University of Huddersfield
University of Huddersfield Press

Fields: journal of Huddersfield student research
Available open access at: https://www.fieldsjournal.org.uk/

FIELDS Journal of Huddersfield student research

Turbo-expander cooling for NO_X control in diesel engines

Liam Draper

University of Huddersfield – School of Computing and Engineering, Queensgate, Huddersfield, HD1 3DH

ARTICLEINFO

Article history:
Received 19 October 2020
Received in revised form 14 February 2021
Accepted 07 April 2021

Keywords:
NO_X
Emissions
Turbo-Expander
Diesel Engine
Automotive
Intake Temperature
Exhaust Temperature

ABSTRACT

This report details the testing of an ACT turbo-expander on a high-speed diesel engine to explore if NO_X reduction can be achieved by turbo-expansion cooling. NO_X reduction in diesels is needed due to the detrimental environmental and health impacts it has across the globe. Testing was completed using a Ford 1.5 DuraTorq engine and a custom test cycle. The test cycle was developed to test the most used section of the engines speed range, whilst also overcoming oil cooling and low intake temperature issues. A NO_X analyser failure meant that the NO_X emissions result could not be gathered directly, so exhaust temperatures were compared between the standard engine and turbo-expander equipped engine, as a decrease in exhaust temperatures would indicate a reduction in combustion temperature and therefore NO_X emissions. 3 tests were carried out under each condition; the results were then analysed using a two-tailed T-test with a significance level of 0.05. The results showed that at an engine speed of 2500rpm or greater, the reduction in exhaust temperature was statistically significant, with the largest reduction in exhaust temperature being 34.51°C at 2750rpm at 70% throttle. At low engine speeds the turbo-expander was showed to increase the exhaust temperature with the largest increase being 52.28°C at 2000rpm and 70% throttle. The turbo-expander was also proven to reduce engine power by an average of 1kW due the reduced intake pressure resulting from the frictional losses in the turbo-expander rotating assembly. If testing is repeated, changes to the test setup must be made in order to make it more repeatable and to capture more data.

Introduction

ACT have developed a turbo-expander system that has previously been shown to provide sub ambient intake temperatures on spark ignition engines, with the benefit of increasing power output and reducing knock (Whelan & Allport, 2017). ACT believe that this system can be fitted to a diesel engine with the aim of reducing NO_X emissions. NO_X emissions are a key focus in diesel engine development due to tightening emissions regulations, as they contribute to acid rain formation (National Geographic, 2019) as well as health issues in humans (Phys.Org, 2015). Current NO_X reduction methods all have trade-offs that the ACT system looks to overcome.

This work aims to determine if turbo-expander cooling can be used to reduce NO_X emissions through the analysis of relevant existing research, and then to create a reliable and repeatable test cycle to provide physical testing of the ACT turbo-expander. The data captured will contain NO_X emissions results as well as other engine parameters to determine how the turbo-expander achieved the emissions result and if it has an impact on engine performance. The data will then be analysed to determine if the turbo-expander had a statistically significant impact on NO_X emissions - if it does, the technology could potentially be implemented across the automotive industry.

NO_X

What is NO_x and why is it an issue?

NO_X is shorthand for nitrogen oxides. Nitrogen oxides can be formed of NO, NO_2, N_2O, N_2O_3 and N_2O_5. Only NO and NO_2 are produced in appreciable amounts in internal combustion engines, the total quantity of NO and NO_2 is normally designated as NO_X. The amount of NO in NO_X is always greater than the amount of NO_2.

(Mollenhauer, Binder, Hagenow, Egler, 2010)

When NO_X is emitted by a vehicle, the NO present is oxidised by the ozone in the atmosphere within 10 minutes, producing NO_2. UV light emitted by the sun splits NO_2 into NO and oxygen, and the oxygen is then oxidised with the O_2 present in the atmosphere to produce ozone. Due to these reactions, NO and NO_2 are at equilibrium as long as there is a sufficient amount of sunlight. Eventually NO_2 is dissolved in rainwater to form Nitric acid which is either absorbed by the ground, vegetation, converted into nitrate containing particles or dissolved into cloud particles. NO_X emissions can travel hundreds of kilometres before they are converted to nitric acid or nitrate particles - because of this, it is estimated that three quarters of the UK's NO_X emissions are exported.

(Apis, 2004)

The Nitric acid produced is key to the formation of acid rain, which is particularly harmful to water species as it raises the acidity level in the water. The acidic water absorbs more aluminium from the soil which produces a toxic environment. It also has a big impact on forests as the acid removes calcium from the soil which promotes aluminium absorption by trees, making it harder for them to absorb water (National Geographic, 2019). If humans breathe in elevated NO_x levels, like those found near busy roads and in built up areas, it can cause respiratory problems which can be severe in people suffering with asthma. Research shows it also causes headaches, reduced lung function, eye irritation, loss of appetite and tooth corrosion.

(Phys.Org, 2015)

NO formation

NO is formed from the Nitrogen present in the cylinder oxidising due to the extremely high temperatures seen during combustion, the temperatures at which NO forms can be seen in Table 1. Air contains 78% nitrogen (Columbia University, 2005) which is the main source of the nitrogen in the combustion chamber. If the fuel contains a significant amount of nitrogen this can be a source. At present, diesel contains more nitrogen than petrol, but it still does not contain a significant amount.

