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Measuring the Effects of Ignition
Angle on Exhaust Gas Emissions of a
Naturally Aspirated SI Engine.

Research Methods and Projects
M6X02206

BSc Automotive Engineering

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P147482

29/04/2019

1. Abstract.

This report will explain the testing procedure and theory behind increasing engine efficiency, both of the tests aims are to achieve the most effective spark ignition point for a given RPM and load, and to identify the largest reduction of exhaust emissions at the given RPM and load. The spark ignition point will be changed from 24-30 degrees at WOT, then 16° to 20° for the partial throttle test, and the data plotted. The vehicle will be tested on a chassis dynamometer whereby the car can be driven under load in a controlled environment. The exhaust emissions will be measured on a bosch 5 gas analyser where it will allow up to 5 gases to be sampled at once during the test, and the results plotted. The test will be carried out on a Maha MSR 500 dynamometer which will be equipped with a wideband lambda probe which will insure the AFR is within safe limits. The data will be plotted to allow direct comparison between each ignition interval, at test sites 4 and 15. During the test the variables will be discussed as well as any external factors that influenced the data.

The largest reduction of NO_x occurred from 26° to 25°BTDC with a reduction of 200ppm at the WOT test, with the largest reduction at the partial throttle tests occurring at 20° to 18°BTDC with a total reduction of 65ppm. The MBT timing angle was found to be at 27°BTDC under WOT conditions with a torque value of 109.098N/m and was the point at which the engine produced the most amount of torque for the least amount of ignition timing, noting the MBT point for the partial throttle test was at 18°BTDC whereby the engine produced 34.637N/m of torque. The data gathered during the test will be compared to those carried out by other engineers who have investigated the subject area. The data collected from secondary sources will be used to evaluate the reliability of the data, as well as to compare the testing methodology to identify any points at which the testing could be improved and the reliability of the data increase. A margin of error will be calculated to further evaluate the repeatability of the test, and the influence that the variables had on the data.

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4. Introduction.

This paper will outline the aims of the proposed project idea, during this paper there will be current secondary research methods used to gain knowledge on MBT timing, and the influence that changing ignition timing has on the exhaust gas emission levels. The test methodology will be discussed as well as the control variables that could have an affect on the data.

The primary aim of the project is to identify the point at which a reduction in exhaust gas emissions occurs at the specified load site, the exhaust gas emissions that will be targeted for reduction will be disclosed in the literature review. The ignition timing angle at which the largest reduction of the specified exhaust gas emissions will be noted, as well as the load site which was tested.

The secondary aim of the project is to identify the point at which the test car will produce the highest torque output for the least amount of ignition timing, also known as MBT or Maximum Brake Torque. J Heywood, 1988 describes MBT as a condition whereby the maximum torque is produced for the least amount of ignition timing, this also allows the greatest torque to be produced for the least amount of brake specific fuel consumption, therefore allowing the engine to operate more efficiently.

The testing will be carried out using an MSR 500 AWD chassis dynamometer to simulate active road testing, while allowing the conditions to be more controllable than if the testing was to be carried out on the open road. The test will be carried out at a constant rpm site, which will be the point at which the test car produces peak torque and the load varied between 2 sites. This point will be found through preliminary testing whereby the peak torque point will be identified, as well as ensuring the test car's fuelling has been setup appropriately.

Once the data has been gathered, graphs will be produced to illustrate any changes in exhaust gas emission levels with the varying ignition timing angle and load. Secondary research will be introduced to compare the data and evaluate the findings, the test methodology and equipment selected will be scrutinised to evaluate any areas of the test that could be improved to increase the reliability of the data.

5. Literature Review.

Secondary research must be undertaken prior to the live testing, in order to fully understand the methodology and testing procedures. As stated in the introduction, the secondary aim of the test was to identify the point at which MBT occurs. As disclosed in paragraph 3.2, J Heywood, 1988 describes MBT as the point at which the maximum brake torque can be achieved for the least amount of ignition timing angle in CA° before top dead centre. MBT timing is a strategy used in aftermarket or “standalone” ECU tuning used in fast road cars or race cars to calculate the optimum timing angle to be used in different load sites providing the ECU can support such a feature.

The dynamometer use was a Maha MSR 500 which is a 4WD single roller dynamometer, which offers accurate output measurements and a large amount of external measuring probes to be used in one machine. The external measuring devices will be the dynamometers built in lambda probe and engine speed reference probe. Michlberger, A. et al, 2017 describes the benefits of using a chassis dynamometer compared to an engine dynamometer as testing the drivetrain as a complete system, which means that the system has all the frictional losses in terms of the gearbox, differential, CV joints that the vehicle would on the road, as supposed to an engine dynamometer whereby those losses are not present.

The setup tuning procedure of the KMS ECU will be primarily to ensure that the AFR throughout the load sites are consistent, from reading Valle, R 2004. Whereby the test discloses the general tuning procedure that can be widely applied to all spark ignition engines. However, the ignition timing will not be altered and will remain at the values that the car arrived at.

The chosen gear for the testing was fourth gear, this was chosen because the point at which the engine produced peak torque was at 4750rpm. At 4750rpm in 4th gear the vehicle had an effective road speed value of 74.8Mph. This was calculated by using formula 1 in the appendices from Shelquist, 2018. Using Formula 1, the calculated equivalent road speed was 74.8Mph which was considered the maximum road speed likely to occur legally on real road use. The partial throttle test was a more accurate representation of real world driving at 70Mph. This was discovered through live testing prior to the preliminary testing of the test car whereby the cruising speed of the test car was tested to validate the calculations carried out.

From reading M Gogos et al, 2009 report titled “influence of ignition timing on the exhaust emissions of a ford escort fuelled by various ethanol and petrol mixtures”, the conclusion that was made of over advanced ignition timing resulting in increased NO_x emissions, whereas HC and CO emissions were reduced. The conclusion outlined a possible prediction to be made for this test, i.e. increased timing would result in increased NO_x outputs. However, this was with E50 fuel which is a 50/50 ethanol and petrol mix, the influence of ethanol on NO_x production will not be a factor in this test and may provide different results.

Reading “Spark timing and fuel injection strategy for combustion stability on HEV powertrain” by Hyungseuk, Ohn. 2010 identified the requirement for an efficient burn of the air fuel mixture while reducing exhaust gas emissions as much as possible, as the use in series HEV powertrain vehicles would be a prime application of the projects primary aim. Where the generator for the series hybrid system operates at peak torque for the use of the vehicle; the optimisation of ignition timing would result in the engine generator being more efficient at the corresponding load site. The application of the primary project aim could be used in generators that run at a fixed engine speed for the entirety

of their use.

