Investigation of Cylinder Deactivation strategies for better fuel consumption using 1-D Simulation Method

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ABSTRACT

In order to meet consumer and legislation requirements, big investments on key technology strategies have been made to ensure fuel consumption is reduced. Recent technologies for gasoline engines are lean combustion technologies (including direct injection and homogenous charged compression ignition), optimizing intake and exhaust valve timing with valve lift and also cylinder deactivation system (CDA) have been practised to improve the engine efficiency. In this study, the purpose is to investigate the engine behaviour when running at different cylinder deactivation (CDA) strategies. One-dimensional engine model software called GT-Power is used to predict the engine performances. There are total of five strategies that have been studied which include normal mode, spark plug off mode, cylinder deactivation mode, intake normal with exhaust off mode, and intake off with exhaust normal mode. Engine performance outputs of each strategy are predicted and compared at BMEP of 3 bars with engine speed of 2500 rpm. Also, the effect of CDA strategies on in-cylinder pressure and pumping loss are performed. The study shows that all of these cylinder deactivation strategies are significantly reduce the pumping loss (PMEP) and fuel consumption, furthermore increasing the thermal efficiency of the engine. The results suggest that the most beneficial strategy for activating CDA is for the case whereby both the intake and exhaust valves are kept closed. This strategy successfully reduced the BSFC. It found that most of these cylinder deactivation strategies improve the engine performance during part load engine condition.

Keywords:
Cylinder Deactivation, GT-Power, Intake, Fuel Consumption, Pumping Loss

1. INTRODUCTION

Deactivating cylinders is one of the proven method to reduce fuel consumption in a multi cylinder engine. The fuel improvement that benefit from deactivating cylinders ranging from 10% to 20% depending on the technological approaches [1-3].

Deactivation means that the cylinder is not producing combustion. There are several ways to deactivate the cylinder. The simplest method is just switching off the ignition. Since the fuel consumption is the main concern, the fuel injector must also be shut off. Other method includes shutting down the intake and exhaust valve from operating. In 1882, Mitsubishi Company tried several techniques of cylinder deactivation on its 1.4L, 4 cylinders Orion MD engine. The techniques are deactivate both intake and exhaust valves, or shut off the fuel supply while supplying fresh air without throttling, or shut off the fuel supply while re-circulating the exhaust gas, or just simply shut off the fuel supply. By doing so, it manage to reduce the fuel consumption up to 42% at certain engine condition [4].

This paper will look into several options of deactivating the cylinders. The methods of deactivating the cylinders will be implemented in a simulation engine model by using GT Power software. Different options of cylinder deactivation should affect the engine performance in different ways. Cylinder deactivation mainly focuses on reducing the pumping loss. Pumping loss is high at part load engine operation due to partially opened throttle valve [5]. This create negative pressure inside the intake manifold. The pumping loss should also be reduced by increasing the intake manifold pressure or by un-throttled operation [6].

Shutting down some cylinders operation will let the working cylinders to do extra work as to produce the same amount of work as if all the cylinders are running. In order to produce more work, the working cylinders need more air. The throttle opening should be opened wider to allow air access to the cylinders. When the throttle opening is open wider, it will increase the pressure in the intake manifold. This will reduce the pumping loss by the engine as the pressure is pushed into the active combustion chambers [7]

If the intake and the exhaust valves are kept shut, there should be air trapped inside the cylinder. The enclosed air works like a pneumatic spring which is periodically compressed and decompressed without overall pumping work. Therefore, the parasitic losses of the dragged cylinders are reduced [8].

2. METHODOLOGY

2.1 Model Validation

In this study, the strategies to deactivate the cylinders are investigated using 1-D simulation approach. A simulation engine model has been built based on 1.6L Spark Ignition Campro engine. The simulation model is based on one dimensional analysis by using GT Power software. The engine model has been constructed based on actual design, dimensions and parameters. This model has been validated with experimental data as shown in figure 1 [9]. The errors between this simulation model and the actual engine testing are less than 5% which is acceptable to be used as a correlated model. This simulation engine model will be used to run the engine at several different modes.