(Heywood, 1988)

The equations in Table 1, below, for NO formation are generally accepted to be correct for near stoichiometric combustion:

Reaction	Temperature Range Reaction Occurs (K)
$O + N_2 = NO + N$	2000-5000
$N + O_2 = NO + O$	300-3000
$N + OH = NO + H$	300-2500

Table 1: NO formation and the temperatures it occurs (Heywood, 1988)

NO_2 formation

NO_2 is formed in the flame zone of combustion where NO is rapidly converted into NO_2 via the reaction:

$$NO + HO_2 \rightarrow NO_2 + OH \qquad \text{(eq.1)}$$

(Heywood, 1988)

Experimental data has shown that in diesel engines NO_2 can make up 10-30% of NO_X emissions, especially under light engine loads. This goes against chemical equilibrium considerations which indicate that for burned gases, at typical flame temperatures, NO to NO_2 ratios should be negligibly small. In SI engines NO_2 can be converted back to NO by:

$$NO_2 + O \rightarrow NO + O_2 \qquad \text{(eq.2)}$$

(Heywood, 1988)

This reaction still takes place in diesel engines, however the conversion of NO_2 to NO is stopped if the NO_2 is mixed with cooler gases, such as already burnt gas. The mixing of already burnt gases and other cooler fluids is unique to diesel engines due to the fuel air mixture not being pre-mixed before combustion and the combustion happening in stages, which allows burnt gas to mix with fuel and air in the cylinder.

(Heywood, 1988)

Turbo-expander

What is the ACT turbo-expander?

The ACT turbo-expander was developed to decrease intake temperatures in internal combustion engines. In diesel engines, the reduction intake temperature generated by the ACT turbo-expander could reduce combustion temperatures, which would result in lower NO_X emissions as explained above.

Turbo-expanders are not a new concept and research into the use of turbo-expanders to provide reduced intake temperatures in engines started in the 1950s. Since then, numerous companies have looked into the feasibility of turbo-expander cooling. In 1992 Ford looked at using a novel approach that used a turbo-expander to cool both the intake air and the intake manifold on their V8 diesel engines to reduce NO_X emissions (Cikanek, 1992). Mitsubishi Heavy Industries also looked into various turbo-expander layouts on uniflow scavenging 2-stroke diesel engines in 1994 (Europe Patent No. EP 0 655 550 A1, 1994). Neither solution made it into production and no data was ever published on how successful they were. Despite this, turbocharger technology has improved significantly from the 1990s making them more efficient - and due to the turbo-expander effectively being a modified turbocharger, it should improve on this efficiency. ACT has already shown that sub-ambient intake air temperatures are able to be created by the turbo-expander unit when they conducted testing on a test track in a petrol-powered car. This showed an intake temperature drop of up to 30°C (Whelan & Allport, 2017).

Other industries, such as aviation and gas production, have been using turbo-expansion for decades. Both industries require systems that are exceptionally reliable over long periods of time, require little maintenance and are cost effective. These are also key parameters for systems within the automotive industry, especially in the heavy goods vehicle industry where diesel engines are used extensively, making turbo-expansion an ideal technology to use if it proves to reduce NO_X.

What is a turbo-expander?

A turbo-expander, also known as an expansion turbine, is a radial flow turbine where high pressure gas expands through a turbine to produce work.

(Almasi, 2019)

The layout of the turbo-expander integrated with an engine is shown in Figure 1, which shows the basic gas flow paths and the main components in the turbo-expander.

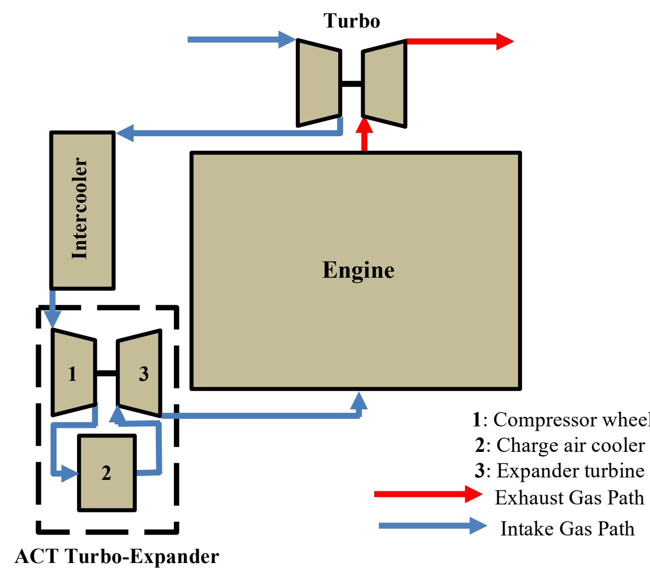


Figure 1: Layout of the ACT turbo-expander when mounted to an engine.

The operational sequence for the layout shown in Figure 1 is:

1. Exhaust gas is produced by combustion in the engine.
2. Exhaust gas flows through the hot side of the primary turbocharger and drives a turbine.
3. The turbine is connected via an axle to a compressor that compresses the intake air.
4. The intercooler cools the compressed intake air.
5. The compressor wheel of the turbo-expander compresses the intake air further.
6. The compressed intake air is then cooled via the charge air cooler.
7. The expander wheel of the turbo-expander expands the intake air, further cooling it.
8. This air is then fed into the intake manifold of the engine at a reduced temperature. This reduces combustion temperatures, with the objective to reduce NO_X.

Thermodynamics of the ACT turbo-expander

The thermodynamic principle of the ACT turbo-expander is a modified version of the Reverse Brayton (also known as the Bell Coleman cycle). The Reverse Brayton cycle is a refrigeration cycle in which the fluid is a gas that is compressed and expanded but does not change phase. After the gas is compressed it passes through a heat exchanger to reject heat from the system - when the gas is then expanded, it results in a reduction in temperature of the gas. In a standard Reverse Brayton cycle, the system is in a closed loop meaning that the gas in the system is constant. In the ACT system the gas is constantly changing as the gas is the intake air used by the engine.

(Nuclear Power, 2017)

The working thermodynamic principle of the turbo-expander using an ideal gas is as follows:

Isentropic compression
Warm intake air flows through the compressor. It is compressed isentropically (constant enthalpy, no heat transfers into the compressor housing). During this the compression volume decreases and pressure and temperature increase.

