8. RESULTS AND DISCUSSION

8.1 Overview

The averaged results obtained for the two throttle settings over the engine speed range, for both conventional petroleum fuelling, and hydrogen-enhanced fuelling may be found in the tables below. A comprehensive list of test data may be located in Appendix G.

Engine torque was determined from the dynamometer calibration equation and was used to calculate the power output and hence the brake mean effective pressure. Specific exhaust emissions were then calculated by dividing the actual emission reading by the brake power of the engine. The test data was manipulated using an engineering software package known as "*Engineering Equation Solver (EES).* " The source code written for the analysis may be found in Appendix H.

The results were then curve fitted as per the equations contained in Appendix I. A sample calculation, as indicated in Appendix J, was performed using the data from the two-thirds throttle, petrol test at an engine speed of 2360 rpm.

The results obtained at a one-half throttle setting will then be discussed independently to those at the two-thirds throttle position, which will be presented thereafter. Finally, results for each test variable at both throttle positions and for both fuelling scenarios will be discussed so as to highlight any trends that may be evident.

It should be noted that the results presented and discussed below exclude the measurement of the hydrogen flow rate, as this proved extremely difficult to accomplish. The mass balance method used to determine the hydrogen production rate could not be used as the mass of the final hydrogen generator was beyond the allowable range of the existing electronic scale. Also, larger scales that were obtainable did not possess the accuracy that was required in order to measure such small changes in mass as indicated in the preceding sections.

Another problem with the abovementioned method is that it determined the rate at which hydrogen was produced and not that at which it was being consumed. Therefore, this method will only be valid if it is assumed that all the hydrogen that was being produced was utilised by the engine. This argument is invalid as the hydrogen generator was not airtight, and a percentage of the hydrogen being generated could have dispersed into the surrounding air.

Therefore, it was then decided that a hydrogen flow meter would be fitted to the hydrogen fuel line before it entered the gas carburettor so as to determine the flow rate of hydrogen to the engine. This, however, was unsuccessful as no change in the flow meter level was visible once hydrogen fuelling had commenced. It was thought that this was due to a lack of pressure within the hydrogen line. Attempts to further pressurise this supply line by means of an external pump were also unsuccessful as this resulted in the water from the generator being sucked into the supply line.

8.2 Results

Tables 8.1 and 8.2 below, contain the one-half throttle results for petrol and hydrogen-enhanced fuelling respectively. Similarly, Tables 8.3 and 8.4 contain the petrol and hydrogen-enhanced results for two-thirds throttle.

Table 8.1: Averaged Results for Petrol fuelling at ½ Throttle

THROTTLE:	½		FUEL:	Petrol					
Engine Speed	Voltage	Torque	BMEP	NO_x	CO	CO_2	Specific NO_x	Specific CO	Specific CO_2
[rpm]	[V]	[Nm]	[kPa]	[ppm]	[ppm]	[ppm]	[ppm.W^{-1}]	[ppm.W^{-1}]	[ppm.W^{-1}]
2000	3.325	3.906	36.31	706	52477	72232	0.863	65.37	88.29
1940	3.34	4.466	41.52	504	62788	81853	0.5555	69.2	90.21
1840	3.35	4.84	44.98	485	66371	81518	0.5201	71.17	87.41
1480	3.355	5.027	46.72	2654	30901	89147	3.407	39.67	114.4

Table 8.2: Averaged Results for Hydrogen-enhanced fuelling at ½ Throttle

THROTTLE:	½		FUEL:	Petrol & Hydrogen					
Engine Speed	Voltage	Torque	BMEP	NO_x	CO	CO_2	Specific NO_x	Specific CO	Specific CO_2
[rpm]	[V]	[Nm]	[kPa]	[ppm]	[ppm]	[ppm]	[ppm.W^{-1}]	[ppm.W^{-1}]	[ppm.W^{-1}]
2000	3.34	4.466	41.51	907	40420	84120	0.9696	43.21	89.93
1860	3.35	4.84	44.99	720	51472	88102	0.7638	54.6	93.46
1740	3.365	5.4	50.19	718	57606	90829	0.7297	58.55	92.31
1280	3.38	5.96	55.4	1509	38555	90902	1.889	48.26	113.8

Table 8.3: Averaged Results for Petrol fuelling at ⅔ Throttle

THROTTLE:	⅔		FUEL:	Petrol					
Engine Speed	Voltage	Torque	BMEP	NO_x	CO	CO_2	Specific NO_x	Specific CO	Specific CO_2
[rpm]	[V]	[Nm]	[kPa]	[ppm]	[ppm]	[ppm]	[ppm.W^{-1}]	[ppm.W^{-1}]	[ppm.W^{-1}]
2360	3.325	3.906	36.31	767	55059	84483	0.7945	57.04	87.52
2220	3.34	4.466	41.5	511	72415	86290	0.4921	69.74	83.11
1960	3.35	4.84	44.99	494	78040	88412	0.4973	78.56	89.00
1660	3.35	4.84	44.98	2581	28975	85055	3.0680	34.44	101.10

Table 8.4: Averaged Results for Hydrogen-enhanced fuelling at ⅔ Throttle

THROTTLE:	⅔		FUEL:	Petrol & Hydrogen					
Engine Speed	Voltage	Torque	BMEP	NO_x	CO	CO_2	Specific NO_x	Specific CO	Specific CO_2
[rpm]	[V]	[Nm]	[kPa]	[ppm]	[ppm]	[ppm]	[ppm.W^{-1}]	[ppm.W^{-1}]	[ppm.W^{-1}]
2100	3.34	4.466	41.51	974.5	9708	82714	0.9922	9.88	84.21
1920	3.365	5.4	50.21	894.5	44266	91842	0.8237	40.76	84.57
1880	3.37	5.587	51.93	616	47234	91396	0.5600	42.94	83.09
1860	3.37	5.587	51.92	643.6	57535	90595	0.5915	52.88	83.27

8.3 Torque

8.3.1 ½ Throttle Results

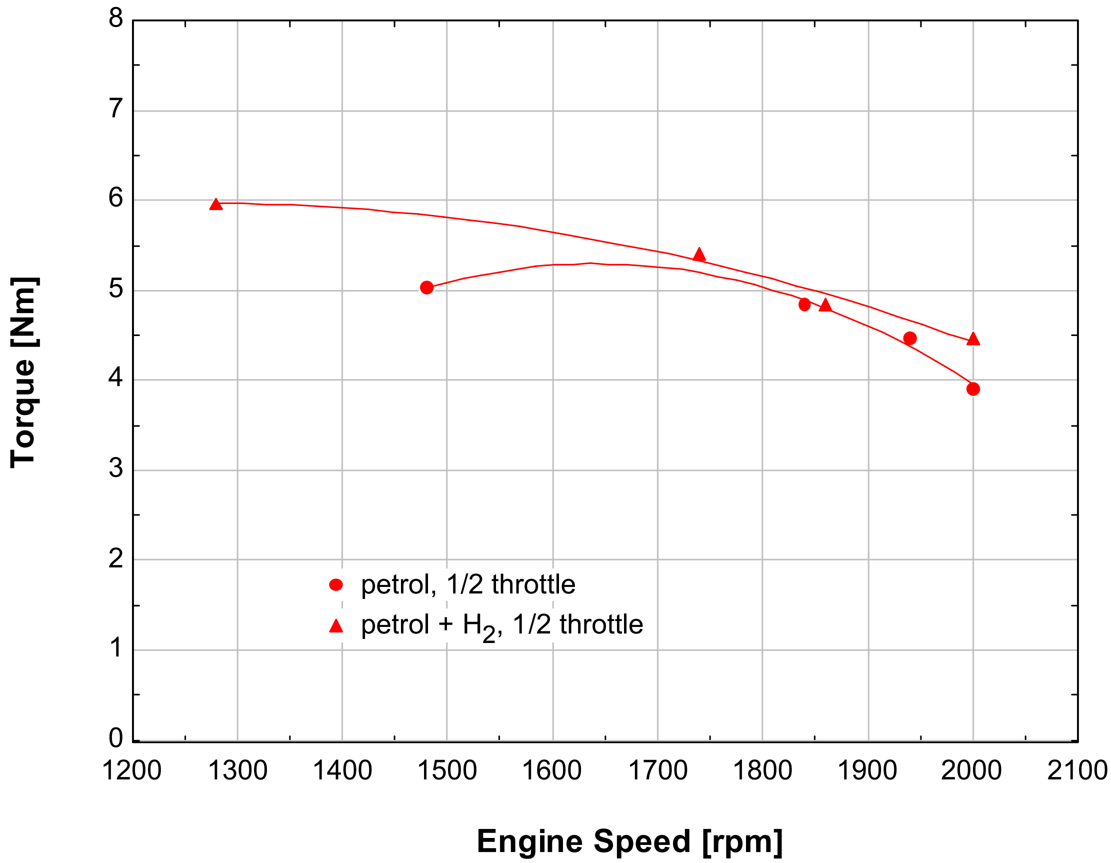

Figure 8.1: Graph of Torque vs. Engine Speed at ½ Throttle

Figure 8.1 above, illustrates the torque curves for both conventional petrol fuelling and hydrogen-enhanced fuelling both at ½ throttle settings.

From the one-half throttle results, it can be seen that the engine torque developed from the use of hydrogen-enhanced fuelling, is greater than that obtained from petrol fuelling throughout the engine speed range.

However, this increase in torque is more pronounced at around 1450 rpm and 2000 rpm, the two extremes of the engine speed domain. Conversely, the increase in maximum torque, which occurs at approximately 1700 rpm, is relatively smaller than those obtained at the abovementioned speeds.

This translates into the fact that hydrogen fuelling, at a throttle position of one-half, results in a flatter, more linear torque band while the petrol results indicate a torque band with a more distinctive peak.

Also, from the one-half throttle torque curves, it can be seen that the maximum torque obtained occurs at a higher engine speed of approximately 1700 rpm under petrol fuelling as compared to a speed of around 1250 rpm for hydrogen fuelling. The speed at which the maximum torque occurs for the use of hydrogen could even be lower than 1250 rpm, since the turning point is not evident on Figure 8.1 due to the lack of data at lower engine speeds.

8.3.2 ⅔ Throttle Results

The torque curves obtained at a throttle setting of two-thirds indicate somewhat of a different trend. Figure 8.2 below, illustrates an increase in torque from the use of hydrogen at engine speeds lower than 2050 rpm. Thereafter, petroleum fuelling resulted in greater torque values.

Also, contrary to the one-half throttle results, the petrol torque curve is flatter than that obtained by hydrogen fuelling as indicated by the steeper gradient of the hydrogen torque curve.

