Single Parameter Engine Analysis and Performance Optimization of a Medium Duty Gasoline Engine

Mohd Faisal Hushim, Zamri Noranai, Daniel Lau Yan How, Zainul Ameerul Ikhsan Zainul Abidin, Mohd Azahari Razali, Azwan Sapit and Akmal Nizam Mohamed

1Automotive & Combustion Synergy Group (ACSG), Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Branch, 84600 Pagoh, Johor, Malaysia.
2Faculty of Mechanical & Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Pt. Raja, Batu Pahat, Johor, Malaysia.

E-mail: mdfaisal@uthm.edu.my

Abstract. This paper examines various attempts to impose a single parameter analysis on the effect of intake valve opening (IVO) timings and intake runner length (IRL) technologies on the engine performance output at full load condition through an engine model representing 1.6 liter in-line 4 cylinders, 4-stroke SI engine constructed using GT-Power simulation software which is then simulated and correlated to the CAMPRO 1.6L model constructed previously with an updated crank train geometry such as cylinder stroke length and the connecting-rod length (con-rod) where comparison results of Volumetric Efficiency (VE), Brake Power (BP-kW), Brake Torque (BT-Nm) are carried out to maintain the accuracy and validity of the model to be used. This model is then used to simulate the engine performance under different sets of intake runner length (IRL) and difference sets of intake valve opening (IVO) timings. The various sets of IRL and IVO are then configured to correspond with each other to predict the most suitable optimization setups at targeted engine speeds, ranging from 2000-4000 RPM in this research to eliminate the existence of performance dip for better cycle efficiency. Results shown significant improvement through the different IVO timings and different IRL setups, as compared to the stock settings

1. Introduction
Improving the torque performance in case of naturally aspirated engines volumetric efficiency is still low which is in the range of 75-80% where in conventional engines it is optimized for a specific speed at which it gives maximum torque. The effects of such engine operating parameters and their control technologies have been studied excessively by researchers and the product designers. In engines, configuration of the intake system plays also an important role on the engine performance, and there are many experimental and theoretical studies on the intake system and manifold design. In this research, analysis were carried out to investigate the design geometry of the intake subsystem on the torque output of an engine using one dimensional (1D) engine simulation program GT-Power by
constructing an engine model of 1.6-liters NA, spark-ignition (SI), port-fuel injection four cylinders engine. Studies showed that longer intake manifolds give peak torque at low engine rpm & shorter engine manifolds gives peak torque at higher engine rpm\(^2\)-\(^4\). Development of the subsystem such as intake manifold length tuning can be improved through simulation work during the engine development process\(^5\). The paper presents the model construction, correlation with actual test data, predicted engine performance at various IRL and IVO timing as well as their optimum configurations at specific engine speeds to determine an optimum value in order for the performance dip at 2000 rpm to 4000rpm to be eliminated.

2. Single parameter engine analysis

In this research, the effects of IRL and IVO timings on engine performances are investigated so as to find out their optimum operating values at a specific engine speeds. Using GT-Power to simulate the one dimensional (1-D) engine representing the targeted engine, which is the CAMPRO 1.6L base model requires the actual input data, representing the actual geometry of the engine\(^6\). Constructed model is then correlated to the model reference of CAMPRO 1.6L provided through the percentage difference in the BSFC and intake manifold VE for the validity of the model well agreed with the exact model. The model is then simulated with different sets of IRL and IVO, comparing their output performances to the stock IRL and IVO setups where 3 DOEs are carried out to determine the optimum values at specific engine speeds.
3. GT-POWER Engine Modelling