(Mecholic, 2018)

Constant pressure Cooling
The warm and compressed intake air is passed through the charge air cooler and is cooled. As the temperature difference is larger due to the added heat by compression than if the air had remained at its pressure created by the primary turbo, the temperature change occurs quicker according to the 2nd law of thermodynamics.

(Mecholic, 2018)

Isentropic expansion
The cooled air is now expanded. The expansion causes work to be done on the expansion turbine, which drives the compressor wheel. This reduces the temperature of the expanded air as the first law of thermodynamics states:

$$H = U + P \qquad \text{(eq.3)}$$

Where:
H = Enthalpy
U = Internal energy
P = Pressure

(Nave, 1999)

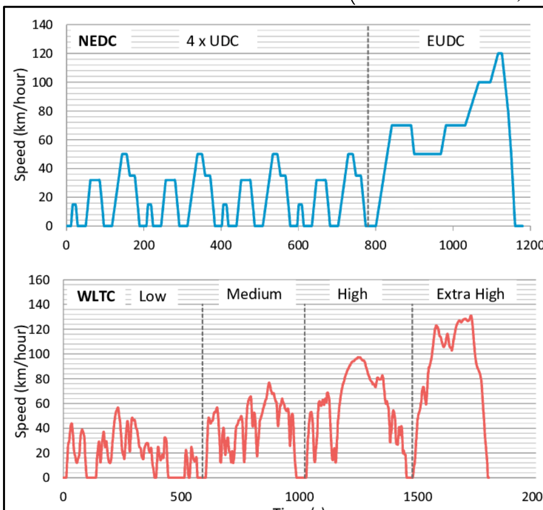
Testing

There are various different methods to use to test if the turbo-expander would result in reduced NO_X emissions. With the facilities available at the University, engine dynamometer testing will be used to test a 1.5L Ford Dura-Torq engine. The engine dynamometer will be used to perform 3 repeat tests in its standard configuration, then 3 repeat tests with the turbo-expander fitted. The engine dynamometer available at the university is a steady state dynamometer, meaning that a typical emissions test cycle used for certification could not be used as these are transient. Emissions test cycles however can be analysed to see what they consist of, and varying engine speeds and throttle positions used to test the engine under similar conditions. As the Ford 1.5 Dura-Torq is designed for a light duty vehicle, test cycles from light duty regulations will be analysed. The most widely used test cycle currently is the WLTC.

WLTC

The WLTC (Worldwide Harmonized Light Vehicles Test Cycle) is a test cycle that is used to determine the Euro emissions standard of a vehicle in Europe and is used under WLTP (Worldwide Harmonised Light Vehicle Test Procedure) testing. It is also has been adopted by China and India to regulate their limits. The WLTP was introduced in 2017 to all types of cars that were introduced and applied to all new car registrations in 2018. It took over from the NEDC (New European Driving Cycle) and created a more realistic driving cycle. It increased the test time from 20 to 30 minutes, increased average maximum speed, increased the driven length of the test, and provided more dynamic and representative accelerations and decelerations which all equate to more realistic emissions figures that are comparable to RDE (Real Driving Emissions) testing. The bottom cycle shown in Figure 2 is the WLTC class 3b, which is the test this engine would be subjected to at the time of this report, as it would be fitted to a vehicle that would be able to reach the cycle's maximum speed. As Figure 2 shows, the WLTC is much more representative of real-world driving, with lots of variation on the acceleration and deceleration sections. It can be seen that the WLTC is broken up into 4 sections, which depict 4 different driving types. These conditions simulate Inner Urban, Outer Urban, Rural and Motorway driving.

(WLTP Facts, 2017)



	NEDC	WLTC
Duration (s)	1180	1800
Total distance (km)	11.01	23.27
Average speed (km/h)	33.6	46.5
Maximum speed (km/h)	120	131.3
Stop duration (%)	23.73	13.00

Figure 2: NEDC and WLTC test cycles (Fontaras, n.d)

Test cycle development

Whether or not the test cycle is a cold or hot start test (i.e. will the NO_X analyser start sampling as soon as the engine starts cranking, or once the engine has reached operating temperature) is the first thing to consider. As NO_X is formed from the high temperatures in the cylinder, a hot start test will be used. This also allows back to back testing without the engine having to soak back down to ambient, which also allows testing to be done in a shorter time frame. A warmup cycle will be used to get the engine up to operating temperature and ensure repeatable tests. This will be used before each test, and the coolant temperature monitored before commencement in order to ensure that the engine temperature is similar before each test.

To develop the test cycle, a base cycle was programmed into the dynamometer using the Sierra Cadet Control System. The base test cycle consisted of various throttle positions and engine speeds across the rev range that tested the engine in its most used engine speeds, allowing assumptions to be made that are comparable to real world driving. Safety measures were put into place to protect the engine by the use of a 1MW heat exchanger that is used to cool the coolant and intercooler, with the engine coolant beginning to be cooled when it reached 50°C and the intercooler beginning to be cooled once it reached 60°C. The engine was then run in its standard configuration with the intercooler, oil and water temperatures being monitored. Intercooler temperature was monitored in order to ensure that the temperature post intercooler was above 30°C, as this would ensure that if the turbo-expander did cool the intake temperature by 30°C, (as seen in previous ACT research) (Whelan & Allport, 2017) it would avoid icing of the intake and potential engine failures. Oil and water temperature were monitored to ensure the engine was testing under safe conditions, with maximum limits being set at 110°C for engine oil and 115°C for coolant temperature. If these were reached the test would automatically shut down to protect the engine.