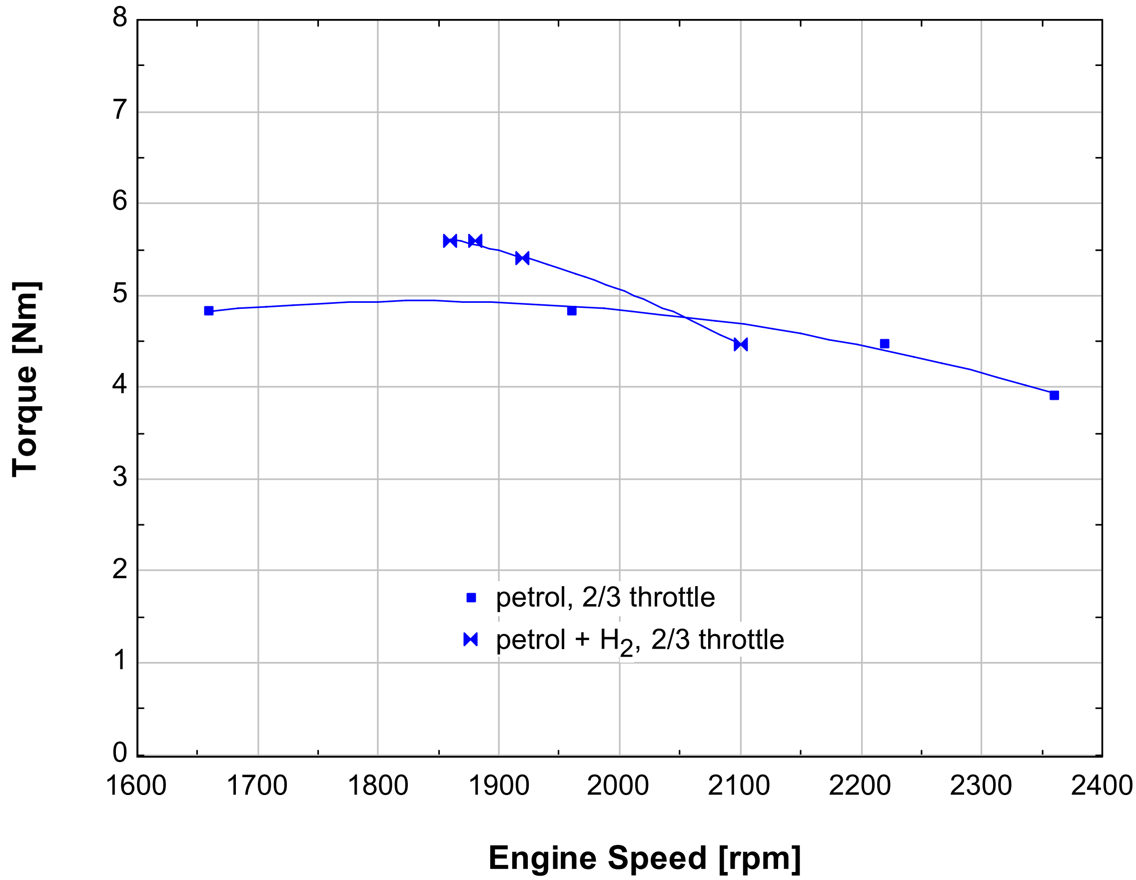

Figure 8.2: Graph of Torque vs. Engine Speed at ⅔ Throttle

From Figure 8.2, it is also evident that the engine speed at which the maximum torque occurs for the use of petrol is approximately 1850 rpm. Again, owing to the lack of hydrogen fuelling data at engine speeds lower than 1850 rpm, the engine speed at which maximum torque is reached cannot be accurately determined.

From the available test results, however, it may be seen that the highest value of torque occurs at about 1850 rpm. Since a distinct turning point is not evident at this speed, it is possible that the torque curve increases as engine speed decreases at lower engine speeds until a peak torque is reached at a lower engine speed.

This phenomenon would be in keeping with the results obtained at one-half throttle setting, in that the maximum torque occurs earlier in the engine speed domain from the use of hydrogen fuelling as compared to conventional petroleum fuelling.

8.3.3 Combined ½ and ⅔ Throttle Results

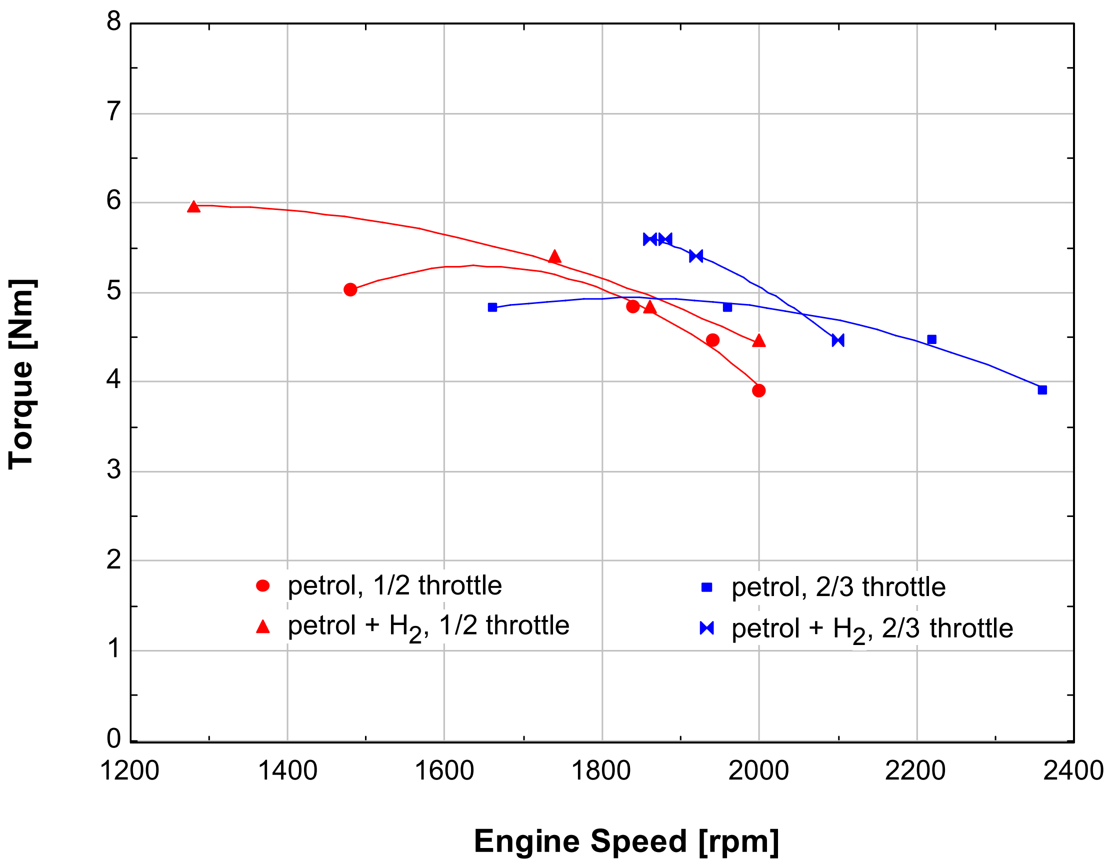

Figure 8.3: Graph of Combined ½ and ⅔ Throttle Torque Curves

Figure 8.3 above, illustrates the torque curves of both fuels at the two throttle positions. It is interesting to note that the torque bands for both fuels occur later in the engine speed range at a throttle opening of two-thirds as opposed to the one-half setting.

This could be attributed to the fact that the increase in fuel available, and hence the increase in energy available for combustion, leads to either higher engine speeds at constant torque, or greater torque at the same engine speed. In this case, since the engine speed was controlled by varying the torque, higher engine speeds were obtained.

The fact that the torque output of the engine was greater from the use of hydrogen-enhanced fuelling can be explained by a similar rationale as presented above. Since the petrol supply to the engine was not reduced as the hydrogen fuel was added, there was more fuel available to the engine upon hydrogen fuelling as the hydrogen supplemented the existing petroleum supply. This, as stated above, resulted in more chemical energy being available upon combustion which, in turn, led to more useful work being generated by the engine in the form of greater torque.

The fact that more torque was produced from hydrogen-enhanced fuelling could also be explained by the fact that hydrogen contains thrice the amount of combustion energy to that of conventional petroleum. Therefore, by supplementing the engine fuelling with hydrogen, more energy can be released during combustion, which would result in more torque.

The lower torque values obtained from the use of hydrogen at a throttle position of two-thirds, at high engine speeds, seem to defy the trends as discussed above. However, this may be attributed to the fact that at large throttle openings, the introduction of more fuel, in the form of hydrogen, may result in the engine being over fuelled. In other words, the air/fuel mixture may be too rich for optimal combustion and hence, the decrease in torque.

Also, the fact that the hydrogen is being introduced into the air inlet and is therefore occupying some volume, however small, that would have previously been occupied by air, could further impact the air/fuel ratio. The effect is heightened since not only is less air now available to the engine, but its volume is being taken up by more fuel.

It is also important to note that the torque values obtained from both fuelling scenarios are for lower than those claimed by the manufacturer. This could have been caused by a fault on the electronic circuit that controlled the dynamometer as this component was repaired and then replaced during testing.

However, if this were indeed the case, it would result in erroneous values that would pertain to both hydrogen and petrol fuelling. Therefore, the trends and relationships between the test variables would still be valid despite the errors in the individual values.

8.4 Brake Mean Effective Pressure

8.4.1 ½ Throttle Results

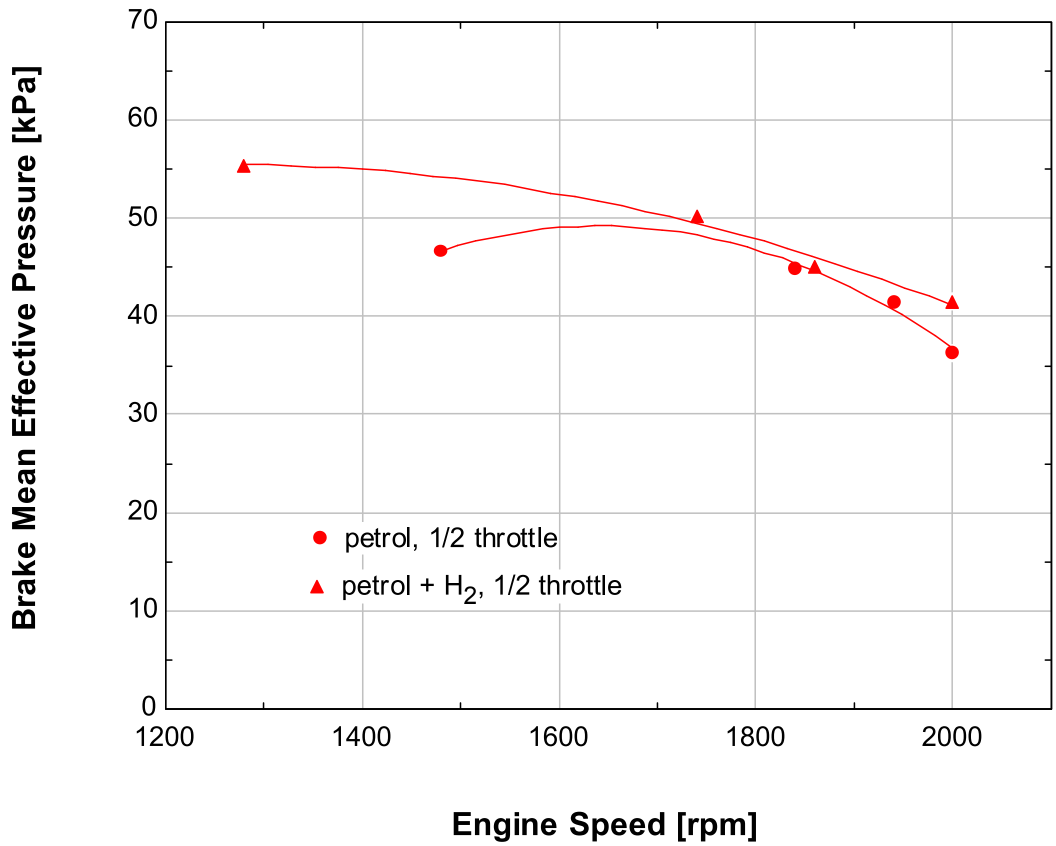

Figure 8.4: Graph of BMEP vs. Engine Speed at ½ Throttle

As was the case with the one-half throttle setting torque results, the brake mean effective pressure (BMEP) curves in Figure 8.4 above show that the BMEP of the engine was greater across the entire engine speed range from hydrogen fuelling as compared to conventional petroleum fuelling.

