Closed Loop Variable Lambda Control for Improved Efficiency in a Gasoline Engine

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Abstract

Closed loop variable lambda control is an effective way of controlling fuel injection through the Engine Control Unit (ECU). Throttle positions and rpm histograms were collected from the ECU by testing the vehicle in different tracks. The logged data obtained from the MoTec i2 software was used to improve the efficiency by varying the air-fuel ratio. Poor throttle response, exhaust back fires and low mileage were controlled by the stoichiometric ratio. Fuel table and necessary sensor setup was carried out by communication to the ECU through the MoTec ECU Manager. A target lambda table comprising of a combination of rich and lean lambda values was formulated. Closed loop variable lambda control showed greater fuel efficiency and lap time when compared with those of the dyno tuned map and the engine map. Collection of the mixture samples from a wideband lambda sensor and analysis of the exhaust gases ensured the stoichiometric ratio as per the lambda table.

1.0 Introduction

It is essential to innovate and develop fuel efficient vehicles in the context of depletion of fossil fuels [1]. Integration of electronics has enabled IC engines to perform better in terms of efficiency and power. Programmable fuel injectors with modern ECU can control precisely the amount of fuel delivered for every millisecond. Diagnostic and data acquisition sensors provide precise data of various engine parameters. A wideband lambda sensor analyses exhaust gas and enables optimal AFR (air to fuel ratio). Leach et al. [1] performed parametric studies on IC engine by varying the AFR. Effect of varying AFR was studied using GT-Power simulation for fuel efficiency in comparison with that of a 4-cylinder DOHC gasoline engine. Authors [5] performed simulation on enDYNA for comparing open-loop and closed loop variable lambda control using a standard European Drive cycle (ECE-15).

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Improved efficiency along with decreasing emission of harmful gases is a priority in gasoline engines. Authors [3] achieved lower emissions of CO, NOx and CxHy using lean mixtures. Maximum of 1.3 lambda corresponded to leanest mixture. Harmful emissions were observed in very high lambda of 1,65 to 1,7. Edward Van Dune patented [8] the method of using a variable AFR by a novel throttle mechanism and Sung-soon Yim [2] patented another closed-loop AFR varying mechanism.

Simulation and experimental studies on AFR and closed-loop control adopting different methodologies are reported. This research adopted direct and analytical methodology of collecting RPM histograms of the vehicle and lambda values developed for different rpm and throttle conditions. It can be used to better the engine response along with fuel efficiency in coasting and idle conditions.