3.1 Constructed Model.
In order for the performance output data from the simulation to be as accurate as possible, it is essential to input the engine data closest to the exact value so that the results obtained and proposed optimum values from the simulation can be made valid. The model is constructed from the initial intake system until the end exhaust systems to include as much as parameters to represent the actual engine operating conditions and was represented by name CAMPROBASE1.6. The intake manifold air-box was modelled in Solidwork CAD with the exact dimensions and was discretized using GEM3D in GT-Power to obtain the exact dimensions of each sub-part in the intake system such as Inlet and outlet diameter of each pipe as well as the length are precisely defined. Non-predictive combustion model known as SI Wiebe function is chosen which imposes a burn rate as a function of crank angle (CA), represented by crank angle where 50% fuel burned and the duration of fuel burned and the burn rate is calculated from measured in-cylinder combustion pressure at various engine speeds under full load conditions. Then, the model is simulated at engine speed of 1500 to 6500 rpm under wide open throttle (WOT). After the simulation, the results of engine performance are plotted in GT-POST.

3.2 Model Correlation: STOCK vs. CAMPROBASE16.
The constructed model was correlated to the stock setups to check on the validity of the model constructed through the percentage difference (%Diff.) method, comparing the BSFC and intake manifold VE. As seen from Figure 1 and Figure 2, the brake specific fuel consumption and intake manifold volumetric efficiency of the built model. Performance difference of less than 1% confirms that it can represent the real engine, there is able to use it for other simulation purpose or predictive

![BSFC %Diff. Stock Model vs. Built Model](image-url)

Figure 1. BSFC %Diff. Stock Model vs. Built Model.
4. Results

4.1 1st Doe: Intake Runner Length (IRL) 350-800 mm

The stock intake runner consists of several discretized part, divided into runner 1, runner 2 and runner 3 with each length of 425.603 mm, 421.461 mm, 422.357 mm, 429.379 mm respectively. To simulate the effect of modified IRL to the performance output of the engine, these values are then modified ranging from a shorter IRL of 350 mm to a longer IRL of 800 mm with a length increment of 100 mm each after 400 mm. Figure 3 shows the overall performance output percentage difference when different sets of IRL are applied and Table 1 shows the percentage difference value comparing to the stock IRL setups.
From Table 1, it is clearly seen that by increasing the IRL from the stock length, starting from the longer IRL of 500 mm to 800 mm, noticeable improvement can be noticed at 2000 rpm to 4000 rpm with an average of 1-5% of improvement obtained. However, performance shows reversed behavior after 4000 rpm where performances are significantly reduced from 5000 rpm to 7000 rpm. The shorter IRL of 150 mm, 350mm and 400mm produced significant improvement at higher engine speeds with an average improvement of 4% at higher engine speeds while suffers an average 0.5-1.7% of performance downfall at lower engine speeds. This matched with the theory where longer IRL can be used to pursue better torque performance at lower engine speeds while shorter IRL can be used to produce better performance output at higher engine speeds. Long runner produced slightly lower BSFC at low-engine speeds with an average decrement of 1% but shoots up to an average increment of 1-5% of BSFC at the higher engine speeds ranging from 5000 rpm to 7000rpm as shown in Table 2.

| %Difference BT_STOCK IVO-108°ATDC_vs_IRLs(150-800MM) based on stock model. | 150MM | 350MM | 400MM | 500MM | 600MM | 700MM | 800MM |
|---|---|---|---|---|---|---|---|
| 7000 | 15.74581 | 6.861847 | -1.22544 | 7.664782 | -13.9574 | -32.2732 | -13.7541 |
| 6500 | 11.9367 | 8.853927 | 3.486986 | 3.311086 | 1.53963 | -25.5108 | -29.6026 |
| 6000 | 2.544208 | 5.526415 | -7.24179 | -1.57997 | -9.59742 | -31.1654 |
| 5500 | -3.54788 | 1.386779 | 1.901775 | -3.0453 | -8.72447 | -4.76311 |
| 5000 | -6.25443 | 0.477758 | 0.782437 | 2.686367 | -5.65936 | -6.30897 |
| 4500 | -7.51495 | 0.052465 | 0.7143 | 1.727355 | 4.46498 | -4.2747 |
| 4000 | -8.04238 | -3.80719 | -1.00164 | 0.670356 | 2.892877 | 7.20859 |
| 3500 | -2.37102 | -5.20256 | -2.25969 | 6.762236 | 7.224787 | 7.567102 |
| 3000 | 2.467428 | 3.077728 | 0.646848 | 1.566288 | 11.13094 | 12.1637 |
| 2500 | -0.20679 | 0.486565 | 0.293237 | -3.86679 | 4.54942 | -4.25417 |
| 2000 | -0.32397 | -0.8628 | -0.21568 | 1.11636 | 2.597884 | -3.00191 |
| 1500 | -3.70537 | -2.70681 | -1.22027 | -0.36891 | -1.02284 | 1.727332 |