Again, this increase in BMEP was more pronounced at either end of the engine speed domain and the increase in maximum BMEP was far smaller than the increases at other engine speeds. Therefore, as with the torque results, the use of hydrogen fuelling resulted in a flatter BMEP curve, while petroleum fuelling resulted in a BMEP curve with a more pronounced peak.

Figure 8.4 also shows that the maximum brake mean effective pressure occurs at an engine speed of approximately 1250 rpm for hydrogen and at around 1700 rpm under petrol fuelling.

It should be noted that the similarities in the torque and bmep results are as a result of the proportional relationship that exists between torque, power and brake mean effective pressure. Therefore, the trends exhibited by these results are expected to be the same.

8.4.2 ⅔ Throttle Results

Figure 8.5 below shows the BMEP curves for both hydrogen-enhanced and petrol fuelling at a throttle setting of two-thirds. It is evident that the BMEP produced by the engine under hydrogen-enhanced fuelling is greater at engine speeds below 2050 rpm; whereafter petroleum fuelling results in higher brake means effective pressures being produced.

Unlike the one-half throttle results, the petrol BMEP curve at two-thirds throttle does not exhibit as significant a change in gradient as compared to its hydrogen counterpart. In the absence of hydrogen data at low engine speeds, it can be seen that the drop off in BMEP is more pronounced for hydrogen fuelling as opposed to petrol fuelling.

However, despite this, both hydrogen-fuelling and petrol results seem to indicate a maximum at around 1880 rpm. This is in contrast to the BMEP results at one-half throttle as discussed in the section above.

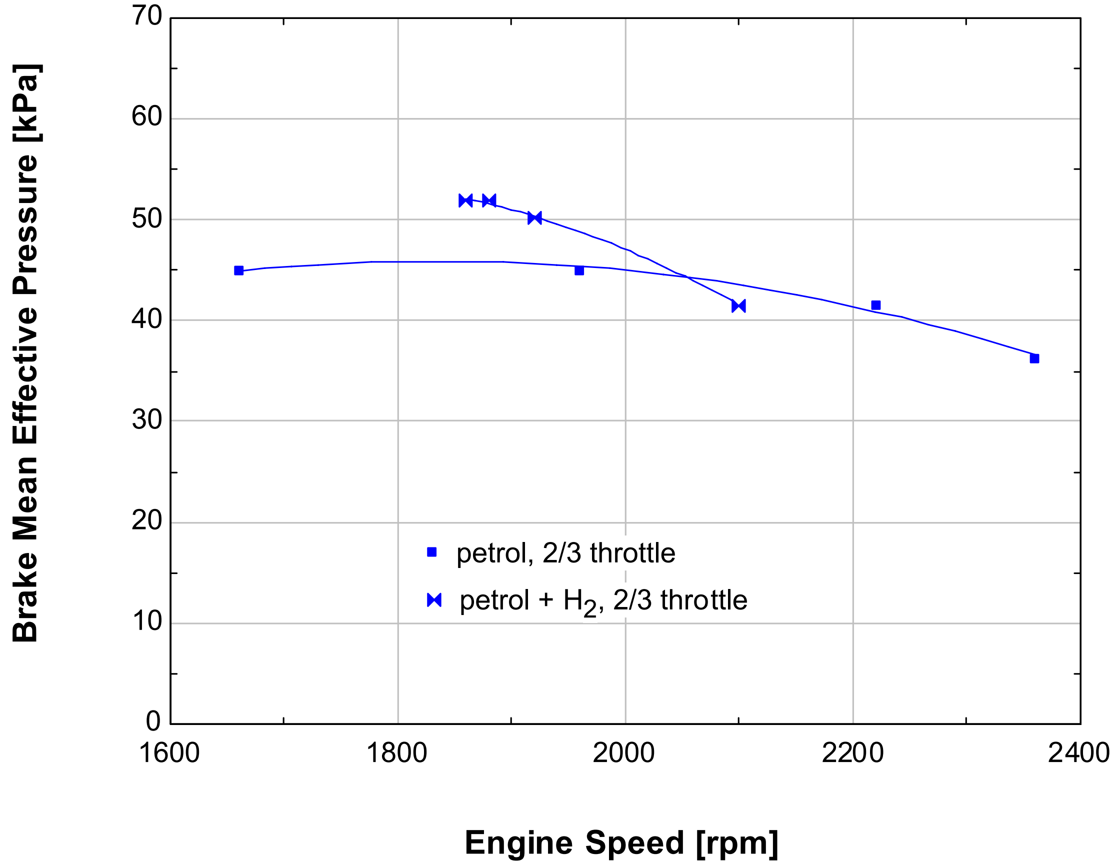

Figure 8.5: Graph of BMEP vs. Engine Speed at ⅔ Throttle

8.4.3 Combined ½ and ⅔ Throttle Results

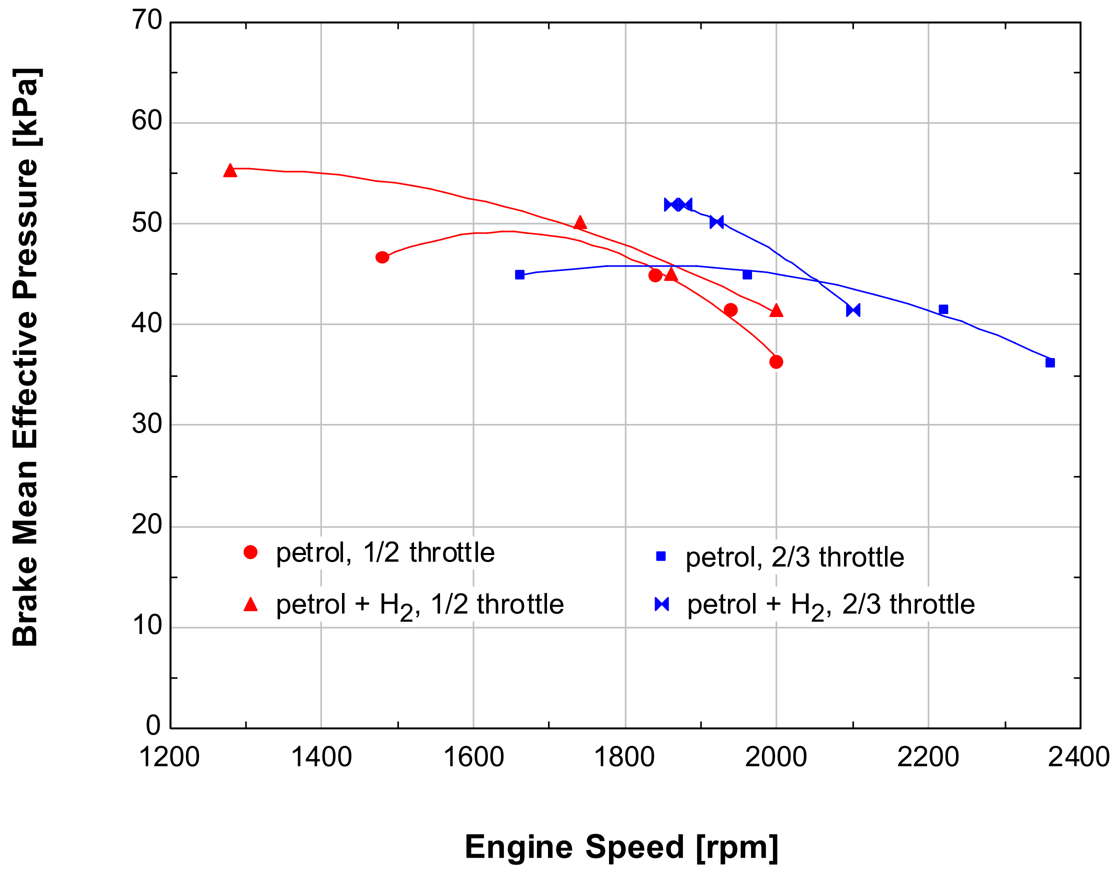

Figure 8.6: Graph of Combined ½ and ⅔ Throttle BMEP Curves

Figure 8.6 above shows the BMEP curves for both hydrogen-enhanced and conventional petroleum fuelling at both throttle positions. Again, the BMEP curves at two-thirds throttle inhabit the higher end of the engine speed spectrum, as was the scenario with the torque results.

The larger BMEP curves at one-half throttle and at the bottom end of the speed range at two-thirds throttle were again attributed to the fact that more fuel was being supplied to the engine when hydrogen was introduced to the air intake. Also, the drop off in BMEP at high engine speeds at two-thirds throttle was thought to be caused by overfuelling of the engine.

The similarities in not only the torque and BMEP results, but also in the reasons given for these results, was due to the relationship between torque, BMEP and engine speed as mentioned before. Also, since the torque applied to the engine was used to control engine speed, changes in bmep, were very similar to those in torque across the same engine speed range.

The fact that the BMEP curves, and hence the power curves for hydrogen fuelling were, on average, higher than those obtained from conventional petrol fuelling is contradictory to the performance of the hydrogen vehicles discussed in the preceding sections. From the literature survey, it can be seen that the maximum power quoted for a particular hydrogen vehicle is less than that of its petrol equivalent.

This may be explained by the fact that the hydrogen powered vehicles reviewed in the literature survey all run either exclusively on hydrogen or on petroleum whereas the test engine was supplemented with hydrogen while still being supplied with petrol. The fact that the entire petrol supply to the engine was replaced with hydrogen would mean that less hydrogen, on a mass basis, can be supplied to the engine. This is as a result of hydrogen’s low density. Therefore, even though hydrogen possesses three times the combustion energy per unit mass of petroleum, the total energy being delivered to the combustion chamber is limited by the small mass of hydrogen fuel present. This results in a decrease in power of the hydrogen-fuelled engine.

From the results contained in Figure 8.6 above, it can be seen that the increase in BMEP from the supplementation of hydrogen to the fuel supply is more prominent at the two-thirds throttle setting as compared to the one-half throttle position.

However, since the rate of hydrogen emitted from the generator is constant across both throttle positions, the amount of hydrogen present as a percentage of the total fuel at one-half throttle is greater than at two-thirds. Therefore, it would be expected that the effects of hydrogen fuelling would be more prominent at the lower throttle setting.

Reasons for this could not be accurately addressed, as the rate at which hydrogen was being generated was not determined. Also, the hydrogen consumption of the engine was not measured as discussed in Section 8.1.