The application of the proposed project idea came from reading Attard, W. Et al 2006, whereby the paper outlines issues with downsizing modern engines having elevated NO_x levels due to higher compression ratios and forced induction being used as methods to improve engine efficiency. During Attard, W. et al paper the methodology describes the ignition timing as being set as MBT, which reinforces the project aim of identifying MBT as a means of improving engine efficiency.

The selected methods for validating the tests are as follows: Repeated tests, Mathematical predictions using excel. Firstly, during the live testing each test will be repeated twice to eliminate anomalous results. Each of the results will be used to create a mean value from which will be used for creating graphs and analysis. Secondly, an excel spreadsheet will be created that will allow optimum ignition angle to be calculated using mathematical equations. From here, the live data results will be compared to that of the excel sheet to aid in validating the test.

The initial test car selected for testing was a Vw Lupo, which has a 1.0 litre 4-cylinder SOHC 8 valve engine. From the preliminary tests the power output was tested at 42.3bhp at 4900rpm, and a peak torque value of 92.4Nm at 4000rpm. However, due to the issues with the initial test car, a secondary test car was used to carry out the test. The final test car was a 1988 Peugeot 205 Gti, with a 1.9, 8 valve, naturally aspirated 4-cylinder engine. However, the test car was not standard, it was fitted with Jenvey 40mm throttle bodies, Cat racing camshaft, 12:1 compression pistons, double valve springs, titanium valve spring retainers and a KMS standalone engine management system.

The standalone ECU that was used on the second test car was the KMS Motor management MP25 ECU, which is a standalone engine management system often chosen for aftermarket and race applications whereby the ECU can be accessed via a serial data cable, and the engine management system modified to the owners requirements. The KMS MP25 utilises a throttle position sensor to calculate load, as supposed to many other aftermarket standalone ECU systems such as the Megasquirt engine management system whereby the Megasquirt ECU utilises a manifold pressure signal to calculate load. Megasquirt, 2012.

The preliminary testing identified an issue that was not considered before the testing had begun. The issue was the viscosity of the gearbox and differential oil causing an increased loss through the drivetrain. The material data sheet, or MSDS for the engine and gearbox oils show a significant drop in viscosity when the gearbox oil is at 100 degrees Celsius compared to that at 40 degrees Celsius as shown in figure 12, therefore when the emissions testing was undertaken, that the engine and gearbox oil must be at full operating temperature prior to any measurements being taken to eliminate the oil viscosity as a variable that could affect the data. The MSDS sheet for the engine and gearbox oil can be found under reference Total, 2004 and msds.castrol, 2004.

Alternative methods to increase engine efficiency are: Increased compression ratio, forced induction, variable valve timing, increased volumetric efficiency of the cylinder head. However, the issue with these methods is that they require additional modifications to the vehicle and can lead to an increase of certain exhaust emissions. The justification for the proposed test methodology comes from the simplicity of the test and the equipment needed which leads to a reduction in cost to improve efficiency, and the necessity to get the most energy transferred from the fuel to useful work.

As later discussed in the methodology, the test car fuelling was tuned so that it would read an average of 0.9 throughout the power run, and at the load sites tested the lambda values were approximately 0.850 which is an AFR of 12.5:1. This AFR was selected after reading Nakata, K. et al 2006 whereby the paper outlines the latent heat of gasoline used in a high compression engine. The paper outlined the effect that gasoline and ethanol had on cooling in-cylinder temperatures due to the vaporisation of the fuel being an endothermic process as the liquid vapour gasoline changes state as it becomes more gas-like absorbs heat energy from both the charge and the cylinder, reducing the temperature of the cylinder and preventing detonation. Therefore, the AFR of 12.5:1 was selected, along with the use of 99-octane fuel to prevent the onset of detonation, this allowed a wider range of ignition timing intervals to be investigated.

Poskart, A. Et al 2016 finds that the formation of Oxides of Nitrogen increases at flame temperatures above 1400°C. Whereby the nitrogen contained in the fuel/air charge combines with excess oxygen in the charge at high temperatures. Joshi, A. 2019 describes a strategy often used to reduce NO_x tailpipe emission levels called an SCR, or Selective Catalytic Reduction system, which has been widely implemented in road vehicles since the last update of the European emission legislation. Targeted news service, 2015 defines the operation of SCR as an additive solution sprayed onto the SCR catalyst, with the additive solution which is called urea and often branded as "AdBlue". The author describes the solution as containing ammonia, which when sprayed onto the SCR catalyst causes a chemical reaction known as a reduction reaction, whereby the additional electron of the NO_x molecule reacts with the Urea solution, this then creates Ammonia, Nitrogen and CO₂.

Another example of apparatus fitted to vehicles to reduce the tailpipe emissions of NO_x is EGR, or Exhaust Gas Recirculation. Lee, H 2016 describes EGR as a means of re-introducing inert exhaust gas back into the cylinder that is then mixed with the air/fuel charge and reburned. The paper describes the effect of re-introducing inert exhaust gas into the cylinder as a method of reducing in-cylinder temperatures and hence reducing NO_x concentration. Mauzerall, D. et al 2004 describes the dangers of NO_x being the impact to the ozone layer, rather than directly to human health. The paper states that NO_x degrades the ozone layer 300 times faster than CO₂ and increases the effect of global warming.

6. Preliminary Test Methodology.

The preliminary test objective was to carry out power, torque and lambda to use as a baseline to ensure the test car was correctly setup in terms of the ignition timing and fuelling. The test apparatus used was as follows: Engine speed reference probe and an external lambda sensor, the Maha MSR 500 dynamometer was equipped with test probes which allowed for the measurements to be taken with minimal external equipment. Once the car was safely secured, the measuring equipment was fitted. The measuring equipment fitted was an engine speed reference probe which would detect when the ECU fired one of the spark plugs, and after setting the dynamometer up for a 4-cylinder engine, an engine speed signal can be generated.

The second piece of measuring equipment was the Maha MSR 500 wideband lambda probe, which was fitted to the exhaust tip, to allow the current fuelling strategy to be measured. The decision was made to use just the two measuring devices for the preliminary tests as they are used for a comparative baseline, the two measuring devices used were key and would be used again during the main testing session to monitor the air fuel ratio. The test car was setup on the dynamometer and the engine speed signal checked against the data from the KMs ECU, and ensuring the fuelling remained stable.