The cycle development testing showed that engine intake temperature was far too low, with an average temperature below 30°C being seen. An investigation was run into the setup of the engine cooling tower and it was found that a manual control valve was open, meaning that the intake charge was being cooled constantly when in fact no cooling should have been happening. This was rectified and the test was repeated. The repeat test proved that at low engine speed and throttle positions, the intake temperature was too low to test. At low engine speeds and low throttle positions, the amount of flow through the primary turbo is reduced, therefore heat added by compression is reduced – in this case, to the point of compromising the test. Less fuel is also being used, so a lower peak cylinder temperature will be seen, which would mean the intake air is absorbing less heat from the engine. Manual control of the dynamometer was taken and it was found that at 2000 rpm at 60% throttle was the lowest engine speed and throttle position that gave a repeatable reading of an intake temperature above 30°C.

With the lower engine speed section amended, the higher engine speed section could be looked at. Another development test cycle was run, but it quickly became apparent that the oil cooling was an issue, with the engine oil becoming close to its temperature limit at 2500rpm at 75% throttle. The reason for the high temperatures was due to the heat exchanger not having enough ports to support running a cooling loop for the engine oil, therefore only the engines standard oil cooler that relied on air flow was in place. Time and budget constraints meant that the heat exchanger could not be modified to incorporate another cooling loop, so a fan was added to the test chamber that was aimed at the sump, as this was found to be the most effective position. The base test cycle was also modified by reducing the engine loads at high rpms and incorporating cooling sections that would allow the oil temperature to drop to 85°C. The finished test cycle was then run 3 times on the engine in its standard configuration to ensure that it produced reliable and repeatable data. The finished drive cycle can be seen in Table 2.

Phase	Duration (s)	Engine Speed (rpm)	Throttle (%)
Warmup	180	1250	25
	180	2000	25
	180	2250	50
	Until Temperature Post Intercooler reaches ≈45°C	2500	70
Test	120	2000	60
	120	2000	70
	120	2250	60
	120	2250	70
	120	2500	60
	120	2500	70
	Until Oil Temperature reaches ≈85°C	2000	25
	120	2750	60
	120	2750	70
	Until Oil Temperature reaches ≈85°C	2000	25
	120	3000	60

Table 2: Completed Drive Cycle

NO_x analyser

A Horiba chemiluminescence NO_X analyser had been planned for use in testing, however, when it was being setup it was found that there was an issue. Other methods for NO_X detection were investigated, but all were too expensive to consider or not feasible in the time frame. Whilst no NO_X data could be captured the intake and exhaust temperatures could be monitored. It should be seen that the turbo-expander reduces intake temperature, which cools the combustion temperature, resulting in a lower exhaust temperature. If this is seen it can be assumed that NO_X emission have been reduced.

Testing

As 3 repeat tests of the engine in its standard configuration had been collected, the engine could be modified to fit the turbo-expander. With the turbo-expander mounted, the instrumentation could be installed. Two K-type thermocouples were installed to measure the air temperature pre and post the water to air heat exchanger which would allow the impact of the heat exchanger to be seen. All bypass ports were blanked through the use of aluminium bungs that were turned on a lathe, with the one post expander having a hole drilled in to allow a pressure transducer to be fitted. The pressure transducer would be used to compare the pressure levels post turbo-expander to the pressure levels created by the primary turbo, and to therefore calculate the efficiency. The channels used for the extra instrumentation all needed calibration which was done using a multifunction calibrator that sent a known voltage to the dynamometer data logger so as to form calibration graphs.

The turbo-expander required oil flow to lubricate the rotating assembly, therefore an oiling rig was used. The rig consisted of a pump that could supply up to 4 Bar of pressure, matching the output of the Ford engine, an oil reservoir, and lines that supply and return the oil to the turbo-expander.

The water to air intercooler requires a constant water supply to remove heat. A 3.5 Bar water pump was used to achieve this. If the ACT turbo-expander was fitted to a vehicle, the water in the system would be cooled via another heat exchanger that would in turn be cooled by airflow. This is not achievable on the dynamometer as no air flow is present, therefore a reservoir of water was used instead as the large heat-capacity and the large volume of water would mean it would heat up gradually and continue to cool the intake air. ACT modelled previous data with the water temperature being set at 60°C - this was not possible in this study due to having no means of heating the water up to this temperature and keeping it stable for a test. As this testing is to prove that NO_X can be reduced through a reduction in intake temperature, a lower water temperature should see a reduced intake temperature and therefore a larger reduction in NO_X. A thermocouple was placed in the water reservoir to ensure all tests had comparable start temperatures.

The dynamometer was put into manual control mode and various rpms and throttle positions were tested to ensure that the setup worked. It was found that at low throttle positions and lower rpms, the engine would surge, ultimately meaning that a constant rpm was not achievable. To overcome this, the test cycle was changed so that the minimum throttle position was 50% with the aim of the baseline testing being repeated, if time allowed, to see what impact this would have. With the setup tested and proven, 3 repeat tests were run successfully.

Results and analysis

Results

To initially analyse the results, statistical analysis was used to determine if the turbo-expander was having a significant impact on emissions. This is a standard industry practice to determine if it can be said with confidence if a reduction in emissions is due to the emissions device fitted. As the NO_X analyser was not working, this cannot be done based off emissions results. However, power, exhaust temperature and intake temperature can be analysed statistically to see what the impact of the turbo-expander was, with the exhaust temperature being an indicator of combustion temperature, and therefore of NO_X emissions.

The correct statistical analysis method first had to be chosen based on the data type. The data captured is quantitative with two independent samples (e.g. testing with the standard engine and testing with the turbo-expander fitted) with the mean of each sample able to be taken, therefore the difference of two means for the independent samples method could be used.