8.5 Nitrogen Oxide Emissions

8.5.1 ½ Throttle NO_x Emissions

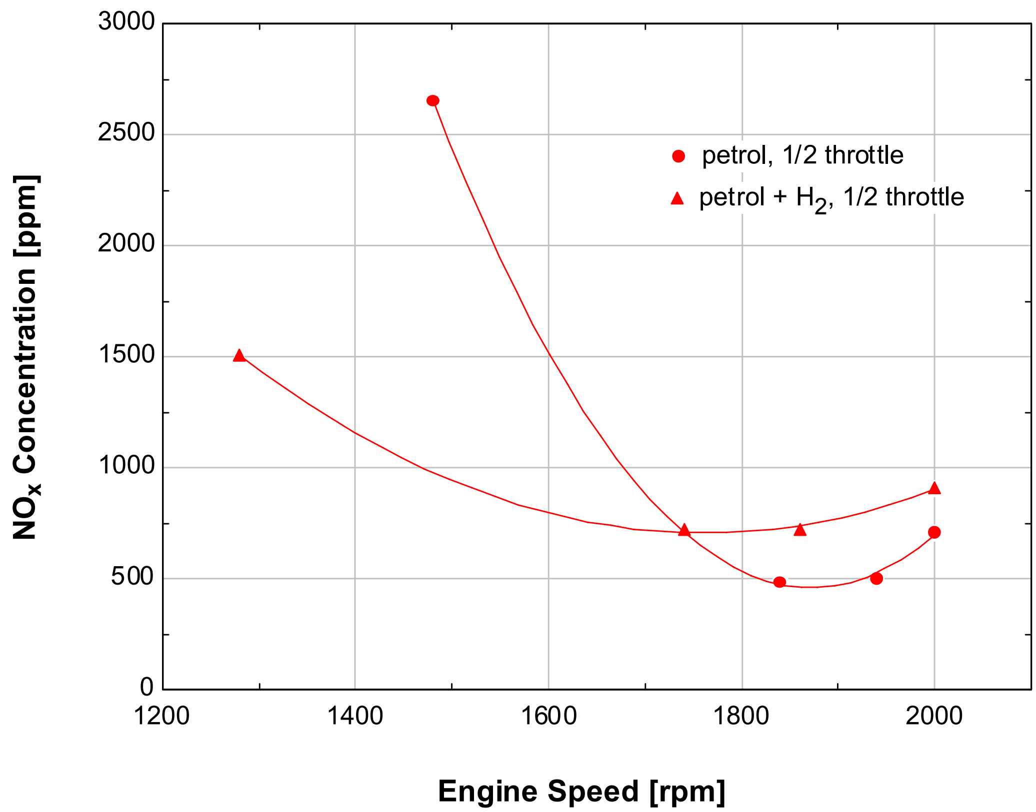

Figure 8.7: Graph of NO_x Concentration vs. Engine Speed at ½ Throttle

Figure 8.7 above, depicts the NO_x emissions of the engine across the engine speed domain for both fuelling scenarios. It is evident that the NO_x concentrations obtained from the combustion of conventional petroleum fuel, are greater than those of hydrogen at engine speeds lower than 1740 rpm. Thereafter, the NO_x emissions from the use of hydrogen are greater.

NO_x concentrations were seen to be the lowest at approximately 1740 rpm for hydrogen fuel as compared to about 1860 rpm from conventional petroleum fuelling. Also, the decrease to this local minimum, and the subsequent rise in concentrations was more pronounced under petrol fuelling than with the use of hydrogen.

8.5.2 ⅔ Throttle NO_x Emissions

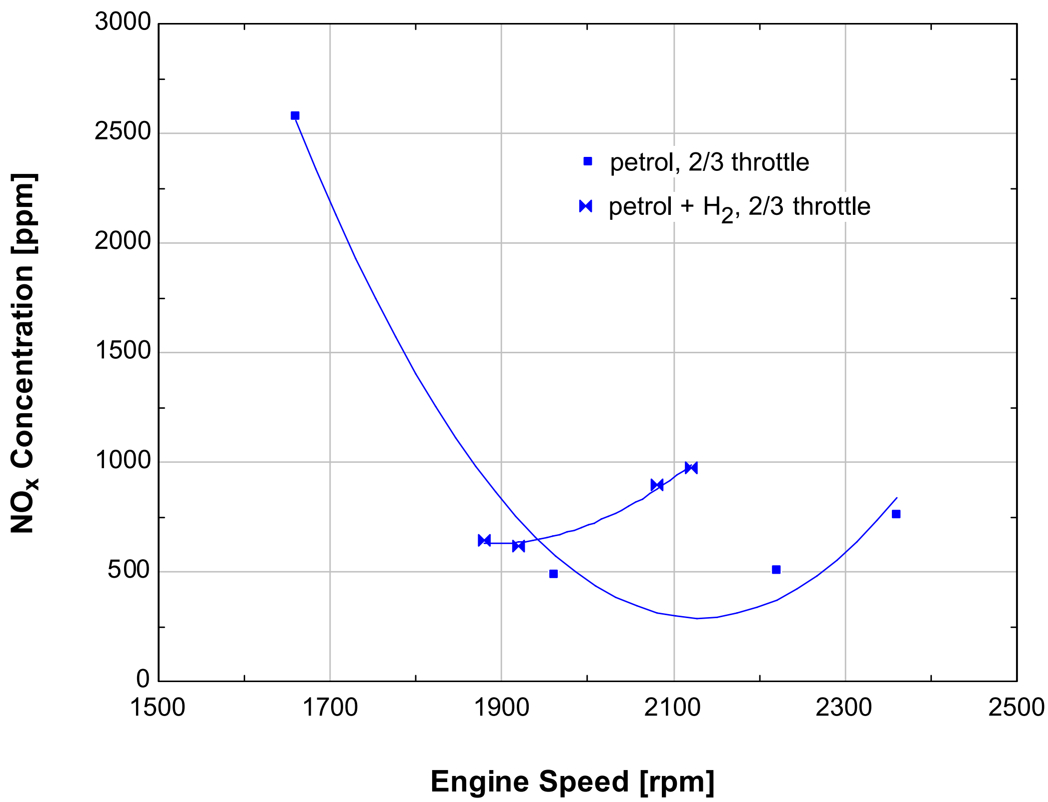

Figure 8.8: Graph of NO_x Concentration vs. Engine Speed at ⅔ Throttle

The NO_x emissions at a throttle setting of two-thirds indicated similar trends to those exhibited at the one-half throttle position. NO_x concentrations were seen to be greater under petrol fuelling at engine speeds lower than approximately 1940 rpm, after which the hydrogen NO_x emissions were the larger of the two.

Again, the engine speed at which the minimum NO_x concentrations were recorded was lower for hydrogen fuelling than for that of petrol. Owing to the lack of hydrogen data at low engine speeds, the rate of decrease in NO_x formation could not be discussed accurately. However, by extrapolating the curve at these low speeds, it can be seen that the trend formed is similar to that of the one-half hydrogen results.

8.5.3 Combined ½ and ⅔ Throttle NO_x Emissions

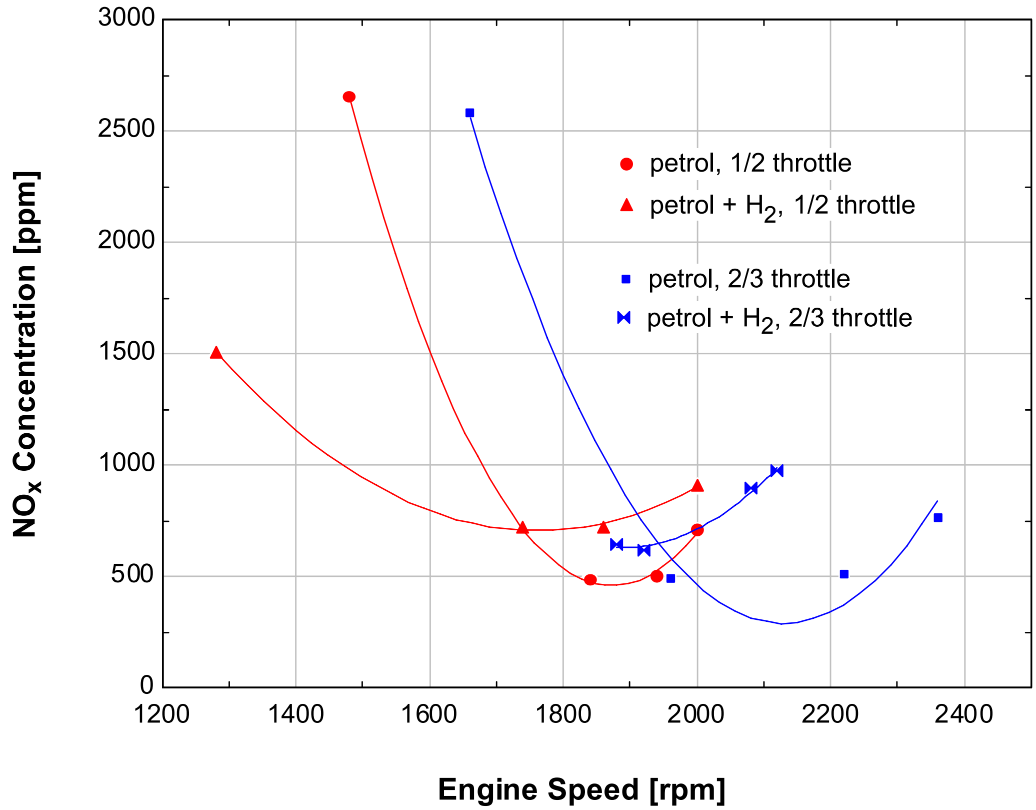

Figure 8.9 Graph of Combined ½ and ⅔ Throttle NO_x Concentrations

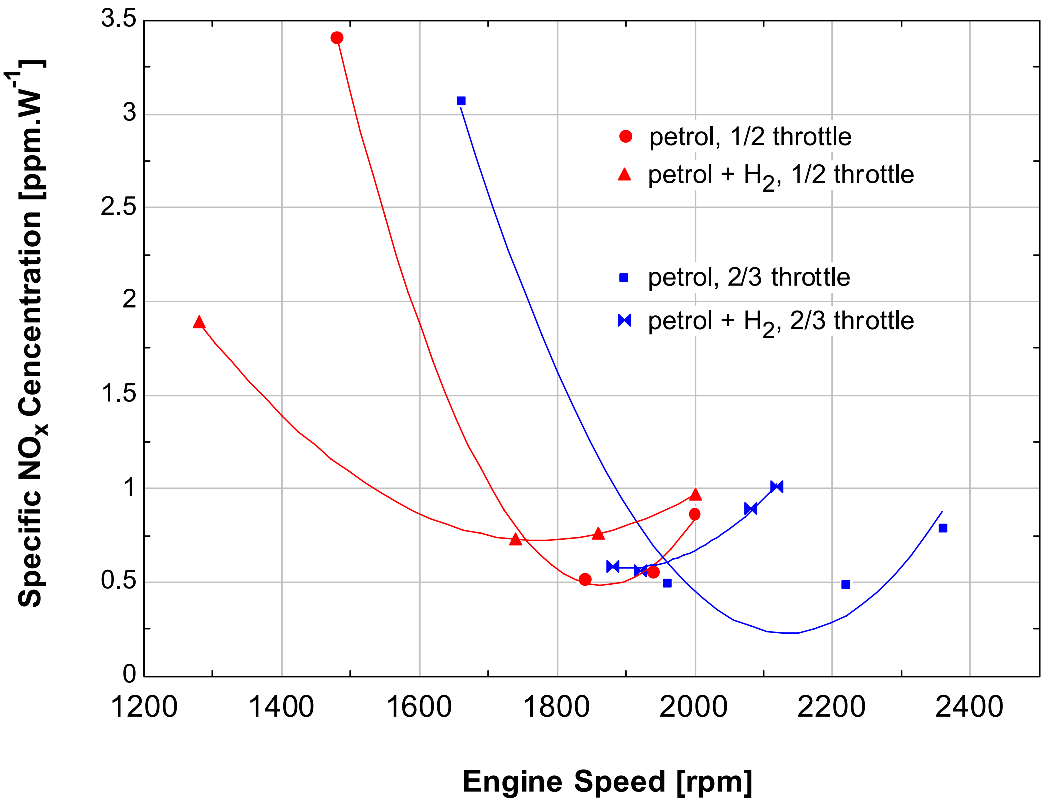

Figure 8.10: Graph of Combined ½ and ⅔ Throttle Specific NO_x Concentrations

Figures 8.9 and 8.10 above, show the combined NO_x concentrations and combined specific NO_x concentrations respectively. It can be seen that there does not appear to be a significant variation in these two sets of results. This may be attributed to the fact that the torque curves were relatively flat over the engine speed range as may be seen in the preceding section.

