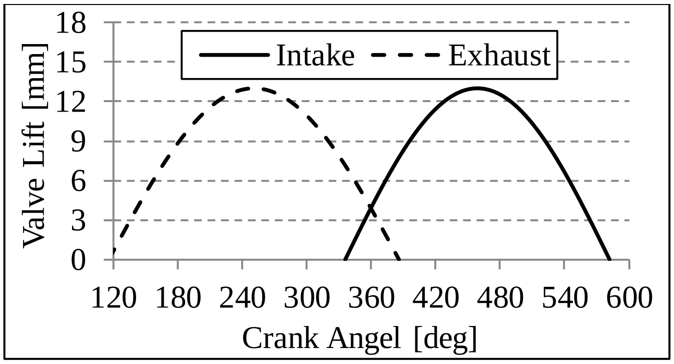

Figure 5: Vavle timing in OM457

In this model, the injected fuel in each cycle is illustrated in Figure 6. This picture indicates the climax of injected fuel at 1100 and 1200 [rpm].

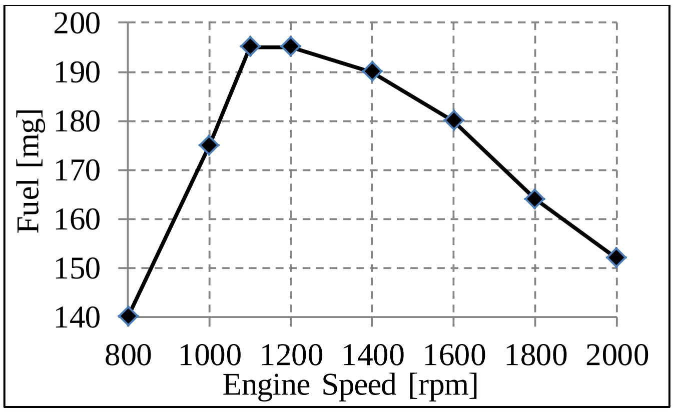

Figure 6: Injected Fuel in ‘OM457’ per cycle

The generated power and torque in ‘OM457’ engine, respect to the previous valve timing and injected fuel are illustrated in Figure 7.

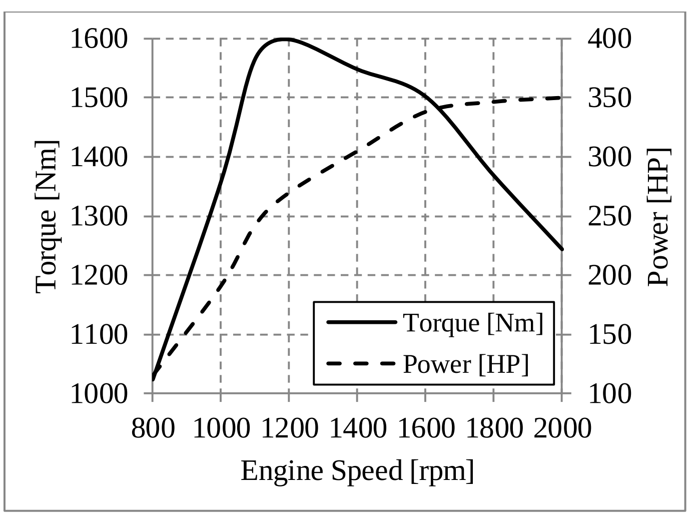

Figure 7: Power and Torque of ‘OM457’

3-1Optimized Angels:

The evaluated results for EVO, IVC and valves overlap for optimum BSFC and optimum NSP are gathered in Table 5 and 6 respectively.

Table 5: Valve Timing for Optimum BSFC in ‘OM457’

Engine Speed [rpm]	Optimized Parameter [Crank Angel Deg]		
	EVO	IVC	Valves Overlap
800	149	528	58
1000	148	541	55.5
1200	146	567	48
1400	144	590	46
1600	142	610	44
1800	139.5	621.5	40
2000	137	631	39

Table 6: Valve Timing for Optimum NSP in ‘OM457’

Engine Speed [rpm]	Optimized Parameter [Crank Angel Deg]		
	EVO	IVC	Valves Overlap
800	128	539	57
1000	129	541	57
1200	130	550	56
1400	134	559.5	54
1600	141	598.5	49
1800	143.5	606	48
2000	143	610	51.5

3-2: Results of Deploying VVT System:

After indicating the best angels in each revolutionary speed, these numbers inserted to 1-D model of engine as lookup tables. The evaluated torque in both economic and green modes is illustrated in Figure 8.