2.0 Methodology

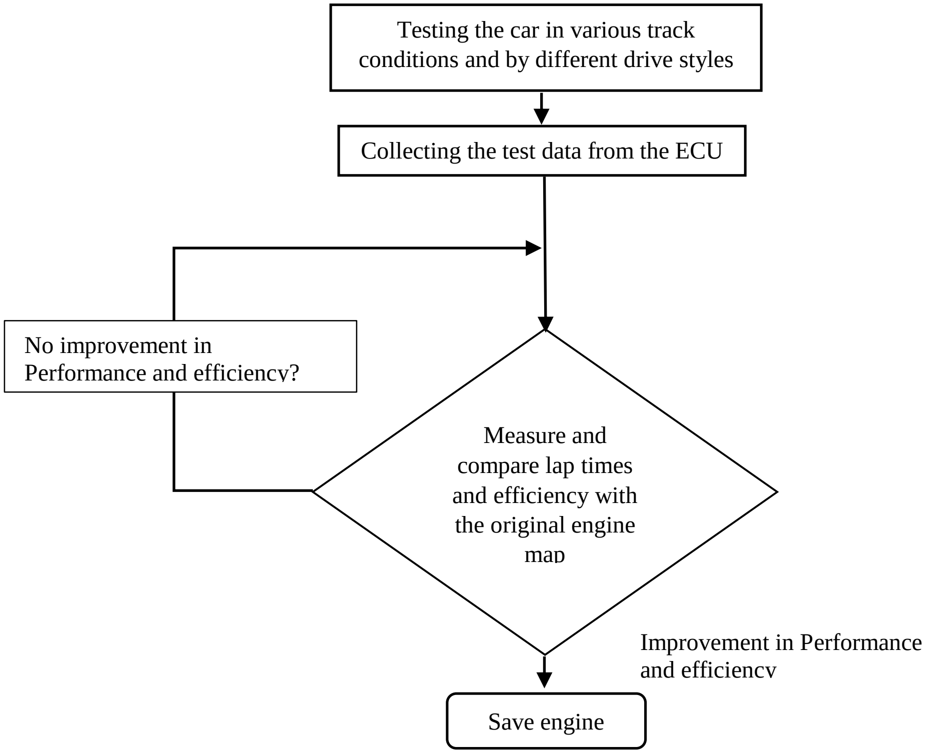

Fig. 1. Process of closed loop variable lambda control

The primary focus of the study was to create a lambda table which developed by an iterative process (Fig.1) by analysing the engine parameters from MoTec i2 Pro which provides the appropriate data. The MoTec ECU manager is the key software used to interact with the ECU.

2.1 Wideband lambda sensor

2.1.1 Lambda sensor set-up

Lambda sensor is used to sense exhaust gases and hence calculate the AFR. Establishing connection between the lambda sensor and the ECU through appropriate wiring harness is critical to retrieve the reliable data. Lambda sensor operates accurately only after it reaches a temperature above 90°C and does not provide accurate values at low temperatures. The sensors are designed with in-built heater coil for heating up the sensor. It needs to be setup in the ECU controller with respect to warm up delay and should only consider the lambda values as valid only after the engine and the sensor is warmed up.

2.1.2 Open-air calibration and characteristic table

Lambda sensor must be calibrated in open air to compensate for its ageing. The sensor is held in open air which is free from hydrocarbons. The calibrated sensor readings must be saved in this condition before it is used for testing. The wide band lambda sensor LSU 4.9 is a planar ZrO_2 dual cell limiting current sensor with integrated heater. Its monotonic output signal in the range of lambda 0.65 to air makes the LSU 4.9 capable of being used as a universal sensor for lambda equal to one measurement as well as for other lambda ranges. The characteristic lambda table is set up in the ECU manager as per the data sheet of the sensor so that the correct lambda value is mapped as per the sensed current values.

3.0 Data acquisition set up

3.1 RPM Histograms

The histogram shows the distribution of rpm and presents the time the engine spends at each rpm. The pattern of the graph should be similar to the power curve of the engine if the engine is performing at the designed rpm and torque. The engine should function for most of the time in the maximum rpm range. Fig 2-5 show the histograms of the testing sessions by two different drive styles A and B.

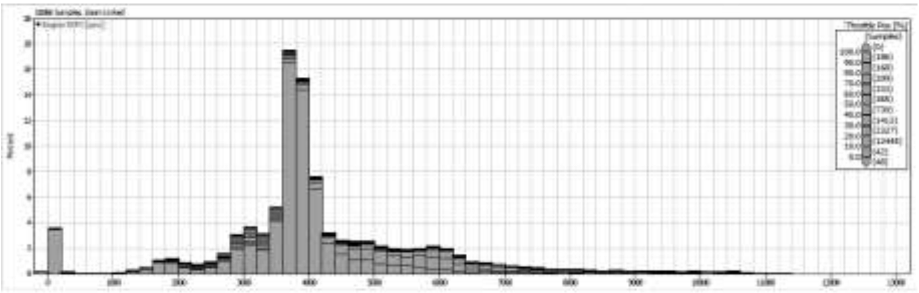

Fig. 2 RPM Histogram of test run 1 by drive style A

Analysis of the driver data (Fig. 2) shows that the drive style A was predominantly in 3500 to 4500 rpm. The sky-blue color shows that the driver held the revs in this range with very little throttle of 20 % to 30%. The Teil and green colour region shows 30 % to 60% throttle present in higher revolution range of 5000 to 7500 rpm. This represents the drive style A.