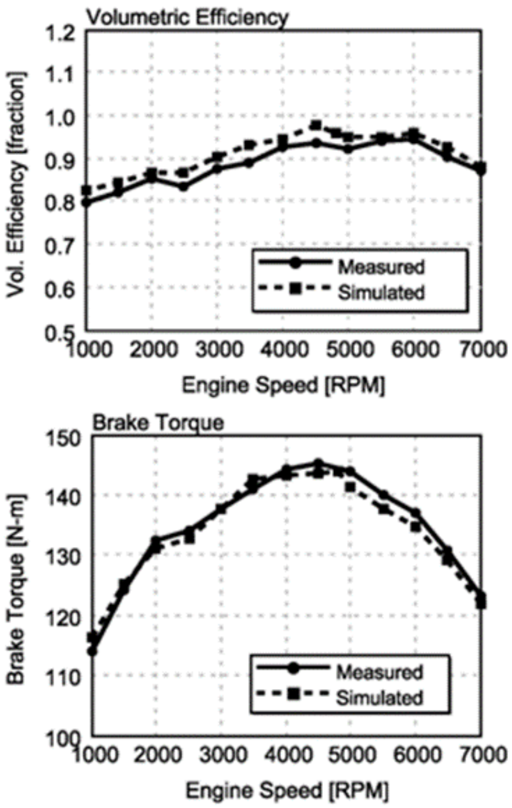

Figure 1: Comparison between Simulated and Measured data [9].

2.2 Parametric Study

For this simulation study, there will be four conditions of cylinder deactivation system to be analyzed. The conditions are based on the active and inactive of these four components which are the intake valve, exhaust valve, spark plug and fuel injector. The simulation will be run in several modes which are in Normal mode and deactivated cylinders modes. There are four conditions of deactivating the cylinders:

a) Spark plug off
b) Cylinder deactivation mode (CDA Mode);
c) Intake valves close; exhaust valves normal;
d) Intake valves normal; exhaust valves close;

Normal mode refers to the normal operating conditions without any modifications to the original 4-cylinder engine model. "*Spark plug off*" condition is when only the spark plugs from the deactivated cylinders are switched off as the engine valves are operating in normal condition. *"Cylinder deactivation"* (CDA) mode is when both intake and exhaust valves are switched off. As for the *intake valves close; exhaust valves normal*, the intake valves are switched off by setting the lift arrays to zero while the exhaust valves runs normally and vice versa. Table 1 summarizes the engine operating modes to be simulated. Note that all of these modes only affects cylinder 2 and 3. Cylinder 1 and 4 are allowed to operate normally without any modification. The performance output of the engine in normal and CDA mode are evaluated based on engine speed range between 1000 to 4000 rpm and at specific engine load which is 3 bar BMEP. This operating conditions are selected based on the common driving conditions in Malaysia [10,11].

Table 1: Summary of engine modes to be simulated.

Modes	BMEP (bar)	Intake Valve	Exhaust Valve	Spark Plug	Fuel Injection
Normal mode	3	On	On	On	On
Spark plug off	3	On	On	Off	Off
CDA Mode	3	Off	Off	Off	Off
Intake valves close; exhaust valves normal	3	Off	On	Off	Off
Intake valves normal; exhaust valves close	3	On	Off	Off	Off

3.0 RESULT AND DISCUSSION

3.1 At Full Load Condition

Comparison of engine brake power for each mode at full load condition is depicted in Figure 2. It shows that by deactivating two cylinders, the power significantly drops to half compared to the power that the normal mode can achieve. The best power curve among the deactivated modes comes from CDA mode where it produces a slightly higher power compared to other deactivated modes. The highest brake power CDA mode can produce is 32.3kW running at 6500rpm. The least production of power is when *intake normal; exhaust off* mode. This mode provides a steady curve between 4kW to 20kW of power between 1000rpm to 4000rpm.