This would mean that the specific emissions were, approximately, scaled values of the true emissions, as the power did not vary greatly over the engine speed domain. Hence, the similarity in trends.

From Figure 8.10, it can be seen that the petrol NO_x concentrations at both throttle settings follow a similar trend in that they decrease to a local minimum and increase again thereafter. Also, the rate at which they decrease appears to be constant for both.

However, the NO_x concentrations at a throttle position of two-thirds were found to occur at a higher engine speed. It is interesting to note that at a given engine speed, the NO_x concentration at one-half throttle was less than that produced from the two-third throttle setting. This was thought to be caused by deviations in the equivalence ratio.

From the literature survey, Section 3.7, it was found that NO_x formation was inversely proportional to equivalence ratio. Therefore, richer combustion mixtures would result in lower concentrations of NO_x than leaner ones. For hydrogen fuelling, the fact that the hydrogen supply to the engine was constant at both throttle settings, and was not reduced in proportion to the reduction in petrol, would mean that the combustion mixture at one-half throttle position was richer than that at two-thirds throttle. This would result in a higher equivalence ratio, which would hinder the production of nitrogen oxides.

Also, Figure 8.11 below, shows the equivalence ratios for both fuels at the two throttle settings. It can be seen that, for petrol fuelling, equivalence ratios were higher at one-half throttle resulting in lesser NO_x emissions as compared to those produced at a throttle position of two-thirds.

The same principle was thought to apply to the fact that the NO_x formation is lower from the use of hydrogen at low engine speeds as compared to that of petrol. The introduction of hydrogen would increase the equivalence ratio as discussed in Section 8.3.3 above. This is clearly shown in Figure 8.11 below. This richer mixture would then result in less NO_x being produced.

It should be noted, however, that the hydrogen equivalence ratios illustrated in Figure 8.11 do not take into account the mass of hydrogen being consumed by the engine, as the hydrogen consumption was not measured. Therefore, these values are lower than the expected equivalence ratio. Had the hydrogen flow rate been measured, this would result in further increases in equivalence ratio under hydrogen fuelling, which would further explain the decrease in NO_x emissions.

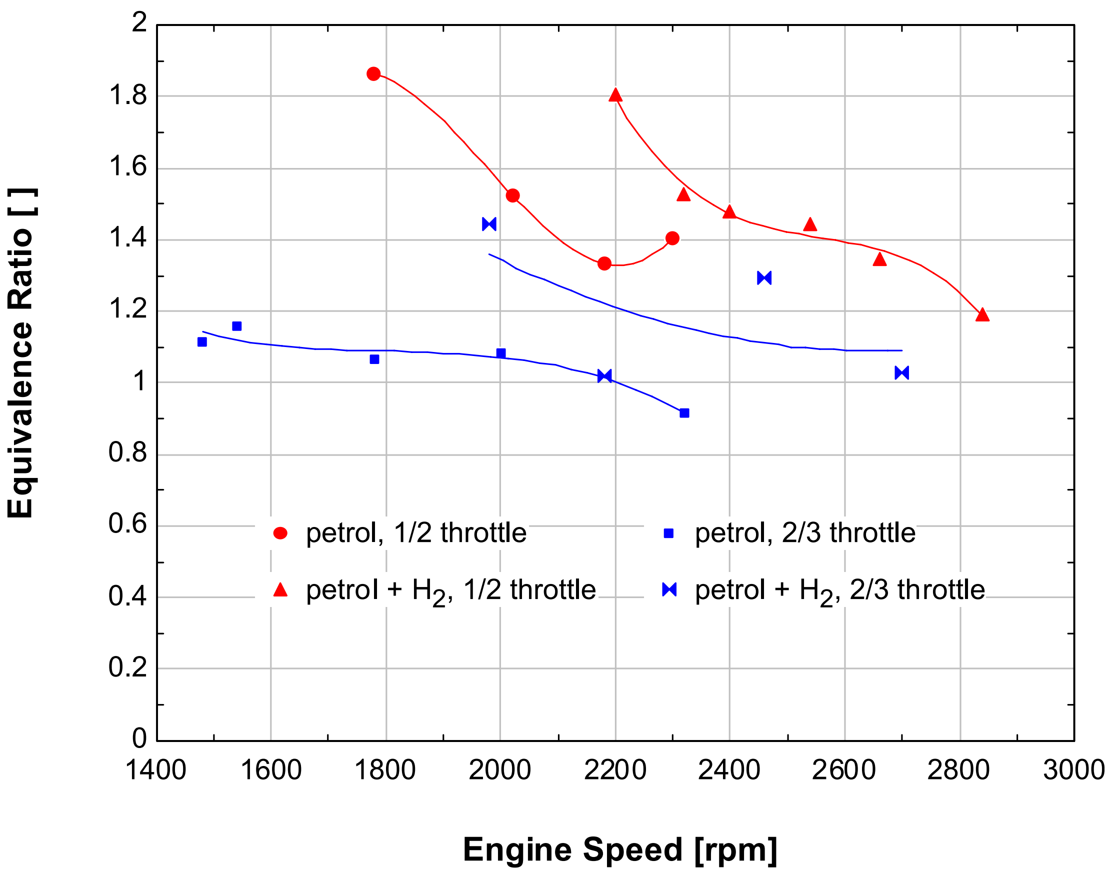

Figure 8.11: Graph of Combined ½ and ⅔ Throttle Equivalence Ratios

The fact that the NO_x concentrations are greater from the use of hydrogen-enhanced fuelling as opposed to petrol fuelling at high engine speeds defies the arguments presented above, as Figure 8.11 clearly indicates that the equivalence ratio remains greater even at these elevated engine speeds.

However, a crucial factor in the understanding of NO_x formation is the combustion temperature. Since the measurement of exhaust temperature was not included in the experiments conducted as part of this study, the relationship between the NO_x emissions and temperature cannot be conclusively explored. Therefore, it is not clear whether these increases in NO_x concentrations are brought about as a result of temperature fluctuations.

Also, from the literature survey, NO_x formation was found to be heavily dependent on the presence of oxygen. This is re-emphasized by the fact that rich mixtures contain less oxygen and hence, the decrease in NO_x emissions.

Therefore, bearing in mind that the fuel supply from the hydrogen generator contains both hydrogen and oxygen, the higher concentrations of NO_x from hydrogen fuelling at high speeds could be attributed to the extra oxygen molecules that are present in the combustion mixture. However, this would not explain why the NO_x emissions are higher only at high engine speeds.

From the literature survey it is also evident that there exists the very complex combined yet counterbalancing influence of both temperature and oxygen content. Thus, it can be said that the trends exhibited by the formation of nitrogen oxide are as a result of combined temperature and oxygen content, the latter being characterized by a change in equivalence ratio.

8.6 Carbon Monoxide Emissions

8.6.1 ½ Throttle CO Emissions

Figure 8.12 below, shows the carbon monoxide emissions of both petrol fuelling and hydrogen fuelling at a throttle setting of one-half. It is evident that the CO concentrations for both fuelling scenarios increase until a local maximum is reached and then decrease thereafter.

It can be seen that the rate at which the CO concentrations increase is greater for petrol fuelling as compared to the hydrogen fuelling. This is indicated by the steeper gradient of the petrol CO curve.

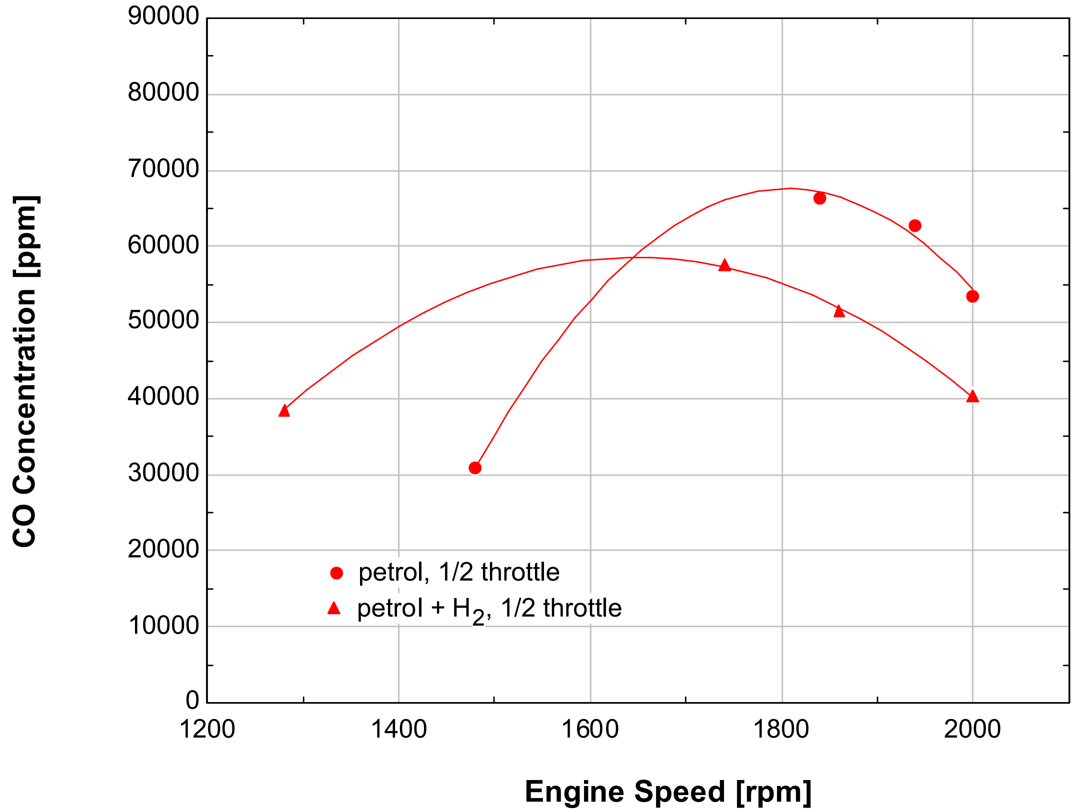

Figure 8.12: Graph of CO Concentration vs. Engine Speed at ½ Throttle

Also, Figure 8.12 shows that the maximum CO concentration produced is far greater from the use of petrol than from hydrogen-enhanced fuelling. The engine speed at which this maximum value is obtained is also higher than the engine speed at which the maximum CO emissions occur for hydrogen fuelling.

Hydrogen fuelling resulted in greater CO concentrations at low engine speeds while for engine speeds in excess of about 1620 rpm, the CO emissions from conventional petroleum fuelling were found to be greater.

This trend seemed to be inversely related to the formation of NO_x, which was greater for petrol at low engine speeds while being less than that of petrol at higher speeds.