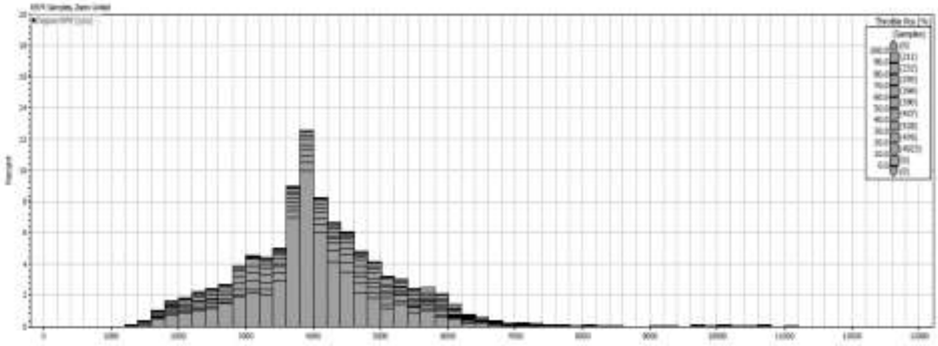

Fig. 3 RPM Histogram of test run 2 by drive style B

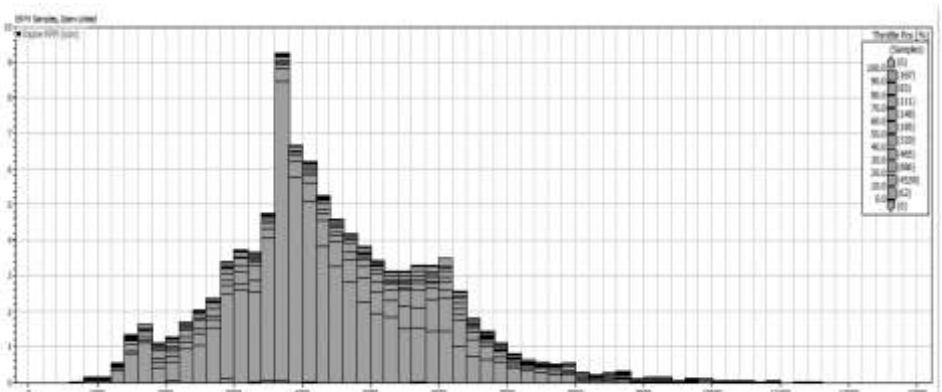

Fig. 4 RPM Histogram of test run 3 by drive style B

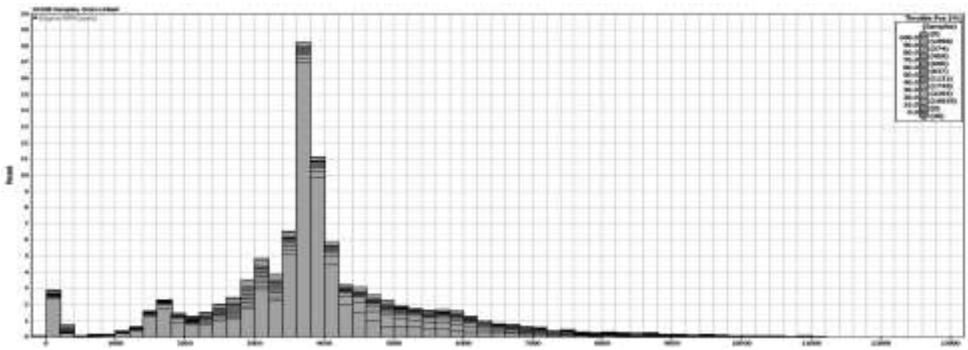

Fig. 5 RPM Histogram of test run 4 by drive style B

The RPM histograms (Fig. 2 to 5) revealed that the driver spent a large amount of time in the range of 3000 - 4500 rpm with very little throttle. Similar pattern of RPM histograms was observed in the other test runs. The repetition in the pattern is favorable for crating maps as the best iteration of target lambda can be obtained. This region of the map can be modified to make the car run leaner. In the region beyond 5000 rpm, the driver has been heavy on the throttle demanding more power in that region and richer mixture delivery.

3.2 Lambda and Fuel set-up

3.2.1 Lambda Table

Lambda table is a characteristic table that provides information on the target lambda that the engine is supposed to run at particular throttle position and rpm. The target lambda values were set as per the trend of the rpm histograms. The regions where the driver used very little throttle and was coasting i.e. with very little throttle 10 to 40% usage and lower engine rpm 1000 to 5000, a leaner AFR was set so that the engine could run efficiently at these regions by minimizing fuel consumption. In the region of 5,500 to 10,000 rpm combined with a throttle usage of 50 to 100%, a richer AFR aim value was set. This table is important as it has a direct effect on fuel consumption and power delivery.