The preliminary test was carried out by driving the vehicle at low throttle until fourth gear was selected, then the throttle was fully depressed, and the power run would begin. The dynamometer would begin the measurement at 2000 rpm, during the run the air fuel ratio was monitored, as well as the intake air temperature to ensure the testing was carried out safely. The adjustments came from discovering the vehicle was lean with a lambda reading of 0.95 or an AFR of 13.97 from 2000 rpm to 3000 rpm, and then would become too rich at 3500 rpm with a lambda value of 0.75 or an AFR of 11.03 using Tattech, 2013. The adjustments were Made to reduce 20% fuel at 3500 rpm and increase fuelling by 10% to 2000rpm to 3000rpm, this fuelling strategy was used to carry out the final testing as it provided stable fuelling throughout the run.

7. Preliminary Results.

The preliminary testing was undertaken to identify the point at which the test car produced peak torque, and to ensure the fuelling was stable throughout the engines rev range. The fuelling had to be adjusted to a lambda value of 0.9 throughout, which is the AFR equivalent of 13.23:1 using tattech.com, 2019 as discussed in the methodology. The fuelling was stable throughout the run with a minimum lambda value of 0.85 or an AFR of 12.50:1, and a maximum lambda value of 0.95 or an AFR of 13.97. The peak torque value was 190.3Nm at 4725 rpm, and a peak power value of 116.9 bhp at the wheels at 6090 rpm at both points the fuelling was 0.89 lambda, or 13.08:1. The ignition timing was unaltered from when the test car began the testing until the final testing to allow for a base ignition timing angle to be used.

The inlet air temperature was monitored throughout the preliminary testing, the maximum inlet air temperature recorded during the preliminary test was 40° Celsius. This was due to the MSR dynamometer ramp rate being such to allow excessive heat build-up during the power runs. This was noted for when the wide-open throttle testing would be undertaken and would dictate the length of time the measurements would be taken to prevent heat build up from effecting the data.

8. Final Test Methodology.

Due to the new test car being modified for fast road/rally use, the exhaust emissions are likely to be higher than expected for a stock Peugeot 1.9 Gti, however the comparisons for this test will be relative to the point at which the setup testing began, as the ignition timing angle was already set by the owner of the vehicle. The fuel selected for this test was 99 octane petrol, from reading Hoth, A. et al, 2019 99 octane fuel was chosen for its ability to increase the detonation threshold and its charge cooling effect.

The final test was undertaken at load site 15 which represented 100% throttle on the KMS ECU. The first test was undertaken at 30° BTDC at throttle position cell 15, which was the timing angle was set when the vehicle arrived. The vehicle was accelerated in 4th gear to the test speed of 4750 rpm, from here the test car was held at full throttle at 4750 rpm for 20 seconds to allow for the dynamometer load brake to not affect the load being applied to the engine. The Bosch 5-gas analyser began measuring when the vehicle had reached its test speed of 4750 rpm, the emission test was terminated once the vehicle had returned to idle. The recorded graphs on the Bosch 5-gas analyser were captured, and the test repeated for 29° until 24° was achieved, throughout each test the intake air temperature and lambda values will be recorded.

The partial throttle testing was undertaken at load cell 4 on the KMS ECU, the testing started at 20° BTDC which was the ignition angle that the vehicle was set to before any adjustments were made. The vehicle was accelerated up to the test speed of 4750 rpm and was held for 20 seconds, once the vehicle was at its test speed the Bosch 5-gas analyser began recording data and terminated the recording once the vehicle returned to idle. The test was then repeated for 19° until 16° was achieved, during each test the intake air temperature and lambda value will be recorded.

During the full throttle test and the partial throttle test the following ambient conditions will be recorded: Ambient air temperature, Ambient air pressure, Lambda, Humidity and Intake air temperature. These are all variables that could influence the final values, and therefore to increase validity to the results they must be monitored and controlled as closely as possible. One factor that was found in the preliminary test that was not expected was the influence that gearbox/differential oil temperature had on the test cars outputs, as the gearbox/differential oil temperature increased with the amount of test runs the cars outputs increased due to the decreased viscosity of the oil.

This dictated that the preliminary test was undertaken first before the final testing to ensure that the gearbox and differential oil was up to operating temperature, to reduce the likelihood of the oil viscosity affecting the data. Due to the influence engine and gearbox oil temperature has on the vehicle's outputs, the measurements must be taken when the oils are between 80 and 100 degrees Celsius as shown in the MSDS report titled figure 12. During this temperature window the oils viscosity has halved and will reduce the effect on the cars output. Each of the tests were repeated to allow for an average to be taken, this will allow any anomalous results to be removed from the tests to allow more reliable data to be produced.