8.6.2 ⅔ Throttle CO Emissions

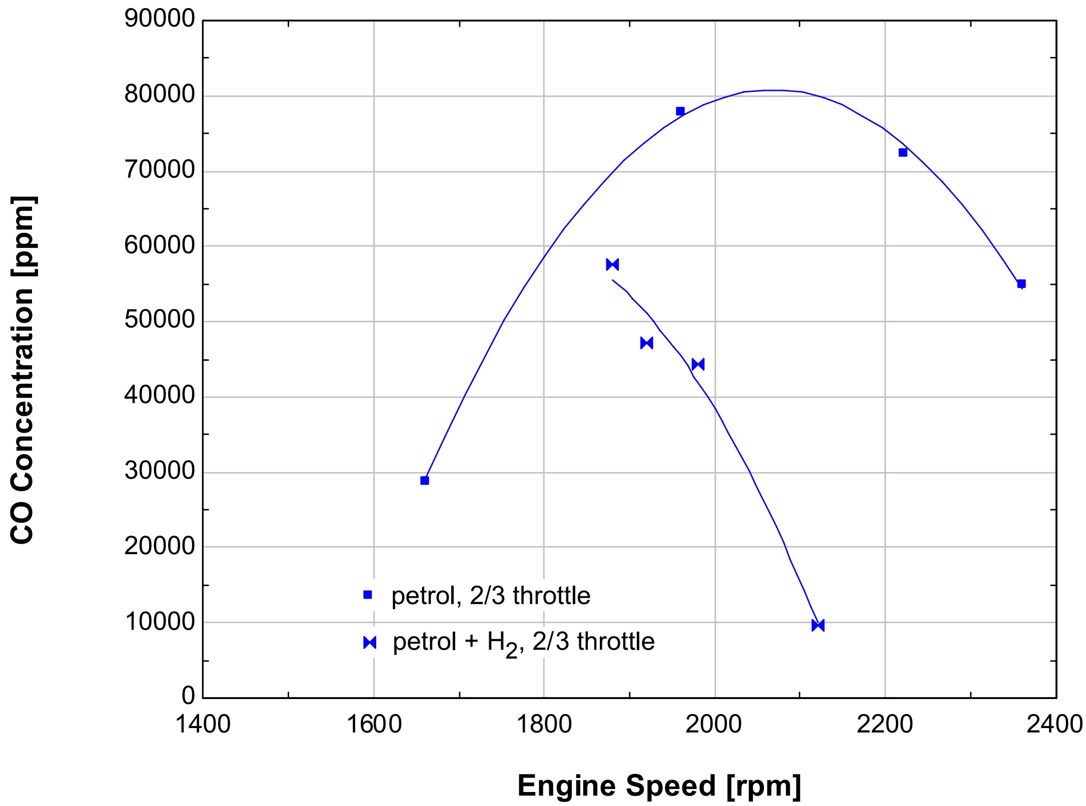

Figure 8.13: Graph of CO Concentration vs. Engine Speed ⅔ Throttle

The results contained in Figure 8.13 above illustrate the relationship between CO concentrations and engine speed for the two fuelling scenarios at two-thirds throttle. It can be seen that these results exhibit similar trends to those obtained at a throttle position of one-half.

The petrol CO emissions increase to a maximum at around 2100 rpm after which they decrease. From the narrow band of CO emissions at two-thirds throttle, it may be seen that the CO concentrations are lower from the use of hydrogen as compared to those of petrol. Again, this conforms to the trends exhibited in Figure 8.12 above.

However, as there were insufficient data points at low engine speeds, it was difficult to predict the magnitude of the maximum CO emission, and at what speed this turning point would occur.

8.6.3 Combined ½ and ⅔ Throttle CO Emissions

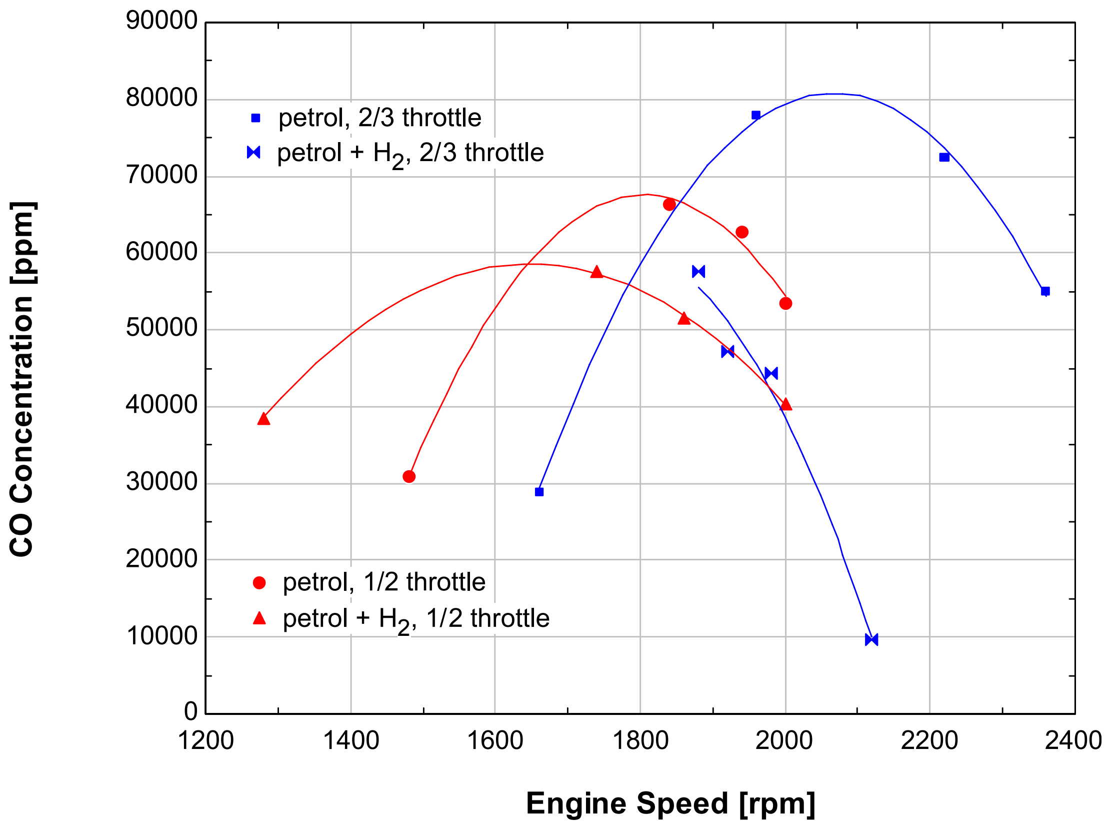

Figure 8.14: Graph of Combined ½ and ⅔ Throttle CO Concentrations

Figure 8.14 above and Figure 8.15 below show the relationships between CO emissions and specific CO emissions, respectively, and engine speed at both throttle settings for both fuelling scenarios.

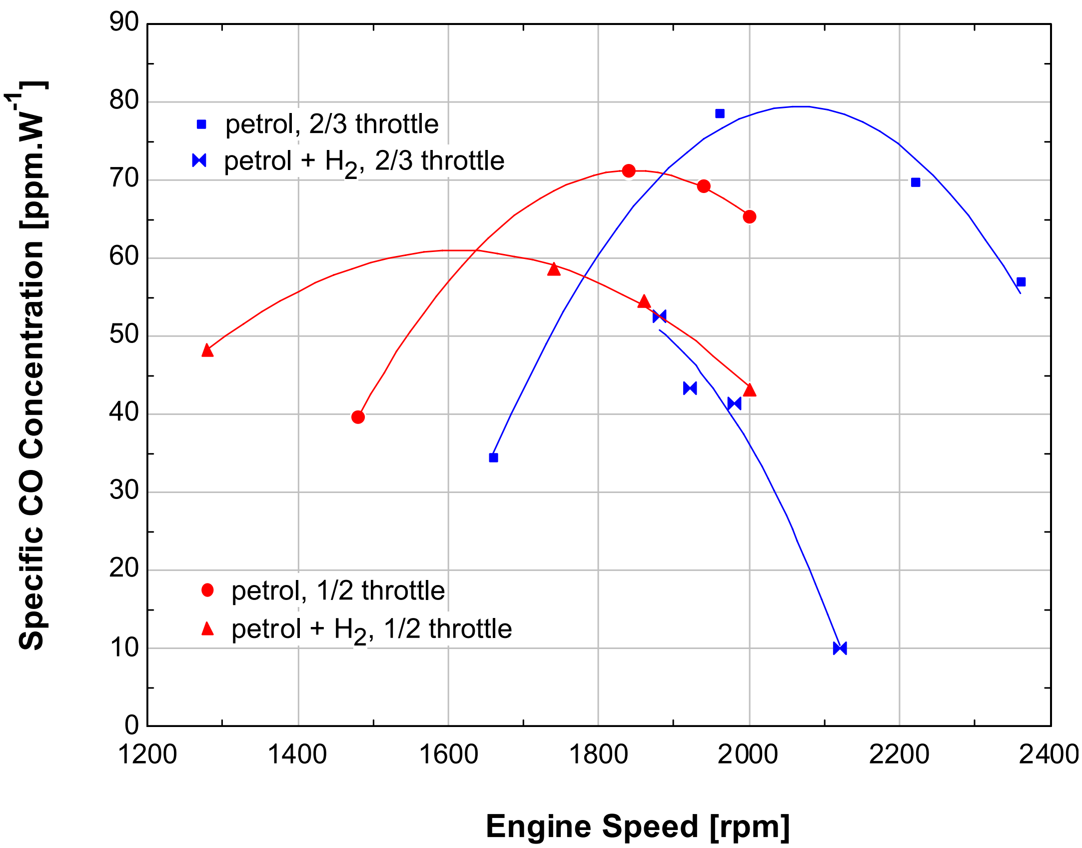

Figure 8.15: Graph of Combined ½ and ⅔ Throttle Specific CO Concentrations

From both Figures 8.14 and 8.15, it can be seen that the CO emissions from the use of petrol are greater at a throttle setting of one-half than at the two-thirds throttle for engine speeds below approximately 1900 rpm. At higher engine speeds, a throttle setting of two-thirds resulted in the larger of the two CO concentrations.

It is interesting to note that the opposite is true for NO_x formation, which is greater at two-thirds throttle at lower engine speeds and less than the CO emissions obtained at one-half throttle position.

This fact further emphasizes the inverse relationship between NO_x formation and CO formation as discussed from Figure 8.12 above.

Therefore, these trends suggest that CO production is dependent on the formation of nitrogen oxides. This could be explained by the fact that as nitrogen oxides are being formed, oxygen molecules are being used up by bonding with the nitrogen molecules. Therefore an increase in NO_x concentrations would imply that there are less free oxygen molecules available to react with the carbon molecules to form CO, hence the inverse relationship between CO emissions and NO_x emissions. It should be noted that this argument suggests that the oxygen-nitrogen reaction is favoured over the oxygen-carbon reaction.

Thus, from the arguments presented above, the decrease in CO concentrations from the use of hydrogen as opposed to conventional petroleum fuelling was thought to have been caused by the increase in NO_x for this fuelling scenario.

Another possibility for the decrease in CO concentrations from the use of hydrogen-enhanced fuelling could be that the extra oxygen molecules present in the hydrogen/oxygen fuel mixture from the generator result in the oxidation of carbon monoxide to form carbon dioxide. This would be either confirmed or contradicted by the carbon dioxide results presented in the section that follows.