A constant target lambda value of 0.9 was set up in Table 1. It means that the engine would always be running at a constant AFR at all rpm and load conditions. The drawback of such a configuration is greater fuel delivery at all times to maintain a rich stoichiometry even when the driver requires no throttle or when the engine is coasting.

Table 1. Lambda Table comprising of constant lambda values

Lambda Table (Lambda)

Load % \ RPM	0	1000	2000	4000	6000	8000	10000
100.0	0.90	0.90	0.90	0.90	0.90	0.90	0.90
80.0	0.90	0.90	0.90	0.90	0.90	0.90	0.90
60.0	0.90	0.90	0.90	0.90	0.90	0.90	0.90
40.0	0.90	0.90	0.90	0.90	0.90	0.90	0.90
20.0	0.90	0.90	0.90	0.90	0.90	0.90	0.90
10.0	0.90	0.90	0.90	0.90	0.90	0.90	0.90
0.0	0.90	0.90	0.90	0.90	0.90	0.90	0.90

In Table 2, the region of lean mixture ranging from 1.05 to 1.30 lambda is highlighted and the region of rich mixture ranging from 0.85 to 0.99 is also highlighted. In this configuration, AFR is well within the safety region of the engine. Very rich mixtures tend to flood the engine making the spark plugs damp leaving unburnt fuel escaping through the exhaust valve and later igniting in the hot regions of the exhaust pipe. During the test sessions, rich mixtures were found to cause frequent engine backfire. It was observed that multiple failed cranks led to wetting of the sparkplugs due to excess fuel in the combustion chamber.

Table 2. Lambda table comprising of variable lambda table.

Lambda Table (Lambda)

TP % \ RPM	[illegible]	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500	7000	7500	8000	8500	9000	9500	10000
90.0	1.00	0.90	0.95	0.95	0.95	0.88	0.88	0.88	0.88	0.89	0.88	0.88	0.88	0.88	0.87	0.85	0.85	0.85	0.85	0.85
80.0	1.00	1.00	1.00	0.95	0.88	0.88	0.88	0.88	0.89	0.88	0.88	0.88	0.88	0.88	0.88	0.90	0.90	0.90	0.90	0.90
70.0	1.00	1.00	1.00	1.00	0.90	0.90	0.90	0.88	0.90	0.90	0.90	0.90	0.95	0.98	0.98	0.98	0.95	0.95	0.95	0.95
60.0	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.98	0.98	0.97	0.98	0.98	0.96	0.99	0.97	0.97	0.97	0.97	0.97	0.97
50.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
40.0	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.00	1.00
30.0	1.20	1.20	1.20	1.20	1.20	1.20	1.15	1.15	1.15	1.10	1.10	1.10	1.10	1.05	1.05	1.10	1.10	1.10	1.00	1.00
20.0	1.20	1.20	1.20	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.15	1.05	1.00	1.00	1.00	1.00	1.00
10.0	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.20	1.20	1.20	1.20	1.20	1.15	1.05	1.00	1.00	1.00	1.00
[illegible]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

The fuel timing map was toned down to achieve lower AFR using Motec ECU Manager. The regions of lean mixture were increased in the lambda table in order to make the engine run lean most of the time. In these trials, the drivers complained on lack of power and very poor throttle response. When the car was coasting at minimum idle throttle position of 10 to 20%, the transmission disengaged after driver clutched in, due to very low fuel supply and engine shut down was observed. This was not favorable for all the drive styles. Very lean mixtures also has the risk of engine overheating.

Rich mixture aids engine cooling since the excess unburnt fuel injected to the chamber absorbs heat and cools the combustion chamber. This is not possible in lean mixture engine map configuration due to lack of excess fuel. After multiple iterations by running the engine with lean and rich mixtures, the engine map Table 2 was found to be ideal. After the engine was warmed up along with the wideband lambda sensor, a closed loop control was initiated. This provided the desired performance. On a previous dyno-tuned base map with no lambda control running at a constant 0.9 lambda, the engine delivered very poor fuel efficiency of an average of 3.3 km/l. Drivers also complained very poor throttle response and flooding of the engine in the previous map. Incorporating a closed loop variable lambda control, the engine performance enhanced to 4.5km/l, i.e. 36% increase in efficiency. Along with improvement in efficiency, the engine was better responsive and the test drivers provided positive feedback on throttle response.