(Dr Nics Maths and Stats, 2012)

Two hypotheses need to be created to allow the data to be analysed. The null hypothesis is that the results under each condition are the same. This report aims to determine if NO_X is reduced by turbo-expander cooling, but it would be socially irresponsible to ignore whether or not it has a negative effect on emissions and other parameters through the use of a one tailed T test. The way to overcome this is a two-tailed T test, that looks at the positive and negative impact of the turbo-expander, meaning the alternate hypothesis is checking if the turbo-expander causes the results between the two conditions to be different.
(UCLA: Statistical Consulting Group, 2017)

A significance level must then be set, and in this instance it is 0.05, as this is commonly used as the significance level in scientific research (Research By Design, 2016). Using the significance level and applying the two hypotheses to the data, using the difference of two means for an independent method, gave the results seen in Appendix A. Condition A is the engine in its stock configuration and Condition B is with the turbo-expander fitted.

Result analysis

Inlet temperature

The statistical analysis in Table 3 showed that the turbo-expander only had a statistically significant impact on intake temperature at 3000rpm - however, the mean data shows that intake air temperature was reduced at all engine speeds and throttle positions. To see why only 3000rpm had proven to be statistically significant, the data needed to be analysed further. Testing happened across multiple days, meaning ambient temperatures and humidity varied, and it was unable to be logged due to insufficient data logging channels. To try and overcome this problem, the warmup held the engine at 2500rpm at 70% throttle until the intake charge post intercooler was 45°C, but a closer look at the data, Figure 3, showed that this did not work. Baseline Test 3 was conducted on a different day to 1 and 2, and once the engine speed had dropped to 2000rpm, the intake temperature was 10°C lower than the other baseline tests and it continued to be lower than the other two baseline tests through the rest of testing.

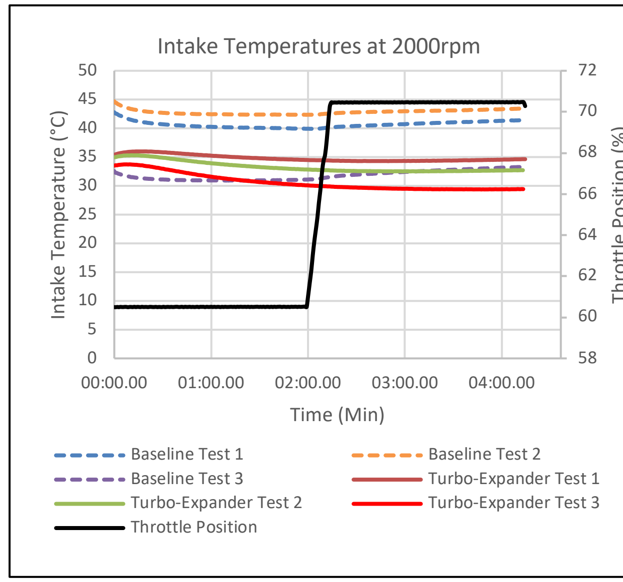


Figure 3: Intake Temperatures at 2000rpm

To see what impact this had on statistical analysis, Baseline test 3 was removed and the analysis re-run, this now showed that the turbo-expander had a statistically significant impact on the intake temperature at 2500rpm at 70% throttle. Baseline Test 3 was then re-considered and an investigation conducted to see at what confidence level it could be said that the turbo-expander was affecting intake temperature at each engine speed. At 2000rpm it could be said with 70% confidence that the turbo-expander is the cause of the reduction in intake temperature and at both 225rpm and 2500rpm the confidence level is 80%. At 2750rpm 60% throttle the confidence level is 70%, however when the throttle position increases to 70% the confidence level drops to 60%. As the confidence levels were so low, the data was plotted to see how the intake air was being affected by the turbo-expander too, with Figure 4 showing an example plot.

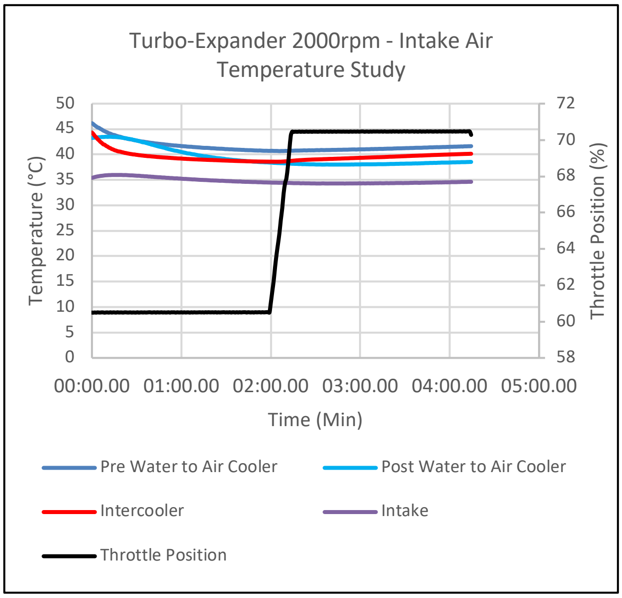


Figure 4: Turbo-Expander 2000rpm – Intake Air Study

Figure 4 shows the results from turbo-expander test 1 which also shows that the compressor of the turbo-expander adds an average of 2.5°C to the intake air, before it is cooled by the water to air heat exchanger. The water to air heat exchanger then removes an average of 2.6°C. The air is then expanded, reducing the temperature by an average of 5.3°C, which shows that the largest reduction in temperature comes from the gas doing work on the expander wheel, which agrees with the theoretical model. Figure 4 also shows that the near constant intake temperature at this rpm is due to the water to air heat exchanger, as the intercooler temperature rises at the same rate as the pre-water to air cooler temperature. The post water to air cooler temperature however, is constant. The 2nd law of thermo-dynamics explains why this happens, as the increase in temperature difference between the gas and the water causes the transfer of energy between the heat sources to occur faster, therefore providing a larger cooling effect. The reason that the statistical analysis did not pick this up as a significant intake temperature drop is due to the large standard deviation between results, which is also seen at all other engine speed ranges. If the testing was more repeatable through the uses of a temperature and humidity-controlled dynamometer cell, as well as a better oil cooling solution allowing a more repeatable test cycle, the variation between intake temperature results would be reduced. This would reduce the standard deviation in the data resulting in the statistical analysis highlighting that the reduction in intake temperature is statistically significant due to the turbo-expander.