Ave %Diff (2k - 4k rpm) -1.69534 -1.26165 -0.50739 1.249689 3.859414 3.936662 5.38288
Ave %Diff (1.5k -7k rpm) 0.060612 1.178676 0.429237 0.915161 -0.4702 -5.10976 -5.64175
Ave %Diff (5k -7k rpm) 4.08479 4.621345 1.638748 0.675009 -5.67632 -15.6907 -18.5455

Table 1. %Diff. of BT for different IRL.
Table 2. Diff. of BSFC for different IRL.

| RPM  | 150mm | 350mm | 400mm | 500mm | 600mm | 700mm | 800mm |
|------|-------|-------|-------|-------|-------|-------|-------|
| 7000 | -2.91884 | -0.55284 | 0.742928 | 1.787139 | 6.458782 | 13.19108 | 2.614866 |
| 6500 | -2.93037 | -1.21983 | -0.4566 | 1.783073 | -0.18804 | 9.360139 | 8.511794 |
| 6000 | -1.65258 | -0.95014 | -0.42398 | -0.4827 | -0.77302 | 2.38278 | 9.511482 |
| 5500 | -0.76879 | -0.69368 | -0.35119 | -0.4522 | 0.100767 | -0.05766 | 3.368701 |
| 5000 | -0.17661 | -0.72894 | -0.31984 | -0.0823 | 0.904797 | 0.001055 | 0.153552 |
| 4500 | 0.348199 | -0.13795 | -0.27561 | -0.3264 | 0.591574 | 1.04228 | 0.292117 |
| 4000 | 0.448152 | 0.378964 | 0.302379 | 0.04905 | 0.470994 | 0.599005 | 0.599316 |
| 3500 | -0.30145 | 0.454579 | 0.15632 | 0.693299 | -0.70857 | -0.22443 | -0.08297 |
| 3000 | -0.58081 | -0.4928 | -0.17147 | 0.147975 | -0.74979 | -1.01155 | -0.82458 |
| 2500 | -0.1135 | -0.04681 | -0.07303 | -0.35499 | 0.56487 | 0.767953 | -0.20145 |
| 2000 | 0.108031 | 0.038113 | 0.015469 | 0.097726 | -0.12704 | 0.31354 | 0.484238 |
| 1500 | 0.188215 | 0.200748 | 0.087189 | 0.008488 | 0.064313 | -0.14361 | -0.19935 |

Ave %Diff (2K-4K)  | -0.08792  | 0.066409  | 0.045934  | 0.126612  | -0.10991  | 0.088904  | -0.00509
Ave %Diff (5K-7K)  | -1.68944  | -0.82909  | -0.16174  | 0.510596  | 1.300657  | 4.97548   | 4.832079