3.2.2 Fuel Table

The base dyno-tuned fuel table which holds the values of the percentage of Injector Pulse Width values had to be altered to initiate the closed loop lambda control. The IJPU values was previously configured on the dyno-tuner. During testing of the car on the road, most drivers complained of poor throttle response from the engine even from a dyno-tuned engine map. Drivers experienced jerking and poor power delivery predominantly at the end of slow corners and uphill. To address this issue, the problem was diagnosed first by checking the condition of the clutches and found no issues. Subsequent attempts were made by changing engine maps. Both iterations of rich and poor maps were tested. This method did not provide favorable results. Even after setting up of the lambda sensor, target lambda table and adding necessary conditions on the MoTec ECU Manager, the Lambda Control feature was not commencing. The engine was not entering into a closed loop lambda control. Finally, the fuel table was toned down in which all the fuel table entries were decreased by a value of 2 IJPU. This enabled the engine to enter in a closed loop lambda control as the necessary change required in IJPU for the ECU to alter the amount of fuel injected was not too high. The regions where there was sharp increase in fuel trims, it was lowered to obtain a steady curve of throttle position vs. RPM vs. fuel. This solved all the issues and drivers found improvement in the engine and throttle response. There was no jerking in each run.

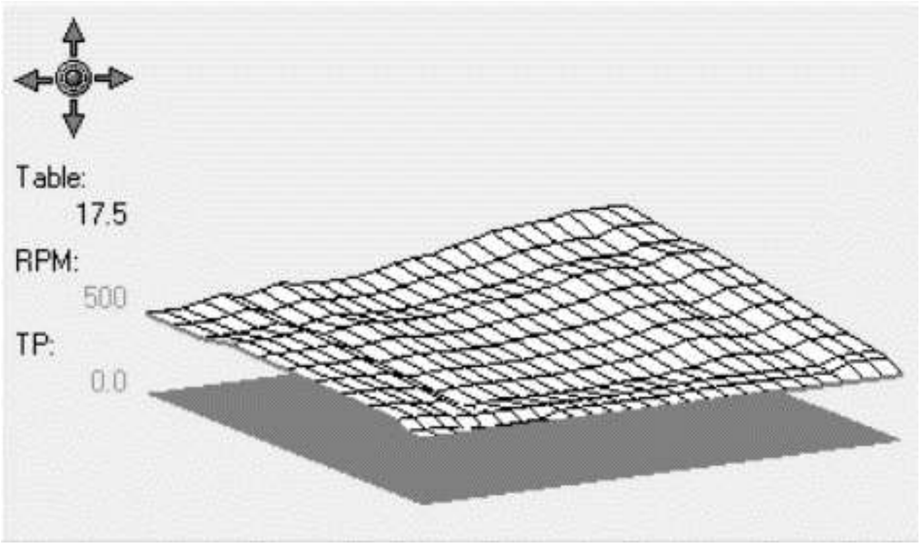

Fig. 5 Fuel graph of base dyno-tuned IJPU map

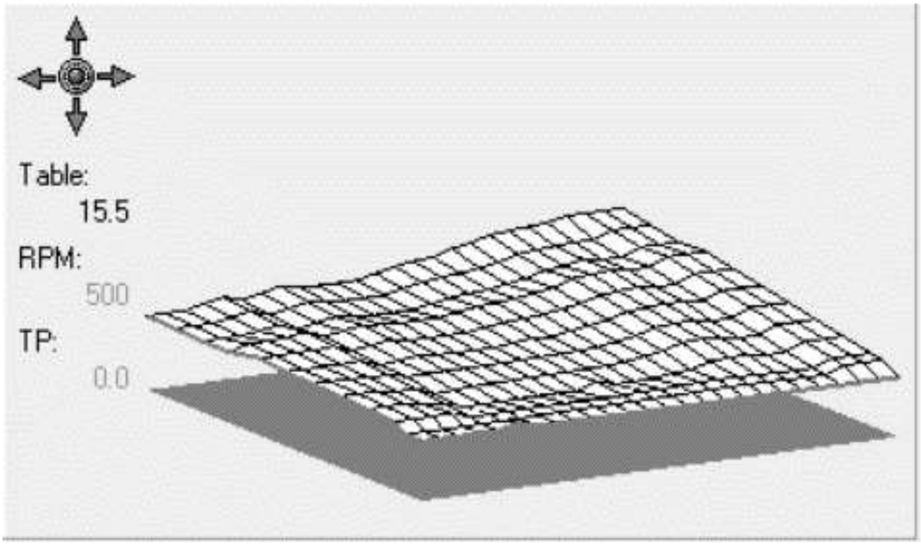

Fig. 6. Fuel graph with modified IJPU map

3.3 Mixture Sample Data

To confirm real time variation of AFR, its data was collected from the lambda sensor. After the ECU collected sufficient lambda plots, there was similar trend of the lambda just like the input table that was set previously.

Figure 7 is a mixture map comprising of lambda values that the ECU collected after the trial run of a very lean mixture map. As per the base engine map, the target fuel IJPU were reduced drastically in the lower

RPM range of 2000 to 3500. This configuration led to poor performance and the drivers complained of very poor throttle response. However, even though the engine was consuming very little fuel, these very high lean mixtures were not favourable.

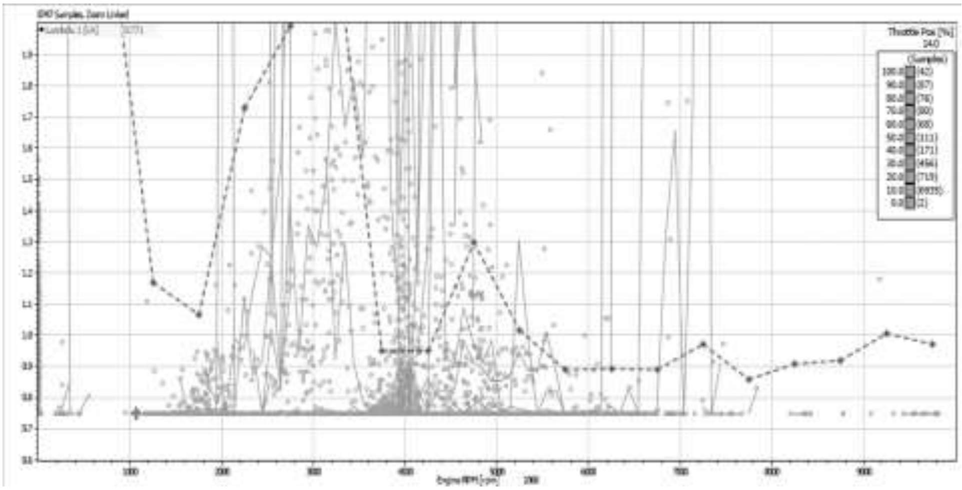

Fig. 7. Lambda plots of variable lambda mixture

Figure 8 is the sample data collected from test runs of different target lambda settings. This was a successful engine map with good throttle response. Along with good throttle response and performance, obtaining better efficiency was obtained. Upon further improvements and discovering regions where the engine could run in lean mixtures, a more efficient map was developed and the end mixture plot is shown in Fig. 9.

