

## Effect of Variable Valve Timing to Reduce Specific Fuel Consumption in HD Diesel Engine

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### Abstract

Applying variable valve Actuation systems is one of the most effective ways to improve 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 and nonlinear regression analysis is investigated for a HD diesel engine to minimize SFC. 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 SFC parameter decreases more than 2% in average. Furthermore, to compare differences in emissions rate, the European stationary cycle (ESC) was applied and generated NOx pollutant was reduced 7.4%.

**Keywords:** OM457 diesel engine; Variable valve timing; Optimization; Specific fuel consumption; Specific emissions

**Abbreviations:** VVT: Variable Valve Timing; VVA: Variable Valve Actuation; EVO: Exhaust Valve Opening; EVC: Exhaust Valve Closing; IVO: Intake Valve Opening; IVC: Intake Valve Closing; SFC: Specific Fuel Consumption; ESC: European Stationary Cycle; DOE: Design of Experiments; MEP: Mean Effective Pressure; CO: Carbon Monoxide; NOx: Nitrogen Oxides; HC: Hydro Carbon; ELR: European Load Response

### 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. Thus, 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. 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]. As one of the most promising control strategies for diesel engine, variable valve actuation (VVA) had attracted increasing attention due to its fast-response characteristics. Recently, several different VVA mechanisms have been implemented into diesel engines for realization of low emissions and high thermal efficiency [3].

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 [4]. The first VVT systems came into existence in the nineteenth century on early steam locomotives. In early 1920s VVT was developed on some airplane radial engines with high compression ratios to enhance their performance [5] and in automotive applications, the VVT was first developed by Fiat in late 1960 [6]. Considering the ability of the system it was soon used by other companies like Honda [7]. General motors, Ford and other automobile manufacturers [8]. The mechanisms currently available on the market allow, as a function of the engine operating conditions, variations in

the timing (VVT) or, in addition, in the lift (VVA). The aim of both the solutions is the adjustment of the load through reduced valve throttling; this adjustment provides a significant positive influence on the pumping work [9].

The aim of this paper is to find optimum angels for EVO, EVC, IVO and IVC in each revolutionary speed of 'OM457' engine to minimizing SFC parameter, regardless of any specific mechanism to operate VVT system. To evaluation of optimum angels, a one-dimensional model of 'OM457' engine was 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. At the second phase of this paper, a control unit will be adding to the 1-D model of engine to change 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. It must be noted that regarding the very stringent emissions limit for nitrogen oxides (NOx) and particulate matter (PM) (which will take effect in the EU and the US from 2008 and 2010 respectively), [10] these are unlikely to be met by using current VVT system.

### Methodology

The specific fuel consumption parameter measures how efficiently an engine is using the fuel supplied to produce work and it can be obtained by equation (1). The theoretical approach of the simulation is supplied by [11-13].

$$sfc = \frac{\dot{m}_f}{P} \quad (1)$$

In this equation  $\dot{m}_f$  is fuel flow rate and  $P$  is engine power. The power of a four-stroke engine can be expressed as

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$$P = \frac{mep A_p \bar{S}_p}{4} \quad (2)$$

where  $mep$  is mean effective pressure,  $A_p$  is area of the piston head, and  $\bar{S}_p$  is average speed of piston. The mean effective pressure or  $mep$  is given by

$$mep = \eta_f \eta_v Q_{HV} \rho_a (F/A) \quad (3)$$

Where  $\eta_v$  is volumetric efficiency,  $\eta_f$  is fuel conversion efficiency,  $Q_{HV}$  is the heating value of the fuel,  $\rho_a$  is the inlet air density and  $F/A$  is fuel to air ratio. The important parameter of volumetric efficiency in equation (3) is defined as the volume flow rate of air into the intake system divided by the rate at which volume is displaced by the piston.