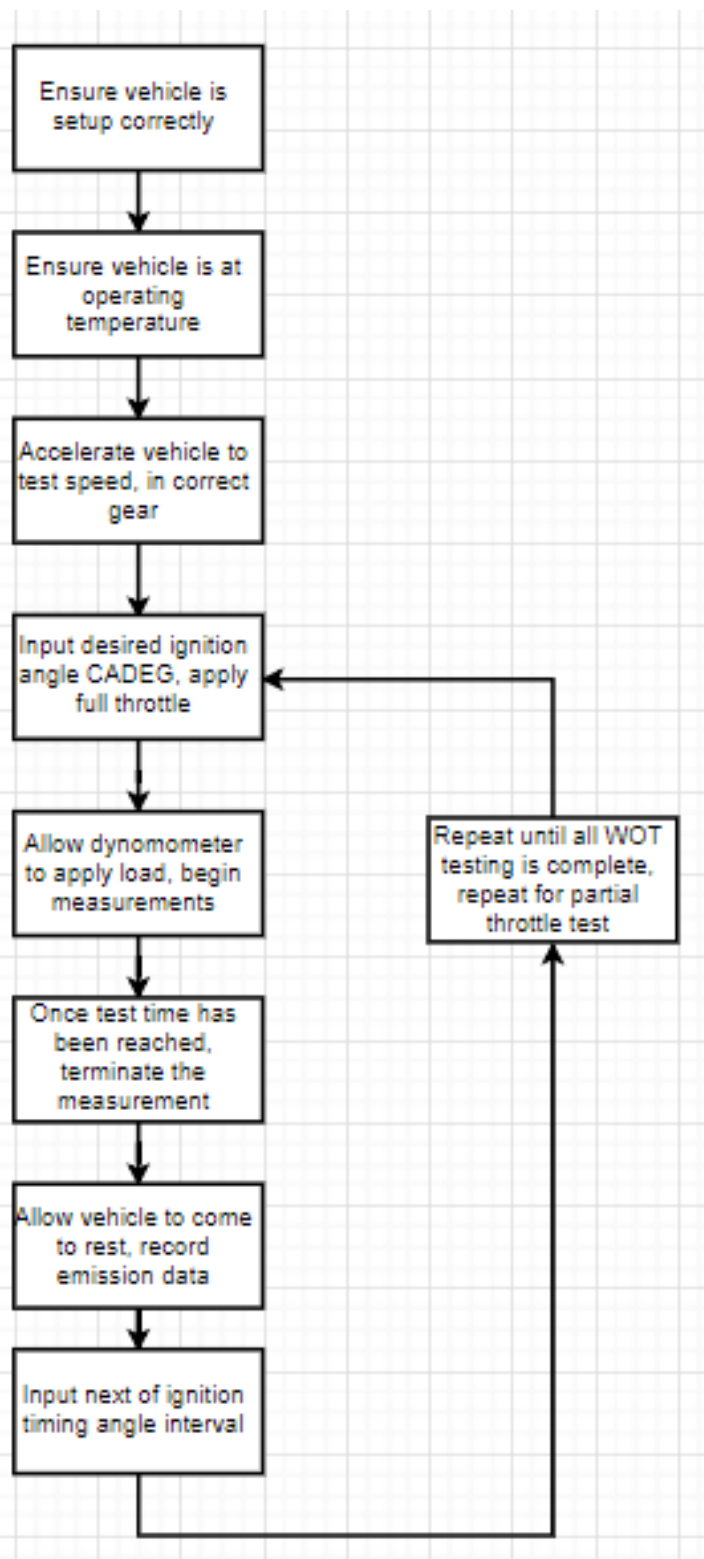


Figure 11 - Flow chart of final test methodology

9. Final test results.

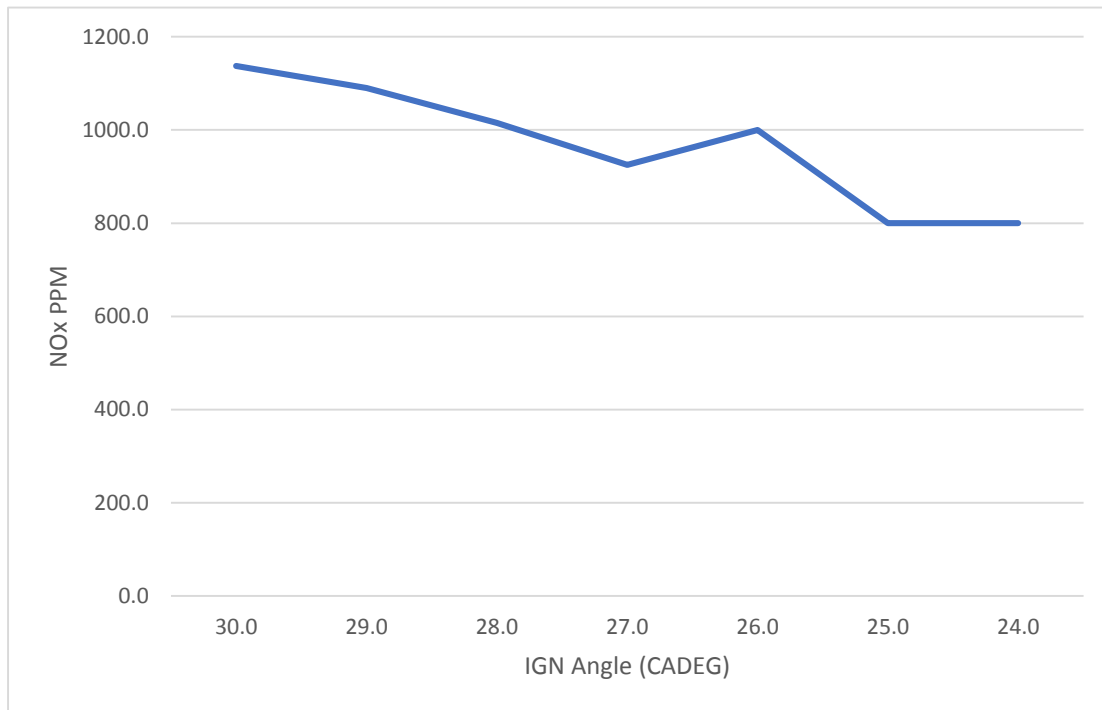


Figure 1 - NOx Against Ignition Angle (Load Cell 15)

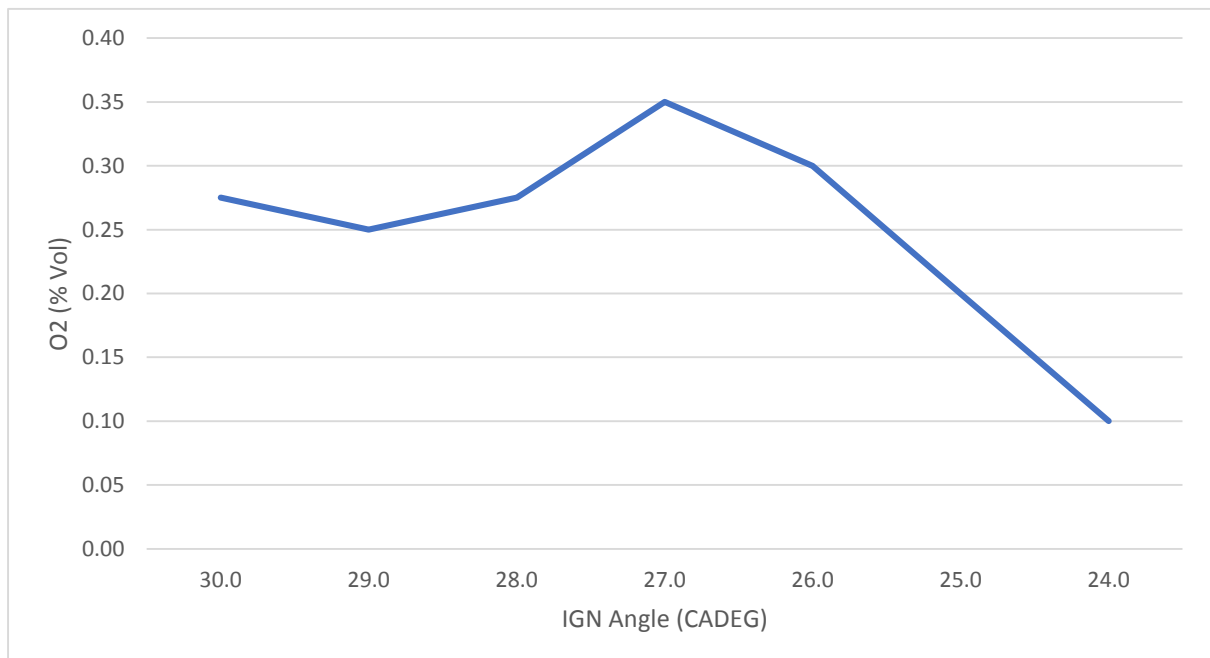


Figure 2 - O2 Against Ignition Angle (Load Cell 15)