4.2 2nd Doe: Intake Valve Opening (IVO) 96°-120° ATDC

Theoretically, the IVO make impact on the engine performances output as it is closely related from the mechanism of intake manifold where the IRL determine the flow characteristics before reaching the intake port. Therefore in this research 2nd DOE, IVO is made as a single parameter that will produce different significant results if being altered, in which the timings are varied to investigate how it affects the BT and BSFC as shown in Figure 4. The IRL was made fixed at the stock length throughout this DOE. Study of the effect started from the analysis of stock IVO that is 108° ATDC. The engine performance simulated from different sets of IVO timings ranging from a retarded 96° ATDC to an advance timing of 120° ATDC where the timings are defined at the crank angle (CA) point where the intake valve opens at maximum lift, known as Maximum Opening Point (MOP) in GT-Suite.
From results shown in Figure 4, it is obvious that by advancing the IVO timings from the stock 108°ATDC, the BT and VE shows significant improvements over the stock timing at higher engine speeds above 5000 rpm. However, the behavior changes when it is at lower engine speeds where decrement in BT and VE is obvious at low to mid-engine speeds from 2000 rpm to 4000 rpm. These can be seen from Figure 5 and Table 3 that the behavior shows reversed behaviors when the timing is retarded from the stock timings. In this DOE, the stock timings of 116° ATDC is said to be the most suitable timing for whole engine speeds. However, IVO 104° can be used as an alternative in pursuing average improvement in engine speeds ranging from 2000 rpm to 4000 rpm while 120° can be chose to seek improvement in 5000 rpm to 7000 rpm as it shows average improvement of 4% in the BT and 3% of improvement in VE as shown in Table 4. IVO 116° opt to be used if average improvement in BT is seek over the entire engine speeds as shown in Table 3.

| RPM  | 96 ATDC | 100 ATDC | 104 ATDC | 108 ATDC | 112 ATDC | 116 ATDC | 120 ATDC |
|------|---------|----------|----------|----------|----------|----------|----------|
| 7000 | -10.2156| -6.5423  | -3.0701  | 0.0000   | 4.7854   | 2.6225   | 6.4588   |
| 6500 | -10.3839| -6.6902  | -3.2134  | 0.0000   | 5.2032   | 2.8155   | 7.0793   |
| 6000 | -8.8446 | -5.6238  | -2.6382  | 0.0000   | 3.9516   | 2.2050   | 5.1921   |
| 5500 | -6.6618 | -4.0282  | -1.7717  | 0.0000   | 1.7310   | 1.1675   | 1.7391   |
| 5000 | -3.9507 | -1.9784  | -0.6286  | 0.0000   | -0.4320  | 0.0139   | -1.2634  |
| 4500 | -2.4289 | -0.9709  | -0.1530  | 0.0000   | -1.2828  | -0.4216  | -2.4833  |
| 4000 | -1.4107 | -0.4688  | 0.0050   | 0.0000   | -1.2869  | -0.4531  | -2.4697  |
| 3500 | -0.8275 | -0.1583  | 0.1518   | 0.0000   | -1.8357  | -0.6654  | -3.4758  |
| 3000 | -1.6766 | -0.5826  | 0.0176   | 0.0000   | -1.8725  | -0.6357  | -3.6368  |
| 2500 | -1.0768 | -0.2212  | 0.1420   | 0.0000   | -1.7323  | -0.6402  | -3.2225  |
| 2000 | -1.0845 | -0.1992  | 0.1850   | 0.0000   | -2.0959  | -0.7713  | -3.9026  |
| 1500 | -0.6255 | 0.1809   | 0.4220   | 0.0000   | -2.7545  | -1.0646  | -4.9434  |

Ave %Diff 2k-4krpm: -1.2152 -0.3260 0.1003 0.0000 -1.7647 -0.6331 -3.3415
Ave %Diff (1.5k-7k rpm): -4.0989 -2.2736 -0.8793 0.0000 0.1982 0.3477 -0.4107
Ave %Diff (5k-7k rpm): -8.0113 -4.9726 -2.2644 0.0000 3.0478 1.7649 3.8412
Table 4. %Difference VE : IRL_vs_IVOs(96°-120°ATDC)