Exhaust temperature

The data from testing shows that the turbo-expander significantly reduced the exhaust temperature when the engine speed was equal or greater than 2500rpm, meaning that combustion temperatures were reduced along with NO_X emissions, but without a working NO_X analyser it cannot be stated to what magnitude the reduction occurred. At 2000rpm it was shown that the exhaust temperature increased significantly. The increase in temperature would indicate an increase in combustion temperature and therefore NO_X emissions - as this outcome is the opposite of the desired affect, it needs to be investigated.

At 2000rpm, the mean exhaust gas temperature increased over the standard engine at both 60 and 70% throttle. An increase in exhaust gas temperature can indicate that there is an increase in exhaust back pressure, which decreases turbocharger efficiency and increases emissions. The turbo-expander could be acting as a restriction in the intake system, causing the primary turbocharger to not be able to spin at its standard speed therefore causing back pressure to build. Plotting the exhaust pressure, Figure 5, shows that the exhaust pressure is comparable against all tests and is therefore not the cause of the temperature rise.

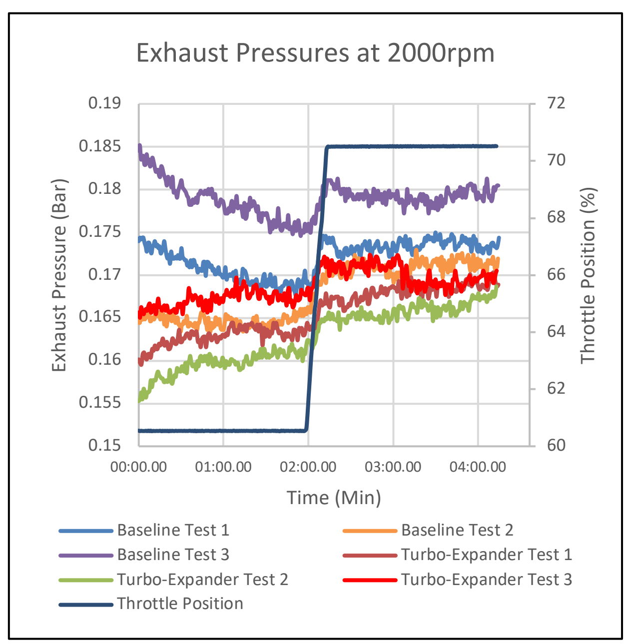


Figure 5: Exhaust Pressures at 2000rpm

The next check is the fueling of the engine under both conditions as the cooler intake air generated by the turbo-expander could cause better combustion and the engine to run leaner, causing higher combustion temperatures. The lambda value for all tests conducted was 1.508, therefore it cannot be said with confidence if this sensor was reading correctly, as the values did not change across all testing. The Visual Basic for Applications based test check template created for this testing did not pick this up because a typical diesel lambda value is between 1.1 to 1.65 (x-engineer, 2017). The fuel flow of each test could be compared to see if the engine's control unit had altered fueling to account for the cooler intake air, however as Figure 6 shows, the fuel flow is comparable against all tests. Another explanation for the higher exhaust temperature is that the EGR (Exhaust Gas Recirculation) valve opened on the baseline tests, causing the combustion temperature to decrease. It is unknown if this happened as intake temperature post EGR or if EGR valve position was not monitored due to lack of data logging channels. This would need to be addressed for any future testing.

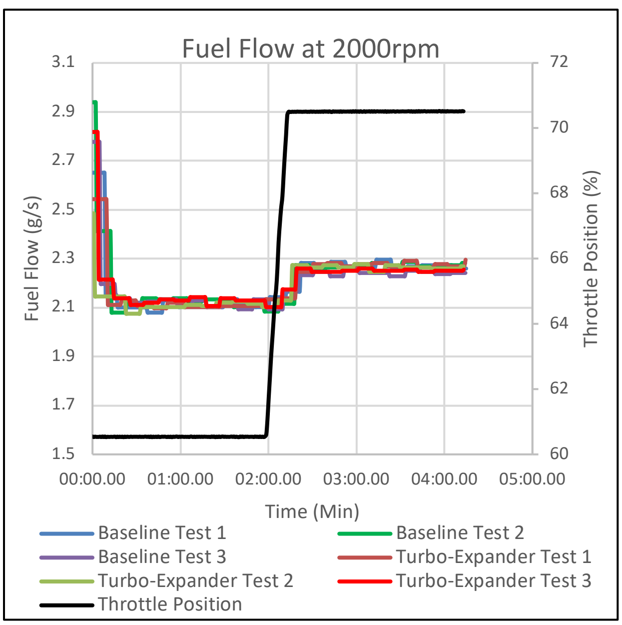


Figure 6: Fuel Flow at 2000rpm

Power

Whilst power isn't as critical as emissions for this study, it is important to consider nonetheless as it correlates to how the engine is running and manufacturers do not want emissions devices to reduce engine power. The statistical analysis showed that at every rpm and load, aside from 2000rpm 60% throttle, 2250rpm 60% throttle and 2500rpm 60% throttle that power was significantly reduced, with the mean data also showing that power was reduced at every engine speed and load. As intake temperature was reduced at every engine speed and load over baseline testing, it would have been expected that power would have increased, as the cooler air would have an increased density. To see why this occurred the data was examined in further detail, with 2500 rpm being used as an example here.