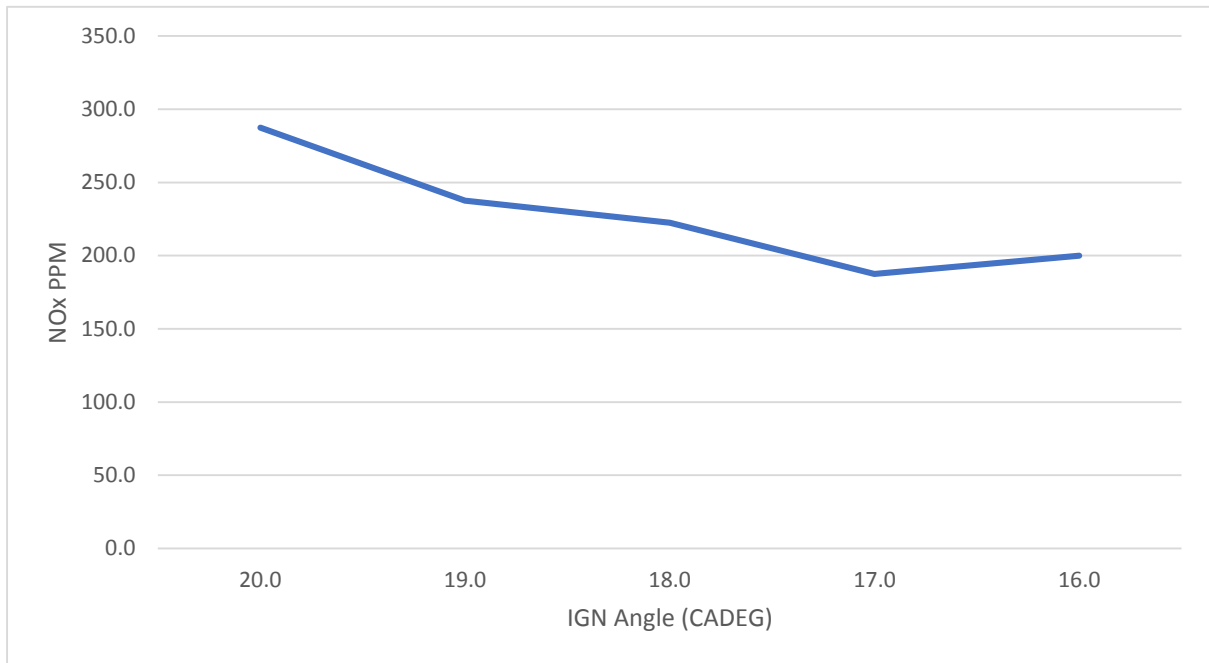


Figure 3 - NOx Against Ignition Angle (Load Cell 4)

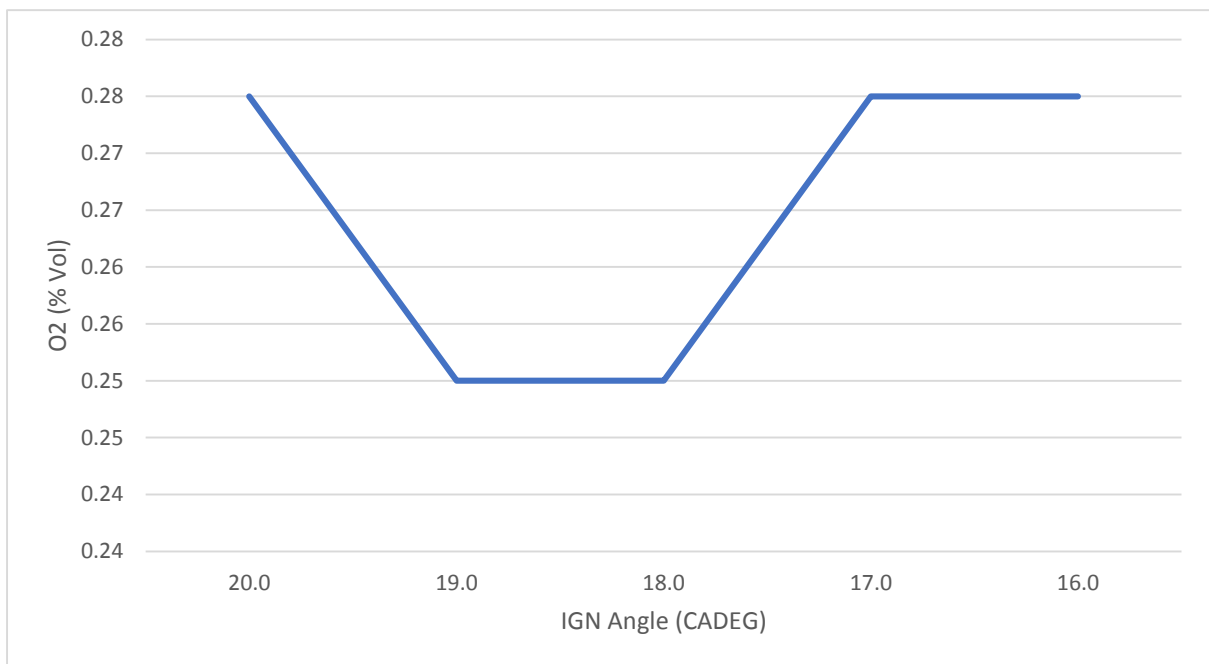


Figure 4 - O2 Against Ignition Angle (Load Cell 4)