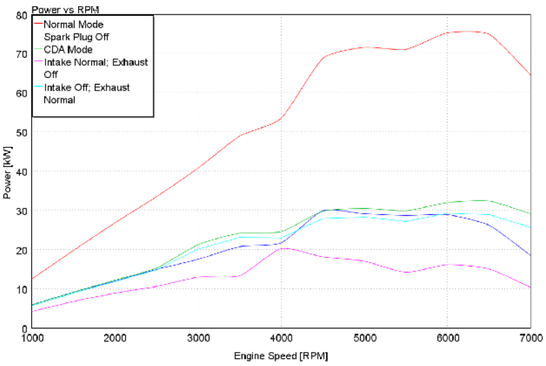

Figure 2: Brake Power versus Engine Speed for all engine modes at full load condition.

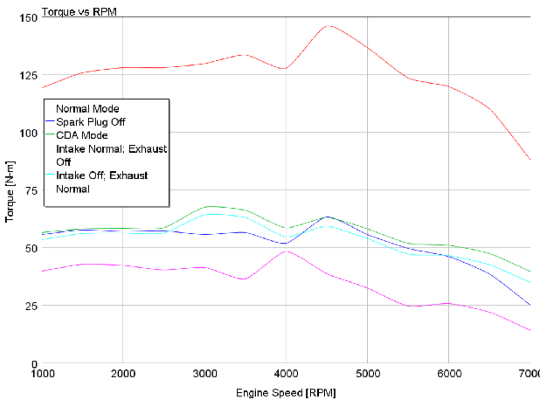

Figure 3: Brake Torque versus Engine Speed for all engine modes at full load condition.

Figure 3 shows the brake torque produced at different engine speeds for all engine modes. Based on the graph, it is obvious that normal mode produced the highest torque among all the modes. The maximum torque generated by normal mode in this simulation is 145.8Nm at 4500rpm. The deactivated mode that produces the highest torque is CDA mode. CDA mode manages to produce a 67.3kW of torque running at 3000rpm. The deactivated modes produce almost half amount of torque of the normal mode. However, these modes are usable and recommended when low torque driving conditions are necessary. Such conditions are during highway cruising just to maintain vehicle speed whereby hard acceleration is not needed.

3.2 At Part Load Condition

This study is to investigate the strategy of deactivating the cylinder especially at part load condition. Thus, engine simulation model is applied to predict the engine performance at several fixed variables. Such variables are:

a) The target engine BMEP for each mode is 3 bar at every engine speed (part load condition).
b) The deactivated parameters include the spark ignition, fuel injectors, and intake and exhaust valves.

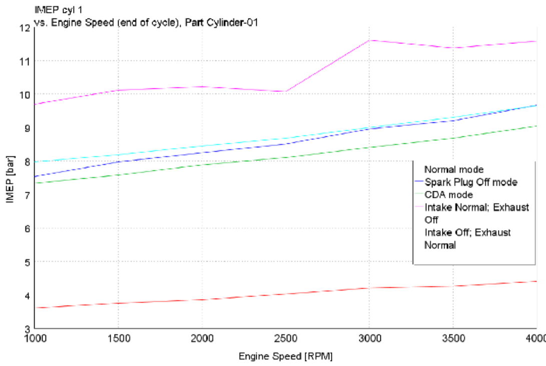

Figure 4: Comparison of Net IMEP per active cylinder versus Engine Speed for different deactivation strategy.

Figure 4 shows the Net IMEP at cylinder #1 for different deactivation mode. The best engine condition to produce high IMEP is when *intake normal; exhaust off* mode is initiated. At 2500rpm, *intake normal; exhaust off* mode manages to produce an IMEP value of 10bar which is 150% increase compared to *normal* mode that only produced 4 bar per active cylinder. *Intake off; exhaust normal* mode manages to produce 8.7 bar IMEP followed by *spark plug off* mode and CDA mode with 8.5bar and 8.1 bar IMEP respectively at 2500 rpm. Each mode contributes more than 100% increase in IMEP when two cylinders are deactivated.

Increase in net IMEP can be related to the reduction in PMEP. The following formula shows the relationship between PMEP and IMEP:

$$\text{Net IMEP} = \text{gross IMEP} - \text{PMEP}$$

By applying cylinder deactivation modes, the amount of PMEP is highly reduced since the intake pressure is increased (Figure 5). Therefore, this produces more positive work to the engine with low pumping work.