$$\eta_v = \frac{2\dot{m}_a}{\rho_a V_h N} \quad (4)$$

In equation (4)  $\dot{m}_a$  is mass flow rate of air,  $N$  is engine speed and  $V_h$  is engine displacement or swept volume. The mass flow rates are adequately represented by standard expressions for steady, adiabatic and reversible flow. For gas flows through restriction (throttle, valves), a discharge coefficient  $C_D$  is introduced to give the effective flow area. The general form of the mass flow rates for an un-choked flow is given by equation (5),

$$\dot{m}_a = \frac{C_D A_R p_0}{\sqrt{RT_0}} \left( \frac{p_T}{p_0} \right)^{\frac{1}{\gamma}} \left\{ \frac{2\gamma}{\gamma-1} \left[ 1 - \left( \frac{p_T}{p_0} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}} \quad (5)$$

And for a choked flow

$$\dot{m}_a = \frac{C_D A_R p_0}{\sqrt{RT_0}} \gamma^{\frac{1}{2}} \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (6)$$

where  $A_R$  is the reference area,  $p_0$  and  $T_0$  are the upstream stagnation pressure and temperature,  $p_T$  the downstream stagnation pressure,  $R$  the gas constant for the gas and  $\gamma$  the specific heat ratio [14]. The flow velocity in this model can be expressed as,

$$v_{ps} = \frac{1}{A_m} \cdot \frac{dv}{d\theta} = \frac{\pi B^2}{4A_m} \cdot \frac{ds}{d\theta} \quad (7)$$

Where  $V$  is cylinder volume,  $B$  is cylinder bore,  $s$  is distance between crank axis and wrist pin and  $A_m$  is the area of valves.

To find the best EVO, IVC and overlap degrees, GT-suite software was applied to study and calculate the optimum parameters related to SFC. 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.

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 three stages:

**Stage 1:** Optimization of EVO, IVC and overlap degrees to achieve minimum value for SFC in each speed.

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

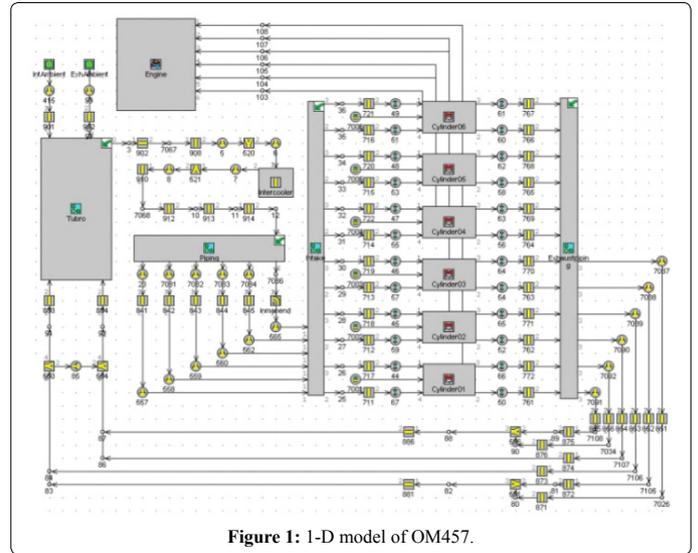


Figure 1: 1-D model of OM457.

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

Table 1: Characteristics of 'OM457'.

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

### Stage one

For these types of optimization problems, different methods like sensitivity analysis [15] or variation methods, genetic algorithm [16] neural networks [17] and the cascade model [18] have been applied. In this paper, the EVO, IVC and overlap degrees considered as input variables and the SFC is the output.

In some cases, due to the decoupled response of parameters respect to the EVO, IVC and overlap degrees, it is possible to find best value for EVO, IVC and valves overlap as follow:

1. Finding the best EVO, considering a fixed value, equal to primary engine, for IVC and overlap.
2. Finding the best amount for IVC, considering the best amount of EVO but maintaining the overlap value.
3. Find the best value for engine overlap, considering the optimum amounts of EVO and IVC.
4. After choosing best values for EVO, IVC and overlap values, it is necessary to shift them 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. Utilizing Minitab software, it was specified that the EVO, IVC and valves overlap degrees haven't any interaction in the proposed range.

### Stage two

The obtained values for 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 minimum SFC.