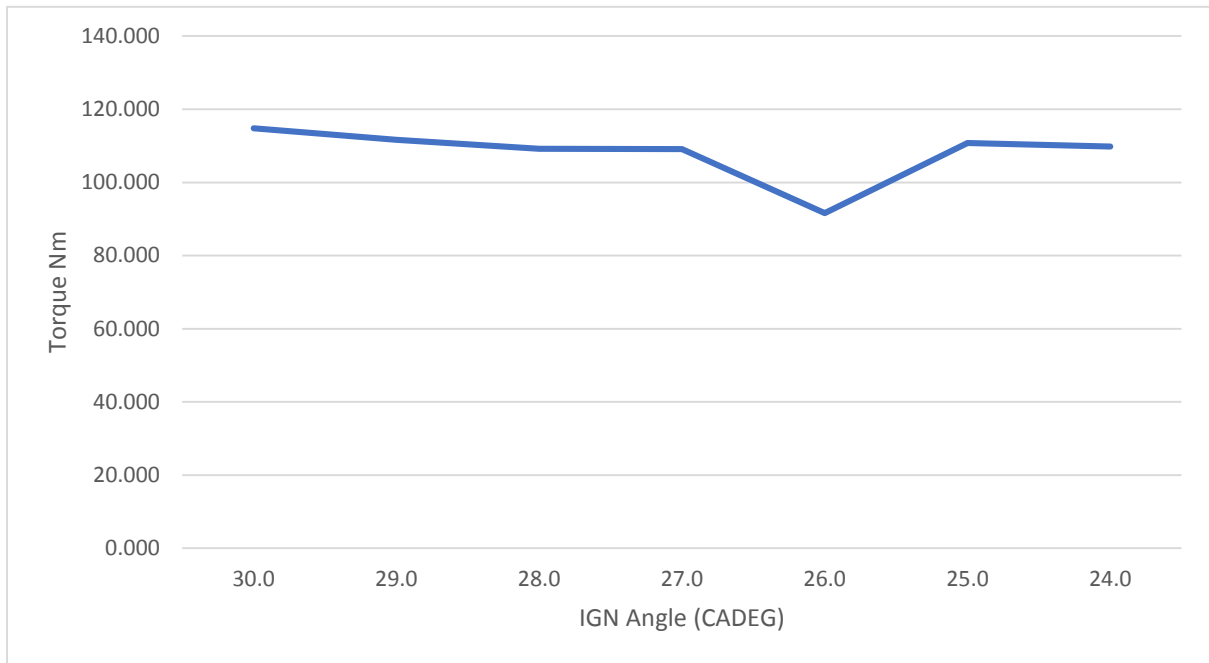


Figure 5 - Torque Against Ignition Angle (Load Cell 15)

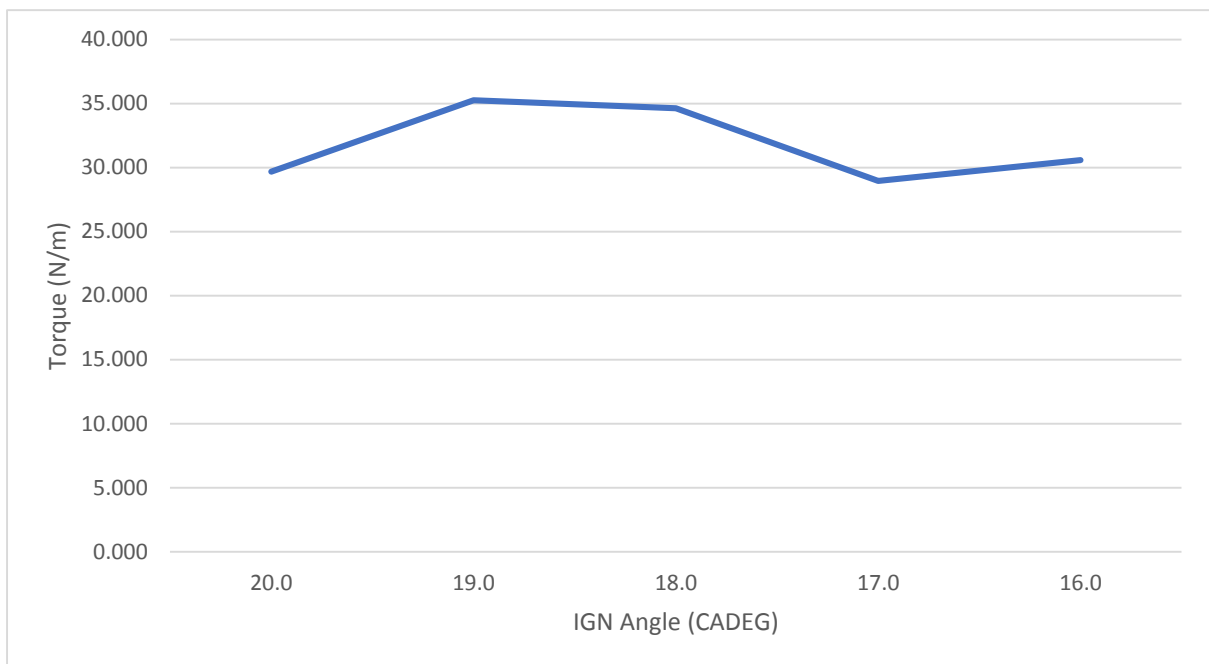


Figure 6 - Torque Against Ignition Angle (Load Cell 4)

10. Analysis.

All the measurements used in the graphs were taken 10 seconds into each steady state period, this was done to allow the dynamometer to apply even load to the vehicle and allow for more accurate measurements to be taken. During the test, the throttle was fully depressed when 4th gear was selected to carry out the test, however by doing this the dynamometer has to apply load to the rollers to control the engine speed to 4750 rpm. By applying full throttle, the dyno will apply and release load to steadily control the desired engine speed, however this takes time for the dyno to control the engine speed.

From the testing carried out, 10 seconds was deemed a sufficient amount of time for the load to become steady and ensure reliable measurements were recorded. This can be observed in the raw data labelled figures 13 – 81, where each start of the emission measurements has a small increase at the start of the run and then the emission levels become more stable, this is due to the dynamometer increasing and reducing load to control the speed.

Looking at figure 1, the data shows a decrease of NO_x concentration from load cell 15 test from 30° BTDC to 29° BTDC, with no change from 26° to 25°, and a smaller reduction of 75ppm from 25° to 24°.

Ignition Angle (BTDC).	Exhaust Emissions.	Change in concentration (PPM).
30 to 29	NO _x	-47.5
29 to 28	NO _x	-75
28 to 27	NO _x	-90
27 to 26	NO _x	+75
26 to 25	NO _x	-200
25 to 24	NO _x	0
Table 1 - Change in NO _x Concentration Per Ignition Change Interval (Load Cell 15)		

Table 1 shows the change in NO_x concentration through the varying ignition angles. The greatest reduction of NO_x concentration was between 26° and 25° BTDC with a total reduction of 200ppm. Taylor, C 1985 describes the formation of Nitrogen Oxides or NO_x occurring at high in cylinder temperatures and increase exponentially as the peak combustion temperature increases.

Therefore, with reduced ignition timing angle, and reduced in-cylinder pressure/temperature the result will be reduced NO_x concentration which correlates with the data from 30° to 27°. However, from 27° to 26° there is a small increase of 75ppm of NO_x that does not match the general trend of figure 1. Looking at the intake air temperature, the test carried out at 26° BTDC had an intake air temperature of 30°C which comparatively was 4.5°C lower than the previous test. This will influence the density of air traveling into the engine, Formula 2 shows the equation used to create the graph labelled figure 7. Figure 7 shows the changes in the air density with an increase of intake air temperature as the tests were carried out.