8.7 Carbon Dioxide Emissions

8.7.1 ½ Throttle CO_2 Emissions

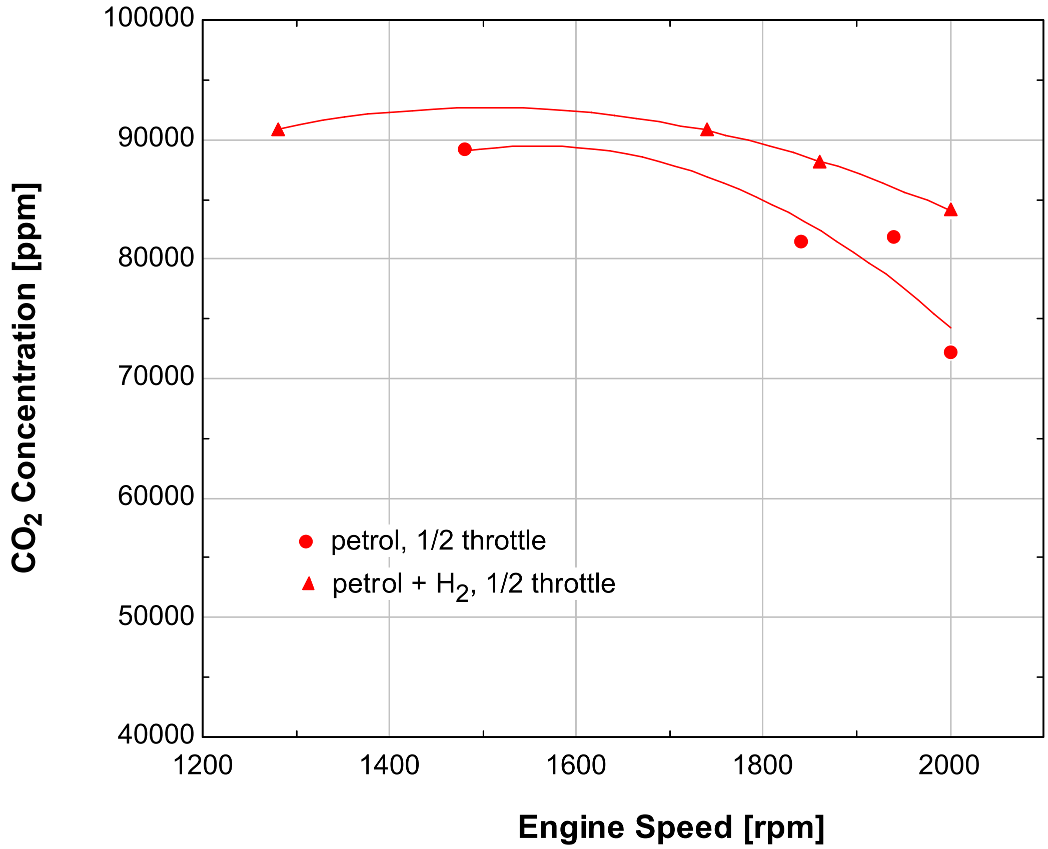

Figure: 8.16: Graph of CO_2 Concentration vs. Engine Speed at ½ Throttle

Figure 8.16 above, illustrates the relationship between carbon dioxide emissions and engine speed at one-half throttle for both fuels. It shows that the CO_2 concentrations produced under hydrogen fuelling were greater than those obtained from the use of petrol throughout the engine speed domain.

It is evident that the CO_2 emissions increase with engine speed to a local maximum, and decrease again thereafter. The engine speed at which the most emissions of CO_2 are produced is at approximately, 1500 rpm for hydrogen and at around 1550 rpm for hydrogen.

Also, the decline in CO_2 concentrations at high engine speeds is more pronounced for conventional petrol fuelling than for hydrogen fuelling. This is shown by the steeper gradient of the petrol CO_2 curve for speeds in excess of 1550 rpm.

However, it should be noted that the CO_2 gas analyser required considerably more time to stabilize than the other emissions analysers. Since high speed petrol tests were performed first, this could have had an impact on the petrol results at high engine speeds, even though this was taken into account when performing the tests.

8.7.2 ⅔ Throttle CO_2 Emissions

From Figure 8.17 below, it may be seen that the CO_2 concentrations for petroleum fuelling result in a parabolic curve across the engine speed range with a maximum at approximately 2000 rpm.

A similar relationship exists between CO_2 emissions and engine speed for hydrogen fuelling in that the emissions increase to a maximum at around 1920 rpm and decrease again thereafter.

However, the rate at which CO_2 concentrations are being produced varies considerably more from the use of hydrogen as compared to petrol fuelling. This is shown by the more distinctive peak in the hydrogen results.

Also, at engine speeds above 2020 rpm, the CO_2 emissions are lower for hydrogen fuelling than for petrol fuelling.

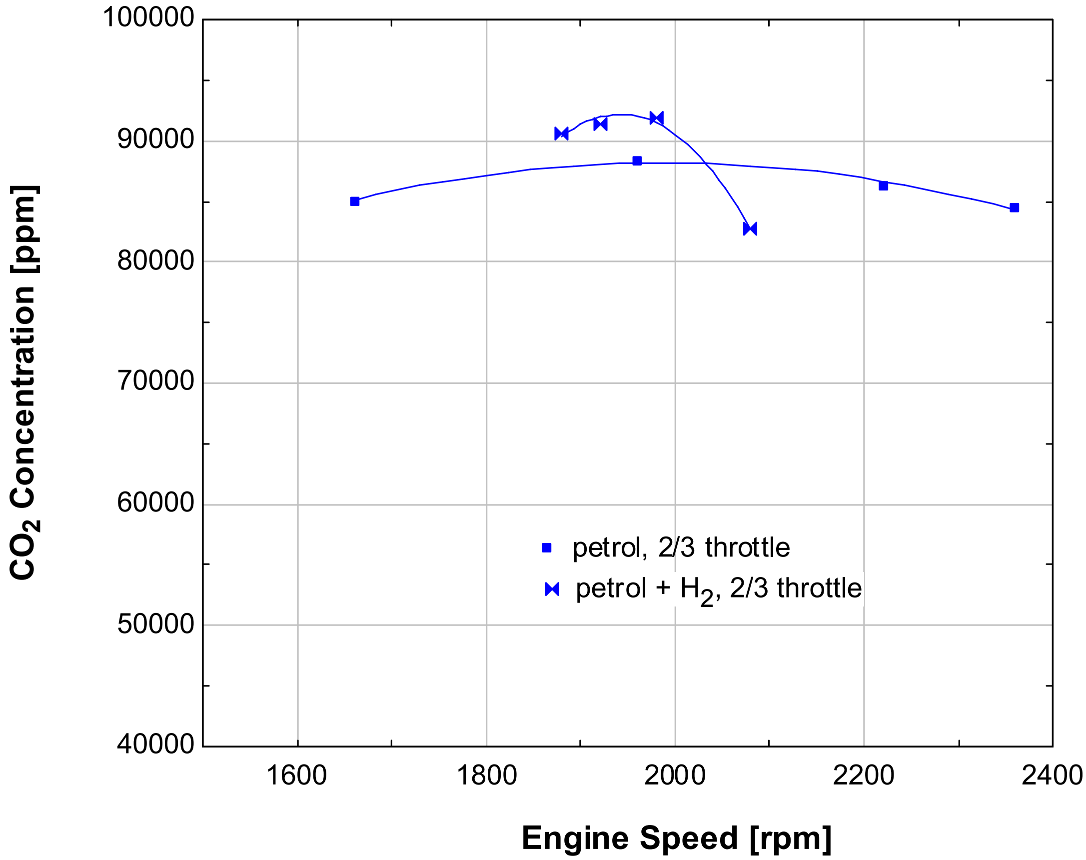

Figure 8.17: Graph of CO_2 Concentration vs. Engine Speed ⅔ Throttle

As was the case with the one-half throttle results, the emissions at high engine speeds under hydrogen fuelling were performed first and could have been negatively influenced by the fact that the CO_2 concentrations had not yet settled. However, the results at low engine speeds indicate that the rate at which the CO_2 emissions decreased was very similar to the rate at which they increased at the other side of the turning point.

The fact that the gradients of the petrol curve were mirrored on either side of the turning point increases the perception that the hydrogen-enhanced CO_2 concentrations should follow a similar trend.

8.7.3 Combined ½ and ⅔ Throttle CO_2 Emissions

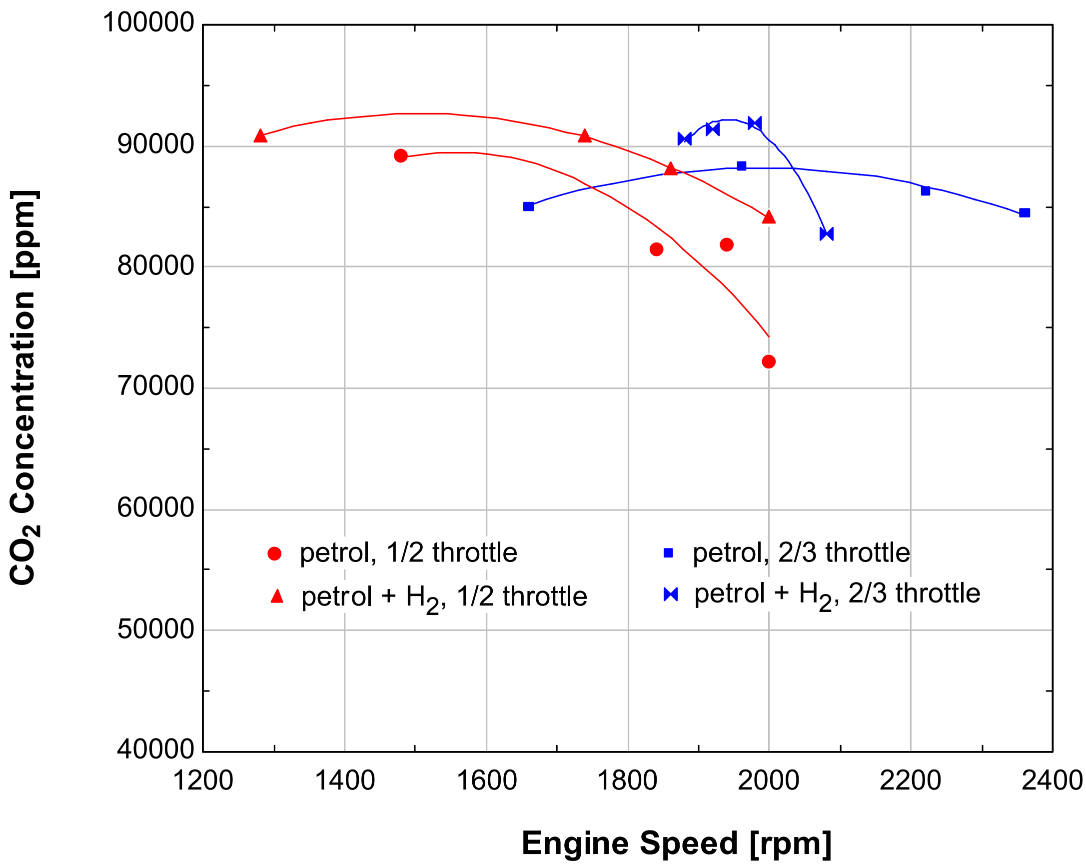

Figure 8.18: Graph of Combined ½ and ⅔ Throttle CO_2 Concentrations

Figure 8.18 above illustrates the CO_2 emissions for both fuelling scenarios at one-half and two-thirds throttle, while Figure 8.19 below, shows the respective specific emissions.