After checking that exhaust pressures and fuel flow had not significantly changed with the turbo-expander fitted, the intake air pressures were analysed which were post primary turbo and post the turbo-expander. As Figure 7 shows it can be seen that the turbo-expander causes an average drop of 0.161 Bar. The reduction in intake gas pressure is expected through a turbo-expander, as when the air provides work on the expander wheel it wastes some energy overcoming the frictional losses in the rotating assembly. The reduction in intake pressure is likely the reason for the reduction in power. ACT claim that the turbo-expander has an efficiency of 85% - looking at the average pressures before and after the turbo-expander at 2500rpm the turbo-expander is operating at an efficiency of 87%, therefore the reduction in power is not due to the turbo-expander operating at a low efficiency. This is an easy problem to overcome for automotive companies as either the pressure at which the primary turbos wastegate opens can be increased or the wastegate can be moved to the turbo-expander itself, meaning that the desired boost pressure can be maintained.

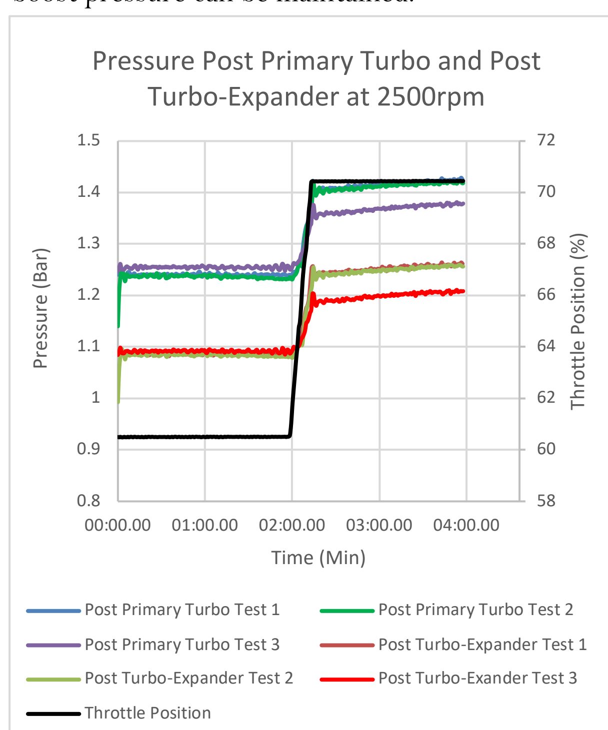


Figure 7: Pressure Post Primary Turbo and Post Turbo-Expander at 2500rpm

Conclusion

The ACT turbo-expander proved to have a statistically significant impact on exhaust temperatures when the engine speed was greater or equal to 2500rpm. Based on the research, the reduced exhaust temperature would indicate a lower combustion temperature which would lead to a reduction in NO_X emissions. However due to a NO_X analyser failure, the exact decrease in NO_X emissions was not determined. The turbo-expander did significantly increase exhaust temperatures at 2000rpm and at 2250rpm at 60% throttle. The data captured does not indicate why this occurred, however this is an undesirable trait as this engine speed range is used frequently during real world driving and would lead to an increase in NO_X emissions, contrary to the aim of the turbo-expander. The ACT turbo-expander decreased engine power across all engine speeds due to the reduction in intake pressure, caused by the frictional losses in the rotating assembly of the turbo-expander. This could be overcome by increasing the primary turbo boost pressure to compensate for the frictional losses or moving the wastegate to the expander turbine of the turbo-expander, rather than on the primary turbo.

Future Work

The testing carried out should be re-run with a working NO_X analyser to determine the exact impact on NO_X emissions, however changes to the test setup should also be made. The introduction of an oil cooling circuit on the cooling tower would be the first consideration. This would negate the need for the cooling sections in the test cycle, which at 2750rpm and 3000rpm caused repeatability issues due to the difference in exhaust temperatures between the standard and turbo-expander equipped engine as a consequence of how long they took to cool the oil down to 85°C. It would also allow a greater range of rpms and throttle positions to be tested, allowing a better comparison against real world driving. More data logging channels should also be installed into the dynamometer, or a separate data logging system should be used. This would allow a thermocouple to be place in the intake after the EGR valve to determine if it is opening at low engine speeds without the turbo-expander fitted, explaining why the standard engine had lower exhaust temperatures. A thermocouple and humidity sensor should also be added at the air box and the dynamometer chamber should be set to a controlled intake temperature and humidity to create a better controlled test environment. This would reduce the large standard deviation seen in the intake temperature results which resulted in the statistical analysis only highlighting 3000rpm as the point at which the turbo-expander had an impact on intake temperatures at a 95% confidence level.

Further development of the turbo-expander itself could be done, as the turbo-expander did not produce a 30°C temperature drop as seen in previous ACT testing. This was expected as the turbo-expander had only previously provided large temperature drops at high engine speeds, but this is not feasible for a high-speed diesel engine that will only rev to 4000rpm and likely spend most of its time at around 2000rpm. A turbo-expander that is better paired to a diesel engine could see sub-ambient intake temperatures, which would see a larger drop in exhaust temperatures than seen in this report and therefore a larger reduction in NO_X.

If this testing is repeated and is shown to reduce NO_X emissions, there are two main routes that could be followed. The first is the use of a transient engine dynamometer to simulate real world driving cycles such as a WLTC. This would provide manufacturers a direct NO_X saving compared to their vehicles, with a similar size engine, and which have also completed that emissions test cycle. The second route, and the preferred, is the use of a chassis dynamometer or PEMS (Portable Emissions) testing. Both would require the system to be fitted to a vehicle, but would prove to manufacturers that it could be successfully integrated into modern engine bays. Both would also simulate air flow over the air to water heat exchanger that cools the water in the ACT turbo-expander, which would in turn give an accurate water temperature compared to real world driving, as well as giving emissions results that are directly comparable to the vehicle manufacturers claims. Chassis dynamometer testing would be the preference as it is reliable and repeatable, but it comes at an increased cost over PEMS testing. If chassis dynamometer testing is out of budget then PEMS testing could be used - but it is less reliable and has uncontrolled environmental variables that can potentially impact results or increase the testing timeframe.