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. Respect to other features of engine such as maximum MEP, the injected fuel into the cylinder in each cycle could be modified. After fuel modification, an alternation in emission rate is expected.

### Stage three

The following table contains a summary of the emission standards and their implementation dates for HD diesel engines [19]. The proposed model of engine in this paper comply the Euro IV standard, so 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. 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 steady and modes (Table 2).

The engine is tested on an engine dynamometer over a sequence of steady-state modes as illustrated in Table 3 and Figure 3. 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 [20].

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

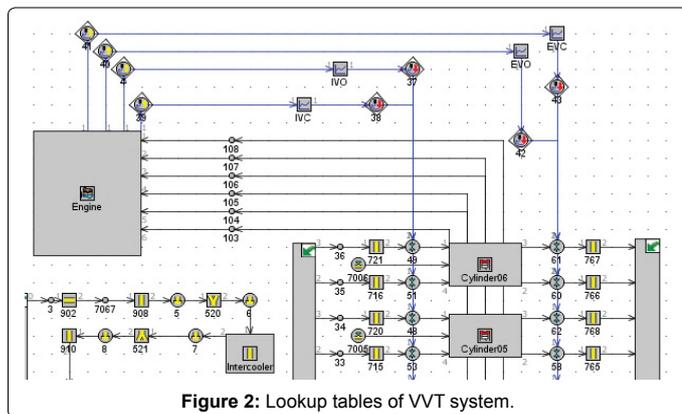


Figure 2: Lookup tables of VVT system.

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	

Table 2: EU emission standards for heavy-duty diesel engines [19].

$$\bar{e}_{g/kWh} = \frac{\sum_{i=1}^{13} e_i * WF_i}{\sum_{i=1}^{13} P_i * WF_i} \quad (8)$$

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 cause up to 95% reduction of NOx. Poor activity of the SCR<sup>1</sup> 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 [21].

### Modelling Results

The OM457 has many applications, including trucks, marine, military, municipal, and agricultural vehicles, as well as stationary settings. The engine has differing trim and power levels [22].

Here are some of the features of this engine:

- In this engine, the dedicated times for exhaust and intake valves are illustrated in Figure 4. Respect to crank angle degree, both exhaust valves open at 118 and close at 387. Moreover, both intake valves open at 336 and close at 576 degrees.

<sup>1</sup> Selective Catalytic Reduction

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

Table 3: ESC test modes [20].

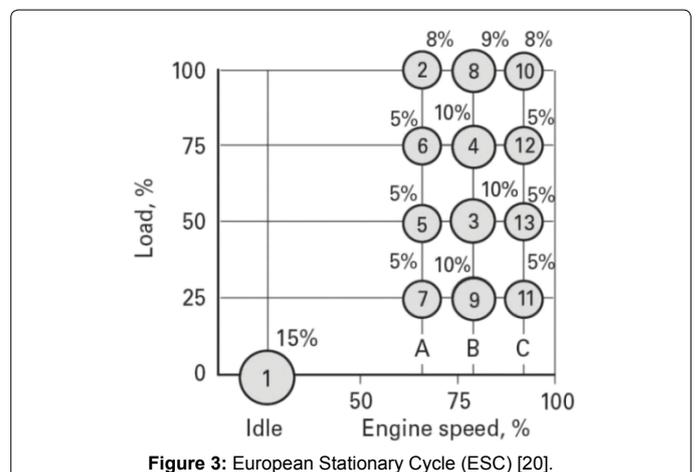


Figure 3: European Stationary Cycle (ESC) [20].

- In this model, the injected fuel in each cycle is illustrated in Figure 5. This picture indicates the climax of injected fuel at 1100 and 1200 (rpm).
- The generated power and torque in 'OM457' engine, respect to the previous valve timing and injected fuel are illustrated in Figure 6.