| RPM  | 96 ATDC | 100 ATDC | 104 ATDC | 108 ATDC | 112 ATDC | 116 ATDC | 120 ATDC |
|------|---------|---------|---------|---------|---------|---------|---------|
| 7000 | -7.8373 | -5.0405 | -2.3799 | 0.0000  | 2.0570  | 3.7862  | 5.1666  |
| 6500 | -8.0664 | -5.2129 | -2.5117 | 0.0000  | 2.2204  | 4.1257  | 5.6539  |
| 6000 | -7.0758 | -4.5075 | -2.1208 | 0.0000  | 1.7851  | 3.2154  | 4.2576  |
| 5500 | -5.5442 | -3.3584 | -1.4817 | 0.0000  | 0.9920  | 1.4968  | 1.5584  |
| 5000 | -3.4191 | -1.7293 | -0.5631 | 0.0000  | 0.0501  | -0.2799 | -0.9204 |
| 4500 | -2.1117 | -0.8515 | -0.1427 | 0.0000  | -0.3434 | -1.0494 | -2.0260 |
| 4000 | -1.1574 | -0.3710 | 0.0161  | 0.0000  | -0.3910 | -1.0947 | -2.0778 |
| 3500 | -0.6960 | -0.1246 | 0.1367  | 0.0000  | -0.5745 | -1.5719 | -2.9565 |
| 3000 | -1.5427 | -0.5567 | -0.0081 | 0.0000  | -0.5328 | -1.5834 | -3.0804 |
| 2500 | -1.0043 | -0.2234 | 0.1159  | 0.0000  | -0.5538 | -1.4998 | -2.7805 |
| 2000 | -1.0328 | -0.2091 | 0.1556  | 0.0000  | -0.6833 | -1.8573 | -3.4505 |
| 1500 | -0.6057 | 0.1492  | 0.3777  | 0.0000  | -0.9616 | -2.4847 | -4.4474 |
| Ave %Diff 2k-4k rpm | -1.0866 | -0.2970 | 0.0832  | 0.0000  | -0.5471 | -1.5214 | -2.8691 |
| Ave %Diff (1.5k-7k rpm) | -3.3411 | -1.8363 | -0.7005 | 0.0000  | 0.2553  | 0.1002  | -0.4252 |
| Ave %Diff (5k-7k rpm) | -6.3886 | -3.9697 | -1.8114 | 0.0000  | 1.4209  | 2.4688  | 3.1432  |

4.3 3rd Doe: IRL (150-800 mm) vs. IVO (96°-120° ATDC) for targeted engine speeds (2000-4000 rpm)

In this 3rd DOE, VE (%) output is the main focus where different sets of IRL are set to correspond with each IVO timings and the percentage difference (%Diff) method is applied to each VE results obtained to determine the most suitable setups with either the least drop in performance or show improvement in the VE output from each sets of IRL-IVO combinations. The representative from each combinations will then be analyzed for the suitability based on the highest positive difference based on the stock setups. The combinations started with the shortest IRL 150mm responding to IVO ranging from 96°-120° ATDC. The steps are then repeated up to the longest IRL 800mm until all the VE output data are obtained and then analyzed the percentage of difference over the stock setups VE values. The optimum IRL and IVO timings combinations for targeted engine speeds of 2000 rpm – 4000 rpm are determined from the overall best setups chosen from each combinations as shown in Figure 5.
As seen from Table 5, the highest positive average %Diff by IRL 800mm explains the theory where longer IRL happens to the best setup as compared to the rest where it is obvious that in order to improve the volumetric efficiency at mid-engine speed it is essential to tune the IRL to a longer length so that maximum in-cylinder pressure can be achieved through better positive pressure difference between the intake manifold and intake port so that the oscillating wave can reach accordingly when the intake valve open while IVO 108° remains as the most suitable IVO timings in terms of CA as it produces highest positive %Diff of VE and BT at mid-engine speeds. However, IVO 104° can be considered although it lacks punch in producing better VE or BT as compared to IVO 108°.