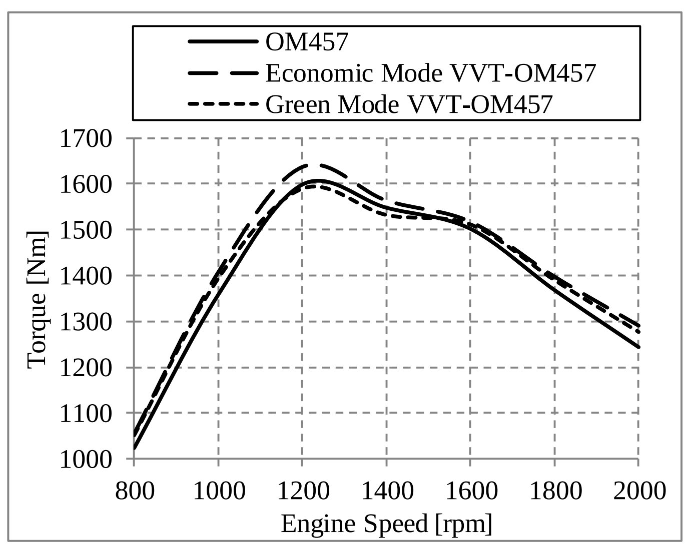

Figure 8: Generated Torque

As expected, the generated torque in E-VVT mode of operation is always greater than primary engine; however this parameter in G-VVT mode, in the middle range of speed is less than primary engine. Due to the constant amount of injected fuel in both modes, the same event is expected for BSFC as illustrated in Figure 9. All charts are drawn in the full load condition with the injected fuel of Figure 6.

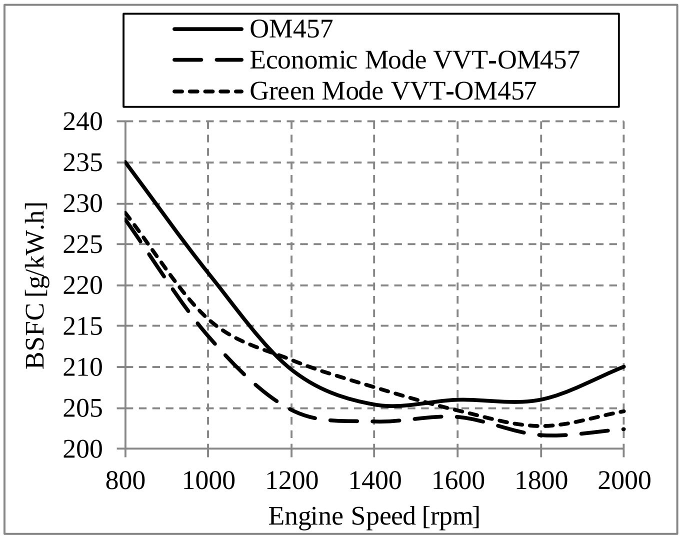

Figure 9: BSFC parameter

The specific emissions rate is showed in Figure 10 to 12. In figure 10 the NOx pollutant in G-VVT mode is always less than primary engine, but values of CO and HC pollutants are do not follow this role. The weighting factors in Table 3 are the main reason. Large weighting factor for NOx pollutant cause to set best angels in a way that engine in G-VVT mode generate minimum amounts of NOx.