### Optimized angles

As mentioned before, DOE determined that in 'OM457' the EVO, IVC and valves overlap are Non-dependent parameters. Then, SFC of several angles were calculated to achieve optimum EVO for each speed. Afterward, Chebyshev approximation formula employed to connect the discrete data by a curve which leads to yield the optimum EVOs. This method was applied to calculate the IVC and valves overlap. The evaluated results of EVO, IVC and valves overlap for minimum SFC are gathered in Table 4.

### Results of deploying VVT system

After indicating the best angles in each revolutionary speed, these numbers inserted to 1-D model of engine as lookup tables. The

evaluated torque in both 'OM457' and 'VVT-OM457' is illustrated in Figure 7.

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 4: Optimum valve timing for minimum SFC.

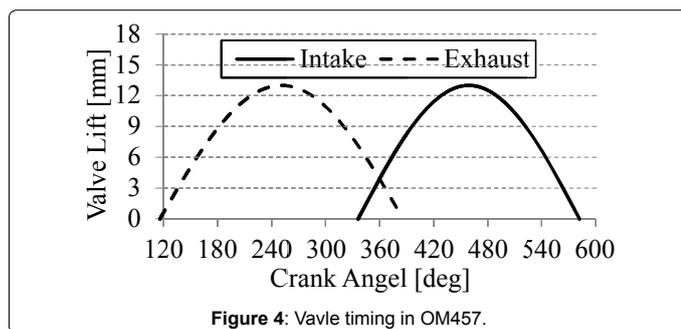


Figure 4: Valve timing in OM457.

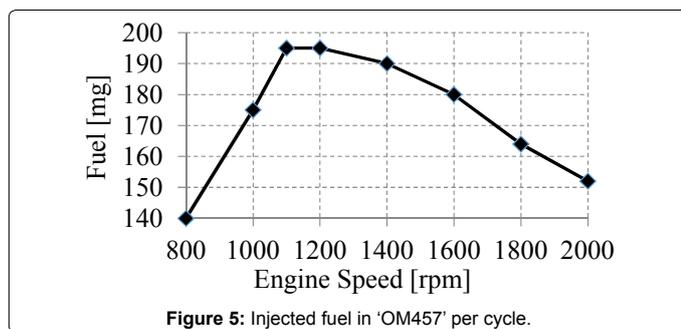


Figure 5: Injected fuel in 'OM457' per cycle.

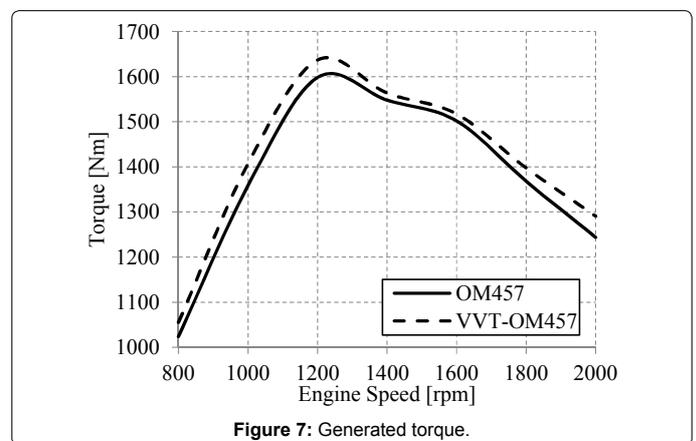


Figure 7: Generated torque.

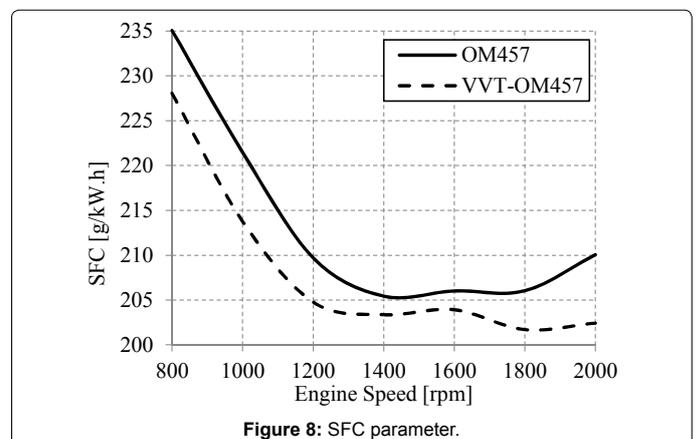


Figure 8: SFC parameter.