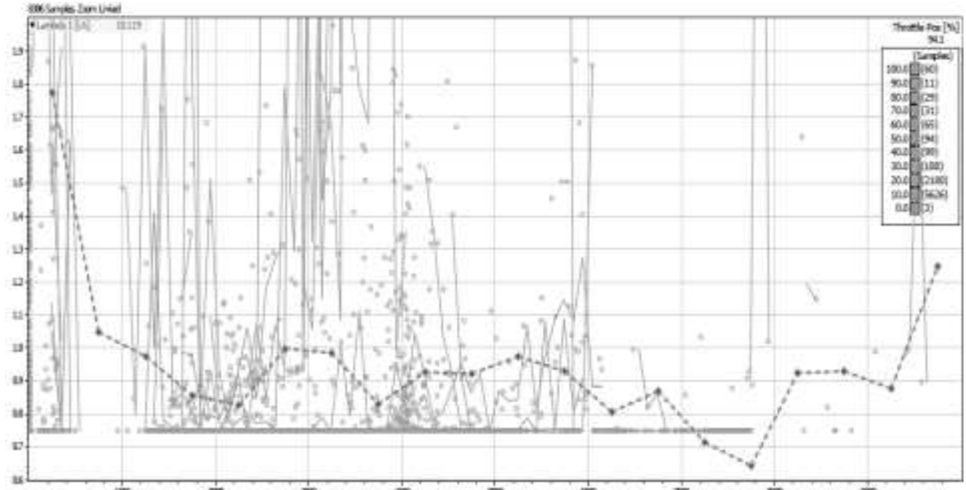

Fig. 8. Variable lambda mixture plot.

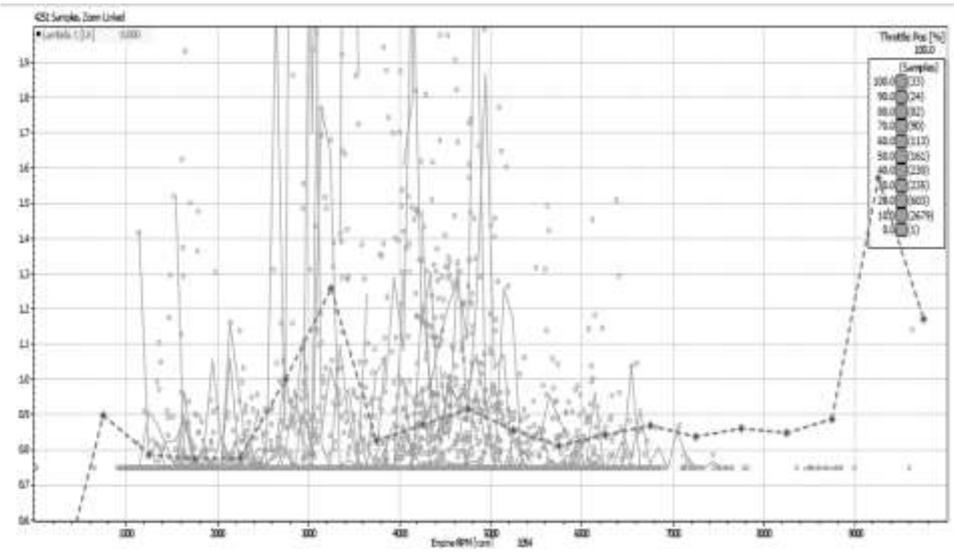

Fig. 9. Lambda plot of variable lambda mixture.

4.0 Summary Results

Comparison was made to the base dyno-tuned engine map configuration by developing engine maps, and the efficiency and lap times were drawn. To measure particularly the role played by this development, all other parameters were kept constant to obtain accurate results. The same driver, track layout, fuel type and track conditions were maintained and the two maps were compared. The engine set-up with closed loop variable lambda control provided an mean increase of 1.2s in comparison to an engine map without lambda control.

The efficiency of the engine was calculated by refuelling with exactly 1L of 99 octane petrol at the beginning of each run and the mileage was calculated by the number of laps. The map without lambda control achieved an efficiency of 3.6 km/l. By repeating the same process with the closed loop variable lambda control, the engine delivered an improved efficiency of 4.2 km/l, thus an improvement of 16.66% efficiency.

5.0 Conclusion

In this study, a systematic approach was followed by collecting the data through the MoTec i2 software and carefully observing and it on various parameters like throttle position, engine RPM, fuel and stoichiometric ratio. Several changes were made in the programmable ECU through MoTec ECU Manager and changes were made to the fuel and lambda tables. The collected data along with its interpretations are presented. To evaluate the improvements in the closed loop variable lambda control, the two maps were compared and the results are recorded.

Closed loop variable lambda control has given favourable outputs as per the simulations conducted in GT Power [4] and enDYNA [5]. Upon implementation by collecting driver and test data, implementing and comparing an open loop and a closed loop lambda control, predictable throttle response with an improvement in efficiency and lap time was obtained.

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