Figure 3 shows the data gathered from the partial throttle test, labelled load cell 4. Figure 3 shows a clear correlation to

increased ignition timing increasing NO_x concentration. Similar to the WOT test at load cell 15, there is a reduction of

Ignition Angle (BTDC).	Exhaust Emissions.	Change in concentration (PPM).
20 to 19	NO _x	-50
19 to 18	NO _x	-15
18 to 17	NO _x	-35
17 to 16	NO _x	+12.5
Table 2 - Change in NO _x Concentration Per Ignition Change Interval (Load Cell 4)		

NO_x with a reduction in ignition timing angle. However, from 17° to 16° the NO_x increases a further 12.5ppm, with the greatest reduction of NO_x concentration occurred at 20° to 19° with a total reduction of 50ppm. Looking at figure 6, 19° BTDC was also the point at which the engine produced

the most torque of 35.244 N/m, with 20° BTDC producing a further 15ppm reduction in NO_x concentration, while also producing 34.637 N/m of torque.

Figure 2 shows the O₂ concentration after each ignition angle change, under WOT conditions of load cell 15. Figure 2 shows an initial reduction of O₂ concentration from 30° to 29° BTDC changes, however, from 29° to 27° BTDC the O₂ concentration increases by 0.1 %Vol with a lambda value of 0.85 or an AFR of 12.5:1. Then 27° to 24° there is a consistent decline of O₂ concentration, with a total reduction of 0.25 %Vol from 27° to 24°.

Table 3 shows the change in O₂ concentration throughout the ignition timing changes. The greatest increase of O₂ was 28° to 27° with an increase of

0.07 %Vol, from analysing the data collected from the test, one possible cause could be that during the second test the intake air temperature reached

40°C, whereas during the first test the intake air temperature was 29°C. This difference in intake air temperature would affect the volume of air entering the cylinder, this could not be avoided as the KMS motor management ECU system utilises a TPS or Throttle Position Sensor to interpret load, and not a Manifold Absolute Pressure Sensor or Mass Air Flow Sensor.

Ignition Angle (BTDC).	Exhaust Emissions.	Change in concentration (%Vol).
30 to 29	O ₂	-0.03
29 to 28	O ₂	+0.03
28 to 27	O ₂	+0.07
27 to 26	O ₂	-0.05
26 to 25	O ₂	-0.1
25 to 24	O ₂	-0.1

Table 3- Change in O₂ Concentration Per Ignition Change Interval (Load Cell 15)

Table 4 shows the O₂ data collected from the load cell 4 testing, the table shows varying levels of O₂ content in the exhaust gas, however with no overall change from

Ignition Angle (BTDC).	Exhaust Emissions.	Change in concentration (%Vol).
20 to 19	O ₂	-0.03
19 to 18	O ₂	0
18 to 17	O ₂	+0.03
17 to 16	O ₂	0

Table 4- Change in O₂ Concentration Per Ignition Change Interval (Load Cell 4)

20° to 16° BTDC. The changes in O₂ concentration from 20° to 19°, and likewise 18° to 17° BTDC could be due to changes in the AFR. The AFR between 20° and 19° BTDC changed from 12.05:1 to 11.76:1, and from 18° to 17° BTDC also changed from 12.05:1 to 11.76:1. Both changes in the AFR occur with only a 1 degree Celsius difference in the intake air temperature, and does not occur at other points in the test with the same difference in intake air temperature occurring. The changes in air density can be found in figure 7, which shows the total fluctuation in air density as the testing continued.

From reading Natti, K. et al, 2013 the change in the O₂ content in the exhaust, as well as the change in the AFR could be due to an issue with the test car, being that the vehicle was not equipped with closed loop lambda control. This means that any changes in the air temperature or pressure, without a change in throttle angle will affect the AFR of the vehicle, and the vehicle will not be able to correct for this difference. Likewise, if the vehicles fuel pressure was to drop due to a faulty fuel pump or regulator issue then the vehicle would have a different AFR value than the specified injection duration would facilitate, due to the pressure being different to that when the fuel table was setup initially.

Figure 8 was created by using existing data from Ford, 2003. The data shows the in-cylinder pressure data gathered during live testing of a petrol Ford Sigma 1.6 4-cylinder NA engine. The Ford Sigma 1.6 engine tested had a compression ratio of 11.6:1 which was similar to the test car's compression ratio of 12:1. Using formula 3, the bore to stroke ratio was calculated for each engine; the Ford Sigma had a bore to stroke ratio of 0.98, which again was similar to the test car which had a bore to stroke ratio of 0.97, both engines were naturally aspirated and featured an inline 4 cylinder layout.

The blue trace of Figure 8 shows the measured in-cylinder pressure during the power stroke, comparatively the yellow trace shows an estimated increase in cylinder pressure with more advanced timing, noting the peak cylinder pressure occurring at approximately 15°ATDC compared to the original peak pressure occurring at approximately 18°ATDC. The grey trace shows the estimated peak cylinder pressure with retarded timing, noting lower peak cylinder pressure occurring later in the cycle at approximately 23°ATDC. The data for advanced and retarded ignition timing effect on peak cylinder pressure was an estimated figure and was not calculated. The estimation came from reading Papagiannakis, R. et al 2017 as well as from the live testing carried out.

11. Conclusion.

Looking at figures 1 and 3, it was found that increased ignition timing has a direct negative effect on the NO_x concentration of exhaust gas emissions, meaning more ignition advance yields higher NO_x levels. This is the case for both the WOT tests at load cell 15 and partial throttle tests at load cell 4. Comparing figures 1 and 5 the optimum ignition angle during the WOT tests at load cell 15 for both the NO_x concentration and engine torque was 27°BTDC, from looking at the respective figures the point at which there was the greatest reduction in NO_x concentration for the most amount of engine torque being produced was at 27° whereby the total NO_x reduction was 212.5ppm from 30°BTDC to 27°BTDC with the total reduction of torque being 5.728N/m. If the ignition timing was to be retarded further there would be diminishing returns in terms of the NO_x reduction to torque loss, being that the next interval of 26°BTDC yielded a gain of 75ppm of NO_x and a loss of 17.5N/m of torque.

Looking at figure 3 and 6, the point at which the engine produces the lowest levels of NO_x for the most torque was at 18°BTDC, whereby the engine produced 222.5ppm of NO_x which was a total reduction of 65ppm. At 18°BTDC the engine produced 34.637N/m of torque, which is a gain of 4.97N/m of torque against the original 20°BTDC timing that the test car arrived with. Furthermore, the point at which the engine produced the least amount of NO_x was at 17°BTDC whereby the engine produced 187.5ppm of NO_x, a further reduction of 35ppm. However, the torque reduced by 5.697N/m giving what would be a drop in performance for a small reduction of NO_x, therefore 18°BTDC was concluded as the MBT point as well as the point at which the maximum NO_x reduction occurred at without a drop in torque.