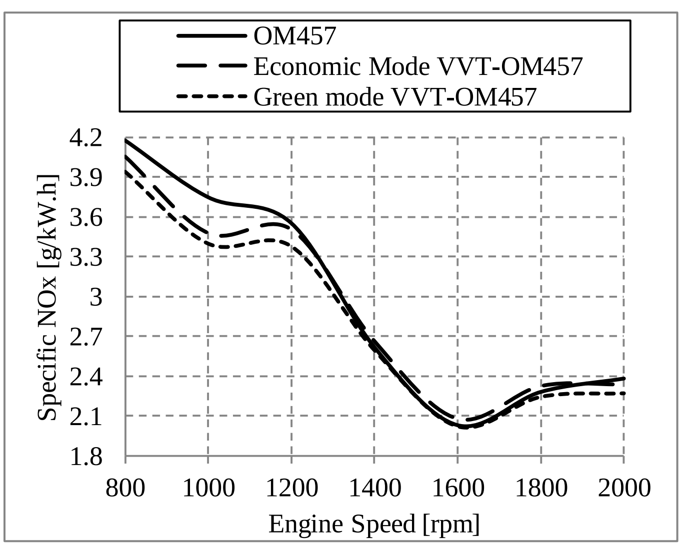

Figure 10: Specific NOx Emission

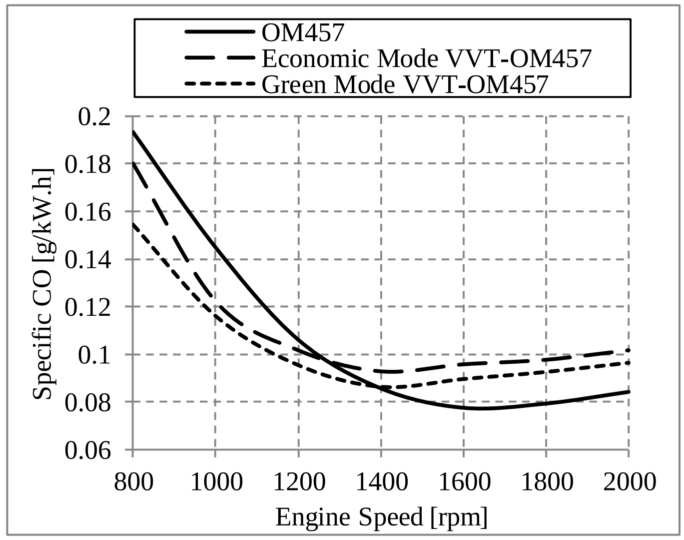

Figure 11: Specific CO Emission

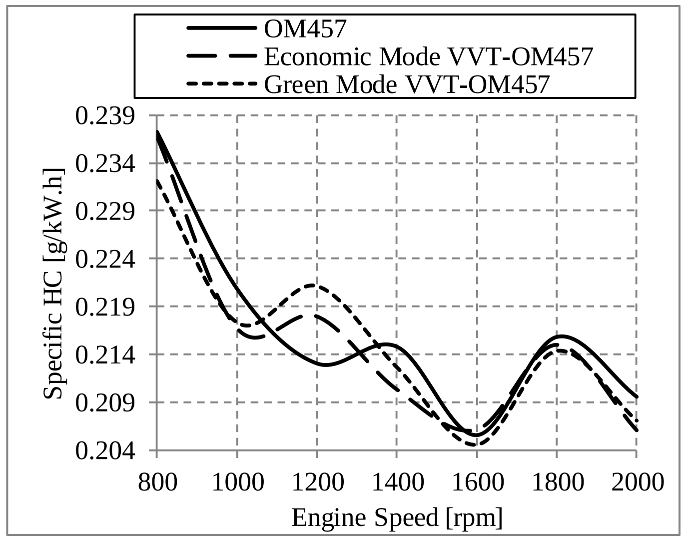

Figure 12: Specific HC Emission

As it can be observed in Figure 10 to 12 the values for both economic and green modes in upper bound of the middle range speed are close to the primary engine. It can be stated that the manufacturer set the valves timing in order to reach the optimum parameters in these speeds which are the average speeds of most standard cycles like ESC, WHSC[1] and even NRTC[2].

3-3 Results of European Stationary Cycle:

According to ESC test, the NOx pollutant rate decreases from 3.07 in primary engine to 2.84 in E-

[1] World Harmonized Stationary Cycle
[2] Non Road Transient Cycle

VVT mode. It also reduced in G-VVT mode to 2.75 [g/kWh]. The CO and HC pollutants had variations but it was not near to the standard bound. Figure 13 illustrates the variation of emissions in primary engine and VVT modes.

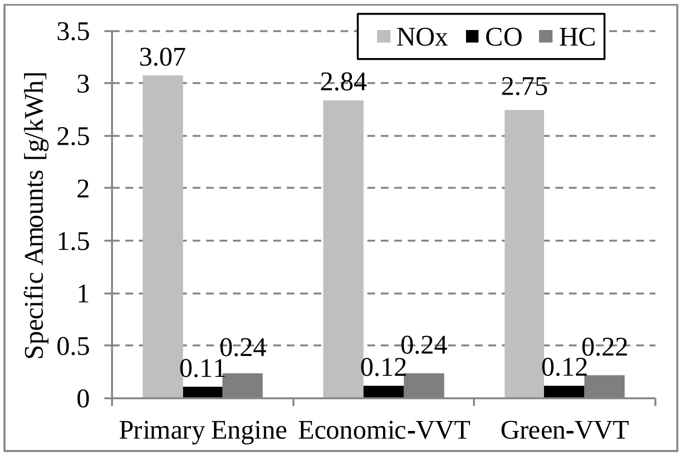

Figure 13: ESC test results

By applying VVT system in this engine the major emission of NOx decreases 7.4% in economic mode and 10.4% in green mode. The CO and HC levels during ESC test did not show any significant change.

4. CONCLUSION:

This paper indicates that generated torque in economic mode increased 2% in average while it increased 1% in green mode, due to primary ‘OM457’ engine. The BSFC decreased 2.3 and 1.2 percent in economic and green modes and NOx pollutant decreased 1.6% and 4.5% in economic mode and green mode respectively on average, from 800 to 2000 [rpm]. CO pollutant cut to 95% of original amounts in green mode and HC diminished 1% in both modes.

However, it was expected to improve emission standard from Euro IV to Euro V by using a VVT system, regarding to the intelligent design of the primary engine there is not much room to improve. The new series of ‘OM457’ also benefits from a better After Treatment System nowadays which improves emission standard up to Euro VI.

The evaluated results for EVO, IVC and valves overlap for optimum BSFC and NSP are based on different speeds of engine. In another approach, it is possible to determine the optimum valve timing as a function of either speed and load of engine.

ACKNOWLEDGMENT

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NOMENCLATURE:

VVT : Variable Valve Timing
EVO : Exhaust Valve Opening
EVC : Exhaust Valve Closing
IVO : Intake Valve Opening
IVC : Intake Valve Closing
BSFC : Brake Specific Fuel Consumption
E-VVT : Economic VVT
G-VVT : Green VVT
ESC : European Stationary Cycle
NSP : Normalized Specific Pollutant
DOE : Design Of Experiments
MEP : Mean Effective Pressure
CO : Carbon Monoxide
NOx : Nitrogen Oxides
HC : Hydro Carbon
ELR : European Load Response