Acknowledgements

I would like to express my gratitude to my supervisor Prof. John Allport for the guidance and continued support during my final year project. The assistance provided by Martin Gargett during the setup and testing phase of the report was greatly appreciated.

Appendix A. statistical analysis results

Engine Speed (rpm)	Throttle Position (%)	Parameter	Condition A Mean	Condition B Mean	Statistically Significant?
2000	60	Engine Power (kW)	33.87	33.20	No
		Exhaust Temperature (°C)	442.91	483.20	Yes
		Inlet Temperature (°C)	38.09	33.70	No
2000	70	Engine Power (kW)	36.81	35.88	Yes
		Exhaust Temperature (°C)	439.93	492.21	Yes
		Inlet Temperature (°C)	38.82	32.16	No
2250	60	Engine Power (kW)	36.00	35.53	No
		Exhaust Temperature (°C)	430.55	442.65	No
		Inlet Temperature (°C)	41.25	33.44	No
2250	70	Engine Power (kW)	44.03	43.52	Yes
		Exhaust Temperature (°C)	468.92	463.95	No
		Inlet Temperature (°C)	43.85	36.86	No
2500	60	Engine Power (kW)	38.35	37.55	No
		Exhaust Temperature (°C)	441.16	422.68	Yes
		Inlet Temperature (°C)	45.70	39.52	No
2500	70	Engine Power (kW)	46.73	46.03	Yes
		Exhaust Temperature (°C)	477.80	455.20	Yes
		Inlet Temperature (°C)	48.16	41.99	No
2750	60	Engine Power (kW)	41.53	40.05	Yes
		Exhaust Temperature (°C)	447.68	435.47	Yes
		Inlet Temperature (°C)	43.89	39.25	No
2750	70	Engine Power (kW)	52.31	51.22	Yes
		Exhaust Temperature (°C)	504.12	469.61	Yes
		Inlet Temperature (°C)	49.7	45.69	No
3000	60	Engine Power (kW)	43.19	41.62	Yes
		Exhaust Temperature (°C)	448.96	439.23	Yes
		Inlet Temperature (°C)	48.28	41.25	Yes

References

Almasi, A. (2019). *Take Advantage of Turbo-expanders.* Retrieved from https://www.chemicalprocessing.com/articles/2019/take-advantage-of-turbo-expanders/ Apis.ac.uk.

Apis. (2004). *Nitrogen Oxides (NOx).* Retrieved from http://www.apis.ac.uk/overview/pollutants/overview_NOx.html

Cikanek, H. A. (1992). Diesel engine turbo-expander. 5,269,143. *United States: Ford Motor Company.* Retrieved from United States Patent and Trademark Office

Columbia University. (2005). *Gaseous composition of dry air.* Retrieved from https://eesc.columbia.edu/courses/ees/slides/climate/table_1.html

Dr Nics Maths and Stats. (2012, February). *Choosing which statistical test to use - statistics help.* Retrieved from You Tube: https://www.youtube.com/watch?v=rulIUAN0U3w

Fontaras, G. *WLTP and NEDC speed profiles.* Retrieved from https://www.researchgate.net/figure/WLTP-and-NEDC-speed-profiles-and-basic-characteristics-Alessandro-Marotta-et-al-2015_fig1_317420498

Heywood, J. (1988). *Internal combustion engine fundamentals.* New York: McGraw-Hill Education

Mecholic. (2017). Air refrigerator working on Bell-Coleman cycle with PV and TS diagram (reversed Brayton or Joule cycle) [Online image]. Retrieved from https://www.mecholic.com/2017/12/bell-coleman-refrigeration-cycle.html

Mollenhauer, K. M., H. P., Binder, K. B. B., Hagenow, G. H., & Egler, W. E. (2010). *Handbook of Diesel Engines* (2010 ed.). New York: Springer.

National Geographic. (2019). *Acid Rain Explained.* Retrieved from https://www.nationalgeographic.co.uk/2019/03/acid-rain-explained

Nave, R (1999). *First Law of Thermodynamics.* Retrieved from http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/firlaw.html

Nuclear Power. (2017). *Bell Coleman Cycle* [Online Image]. Retrieved from https://www.nuclear-power.net/nuclear-engineering/thermodynamics/thermodynamic-cycles/heating-and-air-conditioning/reverse-brayton-cycle-brayton-refrigeration-cycle/

Phys.Org. (2015). *NOx gases in Diesel car fumes: Why are they so dangerous?* Retrieved from https://www.nationalgeographic.co.uk/2019/03/acid-rain-explained

Research by Design. (2016, August). *Step 3 – Select a Level of Significance (8-7).* Retrieved from You Tube: https://www.youtube.com/watch?v=15Ds__9wbHg

Tosa, Y. (1994). *Europe Patent No. EP 0 655 550 A1.*

UCLA: Statistical Consulting Group. (2017, March). *FAQ: WHAT ARE THE DIFFERENCES BETWEEN ONE-TAILED AND TWO-TAILED TESTS?* Retrieved from UCLA: Statistical Consulting Group: https://stats.idre.ucla.edu/other/mult-pkg/faq/general/faq-what-are-the-differences-between-one-tailed-and-two-tailed-tests/

Whelan, C. D., & Allport, J. M. (2017). *Active Charge Cooling.* Retrieved from University of Huddersfield Repository: http://eprints.hud.ac.uk/id/eprint/32001/8/__nas01_librhome_librsh3_Desktop_Active%20Charge%20Cooling%20paper%20rev%2007%20161110.pdf

WLTP Facts. (2017). *WHAT ARE THE BENEFITS OF WLTP?* Retrieved from https://www.wltpfacts.eu/wltp-benefits/

x-engineer. (2017, November). *Air-fuel ratio, lambda and engine performance.* Retrieved from x-engineer: https://x-engineer.org/automotive-engineering/internal-combustion-engines/performance/air-fuel-ratio-lambda-engine-performance/