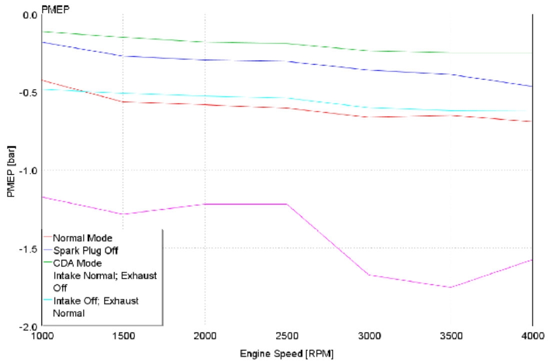

Figure 5: PMEP versus Engine Speed

The main purpose of cylinder deactivation is to reduce pumping work in the engine. Therefore, it is important to evaluate the PMEP of the engine to determine its efficiency in producing positive work.

The engine model that produces the lowest pumping loss is the *CDA mode* where the intake and exhaust valves are both closed (Figure 5). By closing the intake and exhaust valves, the trapped air act like pneumatic spring as the piston move up to compressed it. This will reduce the pumping work done by the engine.

However, the *intake normal; exhaust off* mode shows higher pressure value of PMEP. This indicates that this mode has high pumping loss. It happens due to the working intake valves in this mode while the exhaust valve is closed. Air is sucked into the cylinder during intake stroke, adding fresh air to the existing trapped air inside the cylinder that could not escape due to closed exhaust valve. This caused the pressure in the cylinder to build up and need extra work to compress the air.

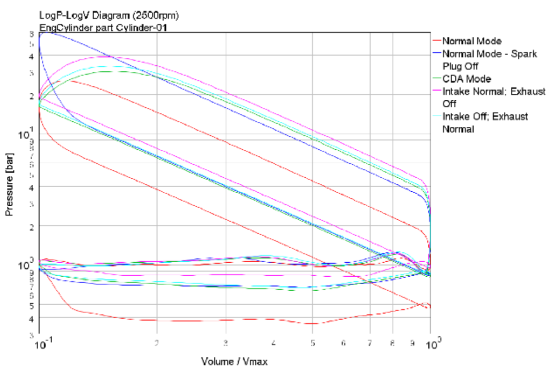

Figure 6: LogP-LogV diagram of all the engine modes (2500rpm; BMEP: 3 bar)

LogP-LogV diagram is plotted for different modes of engine and it is shown in Figure 6. It is clear that all deactivated modes reduce the pumping loss by increasing the pressure in the active cylinders. All the deactivated modes show significant increase in pressure during compression and power stroke. In terms of positive work, the *spark plug off* mode produced a larger surface area in the graph during compression and power stroke. Therefore, it produced more work compared to the other engine modes. Overall, most of the deactivated modes shows significant reduction of pumping loss and increase of cylinder pressure for combustion.

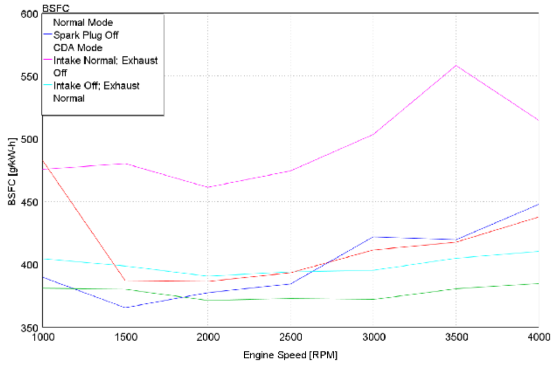

Figure 7: BSFC versus Engine Speed

BFSC is an important parameter in order to identify the fuel efficiency and fuel consumption of the engine. Based on the graph shown in Figure 7, the lowest BSFC recorded is 365 g/kW-h at engine speed of 1500 rpm. This happen when the engine operates with only the spark plug at cylinder #2 and #3 are switched off. However, the BSFC increased when higher engine speed are applied.