Table 5. Best setups chosen based on the average VE %Diff. For engine speeds 2000 rpm – 4000rpm

| RPM  | 150MM-104° | 350MM-104° | 400MM-104° | 500MM-104° | 600MM-104° | 700MM-108° | 800MM-108° |
|------|------------|------------|------------|------------|------------|------------|------------|
| 4000 | -7.3609986 | -3.1664288 | -0.5034527 | 0.78968686 | 3.4394794  | 7.9168844  | 1.8447593  |
| 3500 | -2.394258  | -4.669395  | -2.2108743 | 6.3525414  | 6.866921  | 7.337818  | 13.862206 |
| 3000 | 1.9594609  | 2.5047073  | 0.3938117  | 1.3740511  | 10.756241  | 11.052715  | 11.123277  |
| 2500 | -0.03870736| 0.6984103  | 0.49559128 | -3.721932  | -4.255058  | -3.576603  | 4.1260995  |
| 2000 | 0.26337367 | 0.8462217  | 0.14526978 | 1.346408  | 2.421212  | -2.717544 | -4.2018256 |
| Ave %Diff (2K-4K RPM) | -1.51422588 | -1.09578558 | -0.39403887 | 1.22815107 | 3.845759 | 4.00265442 | 5.35088524 |

5. Conclusion

Through the simulating using GT-Suite, it is found that the performance dip at the targeted engine speed sourced from the sudden drop of VE which causes the BT to drop as well. Therefore, research was focused on the intake manifold runner length where different sets of IRL are implemented into the model and simulated to see the effect on the VE and BT output to propose a valid optimization sets if IRL and IVO in order to improve the performance dip at the targeted engine speeds. In the later part of the research, the different sets of IRLs are used to correspond with different sets of IVO timings (CA-deg) to determine for the most suitable setups from the combinations through the percentage
difference(%Diff) method where the new data resulted from each simulations are compared to the stock setup value. Combinations that shows highest positive percentage difference is chosen to be the choice of optimization setups. The results obtained through the %Diff comparisons method satisfy the theory where long intake runner length such as 700mm and 800mm can be implemented to improve BT and VE performance at low-end to mid-end engine speeds while short intake runner length shows better improvement for the high end speeds. IVO timings of 104° and 108° are chosen as the suitable timings for the CAMPRO 1.6L as these 2 IVO shows highest positive percentage difference which indicates improvement over the stock settings across the targeted engine speeds in this research.

Recommendation
There are some of the options that could bring more accuracy in this research that is to fully model the CAMPRO 1.6L with the exact value and exact environment which is time consuming but could be consider as an option to fully investigate the affecting parameters and to come up with a better solution of optimization throughout the engine components, not just the intake subsystems and also on the engine head components where it involves a deeper review into each components of the engine in order to improve the whole engine cycle efficiency.

A dual intake runner length manifold can be implemented with characteristics such as:
- Provide the optimum length for each engine speeds for maximum performance possible.
- Significant improvement in volumetric efficiency & brake power across the whole engine speeds without any compensation of performance drop in any speeds.
- Brake Torque benefit is obtained in lower as well as higher RPM band for a more balanced drive cycle.

References
[1] G, B. J. & Jadhav, N. P. Effect of Variable Length Intake Manifold on Performance of IC Engine. 5, 47–52 (2016).
[2] Malkhede, D. N. & Khalane, H. Maximizing Volumetric Efficiency of IC Engine through Intake Manifold Tuning. SAE Technical Pap. 2015-01-1738 (2015). doi:10.4271/2015-01-1738.
[3] Ceviz, M. A. & Akin, M. Design of a new SI engine intake manifold with variable length plenum. Energy Convers. Manag. 51, 2239–2244 (2010).
[4] Malkhede, D. N. & Khalane, H. Maximizing Volumetric Efficiency of IC Engine through Intake Manifold Tuning. in (2015). doi:10.4271/2015-01-1738
[5] Safari, M., Ghamari, M. & Nasiritosi, A. Intake Manifold Optimization by Using 3-D CFD Analysis. in (2003). doi:10.4271/2003-32-0073
[6] Said, M. F. M., Latiff, Z. A., Saat, A., Said, M. & Abidin, S. F. Z. Analysis of variable intake runner lengths and intake valve open timings on engine

Acknowledgments
The authors would like to express their gratitude to University Tun Hussein Onn Malaysia (UTHM) for providing the financial grant vote no. H106 (Tier 1) and facilities to carry out this research.