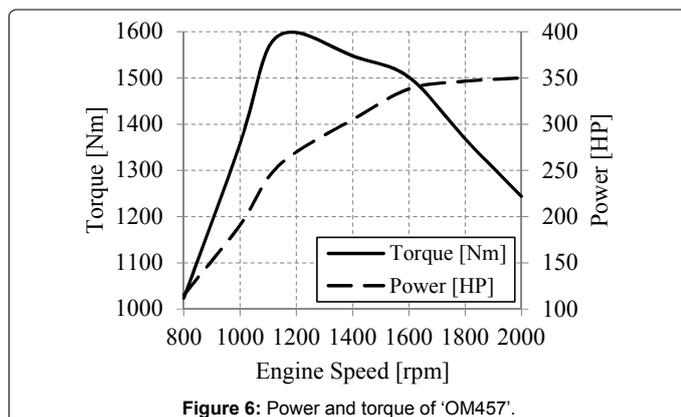


Figure 6: Power and torque of 'OM457'.

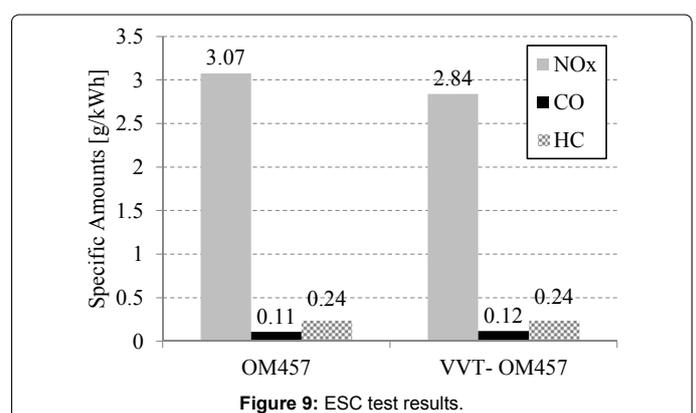


Figure 9: ESC test results.

As expected, the generated torque in 'VVT-OM457' is always greater than primary engine and this increase was more significant in higher and lower range of speed, equal to 3%. But in middle range of speed it was just about 1%.

Due to the constant amount of injected fuel in both modes, the same event is expected for SFC as illustrated in Figure 8. All charts are drawn in full load condition with the injected fuel of Figure 5.

Similar to Figure 7, the greatest improvement for SFC of 'VVT-OM457' took place in higher and lower range of speed and in middle range of speed it is close to SFC of 'OM457'.

According to these results, it can be state that the manufacturer set the valves timing in order reach optimum parameters in these speeds which is the average speed of most standard cycles like ESC, WHSC<sup>2</sup> and even NRTC<sup>3</sup>.

### Results of European stationary cycle

Figure 9 illustrates the difference of emissions in primary engine and VVT engine. According to ESC test, the NOx pollutant rate decreases from 3.07 in 'OM457' to 2.84 in 'VVT-OM457' (considering the same after treatment system for both). In this test the CO and HC pollutants also had slight variations, away from standard bounds.

By applying VVT system in this engine the major emission of NOx decreases 7.4% but CO and HC levels during ESC test didn't show any significant changes.

### Conclusion

This paper indicates that average generated torque in VVT mode increased 2% respect to primary 'OM457' engine while average of SFC parameter decreased 2.3% and average of NOx pollutant decreased 1.6% from 800 to 2000 rpm.

In this paper the evaluated results for EVO, IVC and valves overlap for minimum SFC are based on different speeds of engine. In another approach, it is possible to determine the optimum valve timing as a function of eider speed and load of engine Appendix 1.

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### Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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<sup>2</sup>World Harmonized Stationary Cycle

<sup>3</sup>Non Road Transient Cycle

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