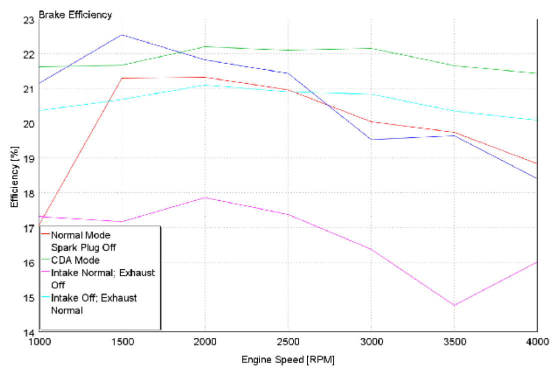

Figure 8: Comparison of engine's brake efficiency for every engine modes

The CDA Mode shows a small fluctuating value of BFSC between 371g/kW-h and 384g/kW-h. The worst performance in BSFC is when the spark plug, fuel injection, and exhaust valves of cylinder #2 and #3 are switched off while the intake valves operates in normal condition which produced 558 g/kW-h at 3500rpm. This can be related with the very high pumping pressure in the cylinder due to the opening of the intake valve which leads to very high fuel consumption to power the engine.

The graph in Figure 8, above shows the brake efficiency of the engine in different engine modes. *Normal* mode starts to increase in brake efficiency from 17% to 21.3% between 1000rpm and 1500rpm. CDA Mode produces steady brake efficiency between 1000rpm to 4000rpm with an average value of 21.8%. CDA mode is clearly the best in brake efficiency among all the modes.

3.3 Summary of the Results

Table 2 shows the results summary between *normal* mode and the *cylinder deactivation* modes. These results are based on part load condition when the engine operates at 2500rpm, BMEP of 3 bar, and AFR of 13.8.

Table 2: Comparison between normal mode and the other cylinder deactivated modes.

Modes / Parameter	Normal Mode	Spark Plug Off	CDA Mode	Intake Normal; Exhaust Off	Intake Off; Exhaust Normal
Net IMEP @ cyl 1	4.0	8.5	8.1	10.0	8.7
Net PMEP @ engine	-0.6 bar	-0.3 bar	-0.2 bar	-1.2 bar	-0.5 bar
BSFC @ engine	393 g/kW-h	384 g/kW-h	373 g/kW-h	474 g/kW-h	394 g/kW-h
Brake Efficiency @ engine	21%	21.4%	22.1%	17.4%	21%
Volumetric efficiency @ cyl 1	0.35	0.67	0.65	0.78	0.69
Maximum Cyl. Pressure @ cyl. 1	25.4 bar	59.5 bar	30 bar	38.7 bar	33 bar
Total Fuel Consumption per active cyl @ cyl. 1	13.1mg/cycle	25.5 mg/cycle	24.7 mg/cycle	29.6 mg/cycle	26.1 mg/cycle

Table 3: Percentage differences between normal mode and the cylinder deactivation modes

Modes / Parameter	Normal Mode	Spark Plug Off(%)	CDA Mode(%)	Intake Normal; Exhaust Off(%)	Intake Off; Exhaust Normal (%)
Net IMEP @ cyl. 1	4.03 bar	111.4	101.5	148.8	116.4
Net PMEP @ engine	-0.6 bar	-50.0	-66.7	100.0	-16.7
BSFC @ engine	393 g/kW-h	-2.3	-5.1	20.6	0.3
Brake Efficiency @ engine	21%	1.9	5.2	-17.1	0.0
Volumetric efficiency @ cyl. 1	0.35	91.4	85.7	122.9	97.1
Maximum Cyl. Pressure @ cyl. 1	25.4 bar	134.3	18.1	52.4	29.9
Total Fuel Consumption per active cyl @ cyl. 1	13.1mg/cycle	94.7	88.5	126.0	99.2

4. CONCLUSION

Computer simulation techniques are applied to obtain better understanding in term of cylinder deactivation technology on engine performance. The engine model has successfully predicted engine performance for various of deactivation strategy (mode). The simulation study shows that cylinder deactivation system in various modes does improves the engine in terms of efficiency and fuel consumption. As for reducing pumping loss or PMEP, the mode that is most effective and suitable is CDA mode where both the intake and exhaust valves are closed. CDA mode also has the lowest BSFC and overall fuel consumption amongst the other engine modes.

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