From Figure 8.18, it can be seen that the petrol CO_2 concentrations are greater at one-half throttle at engine speeds lower than about 1750 rpm. At speeds in excess of 1750 rpm, a throttle setting of two-thirds results in more CO_2 emissions being produced.

The fact that the CO_2 concentrations are greater for hydrogen fuelling was attributed to there being more oxygen molecules present that would react with carbon monoxide to form CO_2. This was supported by the fact that the CO emissions were lower for hydrogen fuelling than under petrol fuelling.

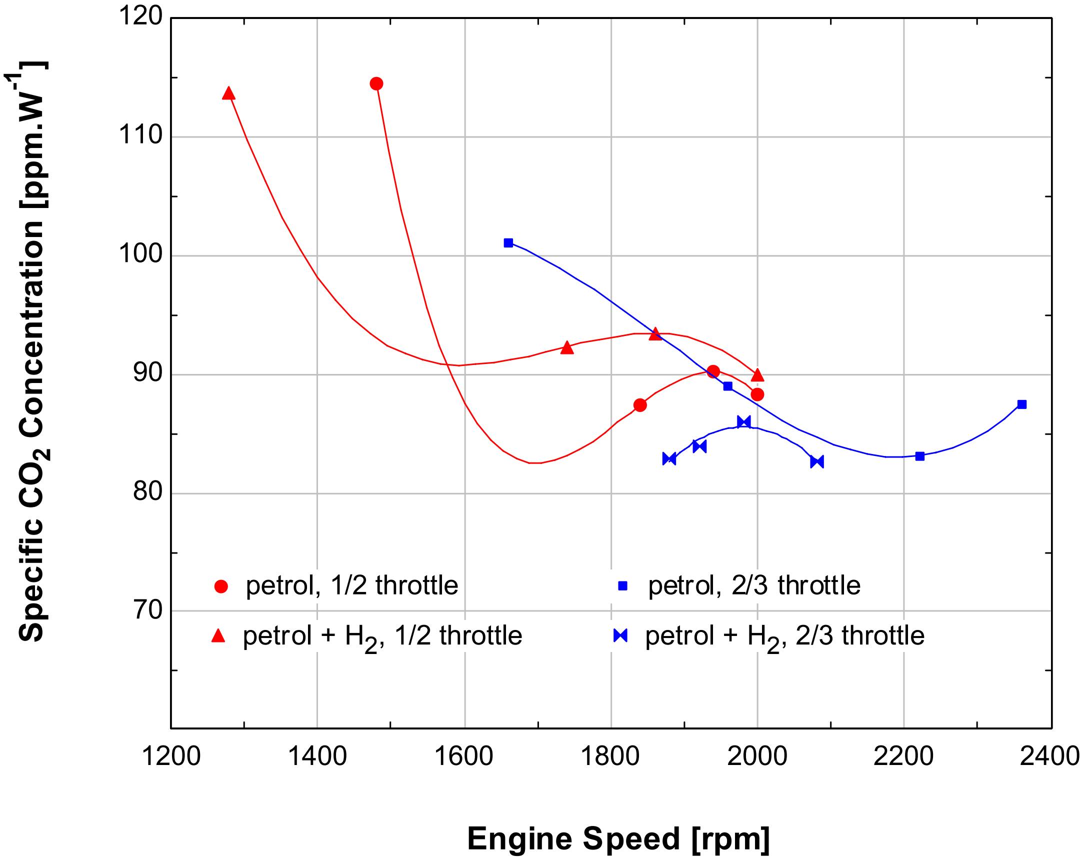

Figure 8.19: Graph of Combined ½ and ⅔ Throttle Specific CO_2 Concentrations

Therefore, it was thought that the addition of hydrogen, and with it oxygen, from the generator resulted in excess oxygen being present. This favoured the formation of nitrogen oxides and carbon dioxide. The oxidation of carbon monoxide to form carbon dioxide resulted in less carbon monoxide being produced under hydrogen-enhanced fuelling.

This is supported by the trends in emissions as indicated in Figure 8.20 below which shows that for engine speeds where the NO_x concentrations are greater from the use of hydrogen than petrol, the CO emissions are correspondingly lower, and the CO_2 emissions are higher. It should be noted that the opposite is also true in that when NO_x concentrations are lower, CO emissions are higher and CO_2 emissions lower.

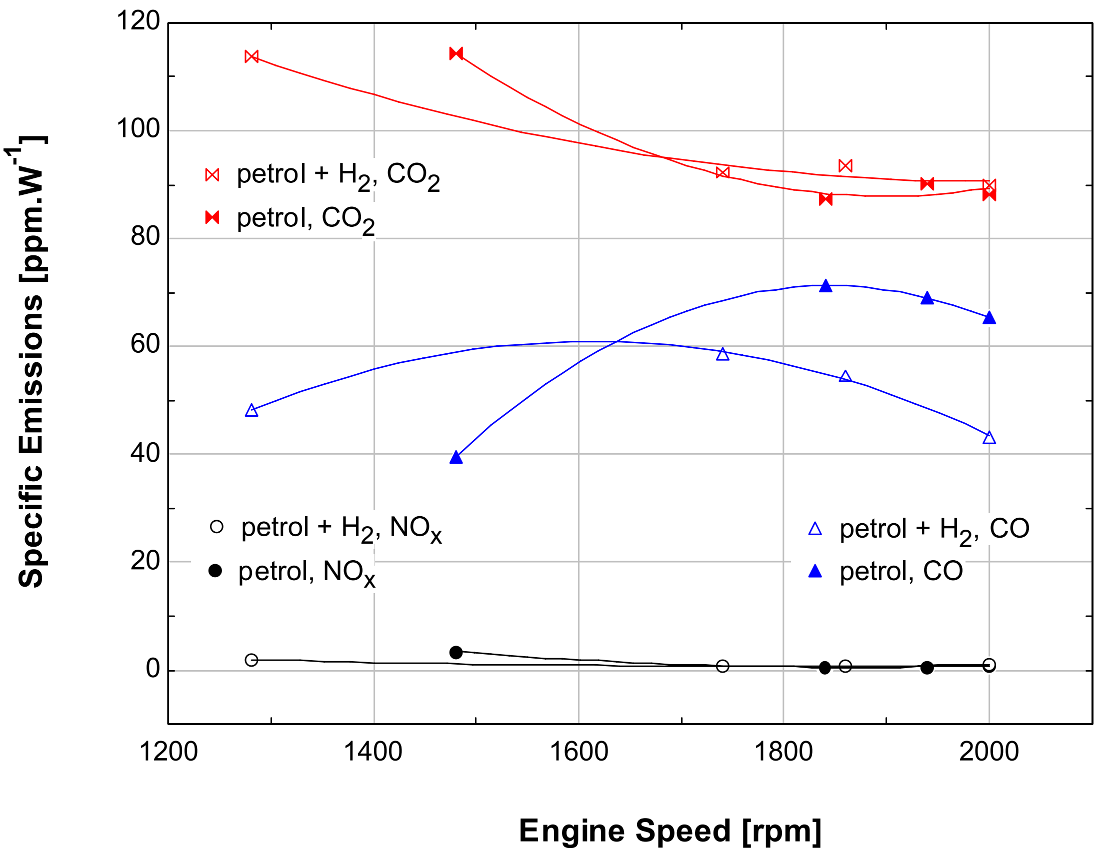

Figure 8.20: Graph of NO_x, CO and CO_2 Specific Emissions at ½ Throttle

From Figure 8.21 below, which shows emissions trends at two-thirds throttle, the inverse relationship between NO_x concentrations and CO concentrations can be seen. However, unlike the one-half throttle results, the CO_2 concentrations do not exhibit the same trend as discussed above. This could have been attributed to presence of total unburnt hydrocarbons (THC).

Since it was not possible to determine the concentrations of these THC 's, it cannot be conclusively ascertained whether the changes in CO and CO_2 were directly related to each other. These variations in CO and CO_2 may have been influenced by the fact that too rich a combustion mixture would lead to incomplete combustion, which would be characterized by an increase in THC emissions.

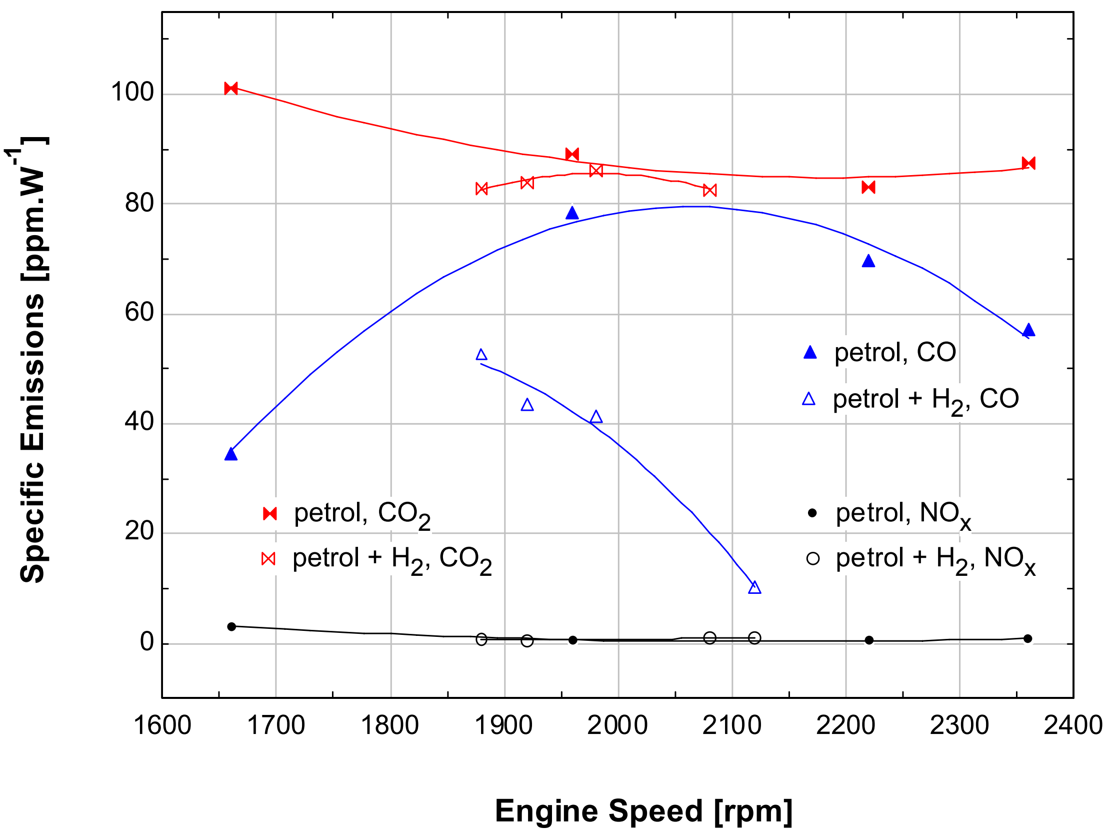

Figure 8.21: Graph of NO_x, CO and CO_2 Specific Emissions at ⅔ Throttle

If this were the case, the decrease in CO and CO_2 emissions from the use of hydrogen could be due to the fact that more of the carbon has been unburnt and hence, unavailable for the formation of CO and CO_2. This trend would correspond with the drop off in torque, especially at two-thirds throttle, which was attributed to overfuelling of the engine as discussed in Section 8.3 above.