Looking at figures 5, the MBT timing point was also 27° BTDC due to that timing angle giving the most torque for its angle. Advancing the timing from 27° to 30° gives an increase of 5.73N/m of torque but would also require a high-octane fuel to ensure no detonation occurred. Kabushiki, A 2018 states that MBT timing is often used in calibration engineering to allow for maximum torque to be produced while maintaining a safety margin with the fuel system or quality. Meaning if the test car was set to 27°BTDC it would only produce 5.73N/m of torque less than 30°BTDC would, but there would be margin to allow for high intake air temperatures, poor quality fuel and insufficient fuel delivery.

The data collected during these tests follow similar trends to other Engineers who have also investigated this subject area. One of which is the work of Gogos, M. et al, 2009 whereby the test was to record the effect that ignition timing had on exhaust emissions when fuelled with ethanol and petrol mixtures. However, for the comparison of the data only the tests containing zero ethanol will be used. Looking at the report, Gogos, M. work shows a clear increase in NO_x concentration with increased ignition timing at all the tested speeds, more noticeably in the data there was a greater increase in NO_x concentration with higher speeds.

Musculusm M. 2005 describes the formation of NO_x at high in-cylinder temperatures often caused by late injection timing in diesels, or in the application of petrol engines more ignition advance whereby there is a higher peak pressure. Boyce, B. Et al 1999 describes ignition timing has having a direct impact on in cylinder temperature due to advanced ignition timing increasing the pressure within the cylinder, examples of this are found in figure 6 of Boyce, B, et al 1999 data.

12. Evaluation.

Figures 2 and 4 show the O² concentration in the exhaust gas, with figure 2 showing the WOT load cell 15 test and figure 4 showing the partial throttle tests at load cell 4 respectively. The O² concentration was measured to monitor the effect of intake air temperature on the exhaust gas emission levels, as well as to monitor the vehicles fuelling reliability. Comparing figures 2 and 4 with figure 7, that shows the changes in air density throughout the test. It is clear that the intake air temperature greatly affected the reliability of the data, as shown in figure 7 the air density continued to decrease as the tests continued until the car was allowed to cool to continue with the measurements.

The changes in air density are reflected in the AFR of the vehicle throughout the test, as shown in figure 9. Looking at figure 9 it is clear that the use of a standalone ECU with only a throttle position sensor to calculate load becomes problematic when dealing with high intake air temperatures, as shown in figure 9 the lambda values for the WOT test at load cell 15 were affected the greatest due to the test being the higher load test out of the two carried out.

If the test was to be repeated, one of the greatest issues that was faced was the intake air temperatures as discussed above. One method to reduce the intake air temperature would be to carry out the tests at lower throttle positions. If the testing was carried out at cruising speeds for different gears, such as at the respective cruising gears for 60mph, 50mph, 40mph, 30mph then it would give not only more real world driving conditions but also would reduce the impact that radiating heat build-up would have on the system, giving more reliable data.

Alternatively, the intake air temperatures could be reduced by reducing the length of time the measurements were taken for. Due to the 20 second measurement period used during the test, and that the values were taken half-way through each measurement period. The heat build-up caused by maintaining high rpm and load could be reduced if the measurement period was shortened, however the throttle would need to be regulated to ensure the dynamometer could apply steady load as the throttle was increased.

One issue with using an aftermarket standalone ECU is the loss of OBD or on-board Diagnostics, meaning that standalone ECU's have no way of ensuring all the necessary parameters are met while the vehicle is in use. In the case of this test the fuel pressure was fluctuating as reflected in the AFR's in figures 43 – 45. One method commonly used in aftermarket ECU tuning is the use of wideband lambda sensors similar to that used in road cars which would be able to provide closed loop fuelling control. Rivard, J. 1973 describes closed loop fuel control as a means of the control unit monitoring and controlling its fuelling independently of the tuner or manufacturers intervention to satisfy a pre-set target Lambda or AFR value. This would have been beneficial as the wideband lambda could have compensated for the fluctuations in fuel pressure that were seen during the test and reduced the impact that it had on the testing.

However, due to the test vehicle not being fitted with a wideband lambda the irregularities in fuelling caused issue with the data. More notably during the first 26°, 25° and 24° BTDC tests whereby the lambda value rose to 1:1, 1.250:1 and 1:1 respectively, meaning that this series of data could not be used in the graphs as it was not reliable enough to draw any conclusions on, based on the unstable fuelling having an effect on the emissions along with the changing ignition angle.

Another example of the vehicle fuel delivery being an issue is in figures 43 - 45, whereby the graph shows a 10 second period of the steady state testing where there is a clear issue with the fuel delivery on the vehicle as all other parameters were consistent with the other testing. The intake air temperature remained between 28^oC and 32^oC during the test. Therefore, if the test as to be repeated in the future, it would be advised that the car be examined, and mock testing be undertaken before the final testing to prevent errors from affecting data.

Due to limited dynamometer time preventing more tests from being undertaken, only one repeat was carried out during the entirety of the test. This was insufficient as although averages were taken from both tests, the anomalous results discussed in the paragraph above still had a great effect on the data and had to be excluded from any graphs and discussion as they were not reliable. From reading Harrington, J et al. 1973, and Zareei, J. et al 2013 it would be advised that at least 3 tests were carried out to establish a mean value from to later be used in graphs and analysis. Having at least 3 tests would allow for an anomalous series of results to be excluded from the data and an average still able to be created.

The reliability of the measurements must be evaluated, using a margin of error calculation or MOE. Using formula 4, the following margin of error was calculated for the results taken. Figure 10 shows the calculated margin of error for the tests carried out. The greatest margin of error occurred at the average O₂ measurement where a 22.917% error occurred. However, the most relevant margin of error was the NO_x measurement which had a margin of error of 18.628 for the Load cell 15 test, and 18.421 for the load cell 4 test. This gives an average margin of error of 18.523%.

load cell 15	Average NOx MOE	18.628
	Average O2 MOE	22.917
Load Cell 4	Average NOx MOE	18.421
	Average O2 MOE	10.000

Figure 10 – Calculated Margin of Error

This margin of error for this test were considered too great, as the data was not repeatable to within a tolerable accuracy. This was due to the variables not being controlled enough during the testing, and the test car not being reliable during the tests. Methods to increase the reliability of the testing, and hence reduce the margin of error value is discussed above.

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