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An investigation to determine how simulation of varying thermodynamic cycles can influence engine efficiency and harmful emissions.

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1. Introduction.

Throughout history the internal combustion engine has been a fundamental instrument of revolutionary progression for various industries, from construction to military, to aviation and energy production. Its versatility and unique construction has given mobility and access to countless numbers of individuals across generations.

And as history has shown us, change is inevitable, and the change of combustion is of the utmost importance given current climate conditions. With the number of vehicles on the roads of the world being some 1.32 billion (Chesterton, 2018), with around 300 million of those vehicles being in Europe alone (ACEA, 2018). Considering there was an estimated production 3.3 billion tonnes of CO₂ across Europe in 2019 (Tiseo, 2019), and knowing that the transport industry accounted for 1.1 billion tonnes of those greenhouse emissions (EEA, 2020), meaning our industry alone accounted for 33.42%, more than all other sectors bar energy supply (EEA, 2019). After recent reports and projections, current legislation suggests that new registration of petrol (58.9% of market) and diesel (30.5% of market) (ACEA, 2019) vehicles will no longer be option by the year 2030, at least in the UK, in a bid to rapidly decrease the greenhouse gases (GHG) (GOV.UK, 2020).

Although this statement suggests that the internal combustion engine is reaching its end, the key point of this net-zero statement is that it's petrol and diesel, it doesn't mitigate the use of new fuels or fuel blends that will still be fundamentally reliant on an ICE or sorts.

"Because it is not combustion that is the problem, but the fuel" (Müller, 2021).

Using these methods of enhancement, the carbon dioxide emission output of passenger vehicles had been on a steady decline since at least the year 2000, but we've now begun to plateau, and if anything, increase average output.

With this unfortunate turn in emission output and the clear pressing of new regulations coming to the industry, the ability to optimise engine design and operation using simulation tools is now the most effective manner of design. Simulation of combustion can save money for the manufacturer, save a significant period during research and development, but most importantly reduce their net footprint by not requiring substantial physical testing.

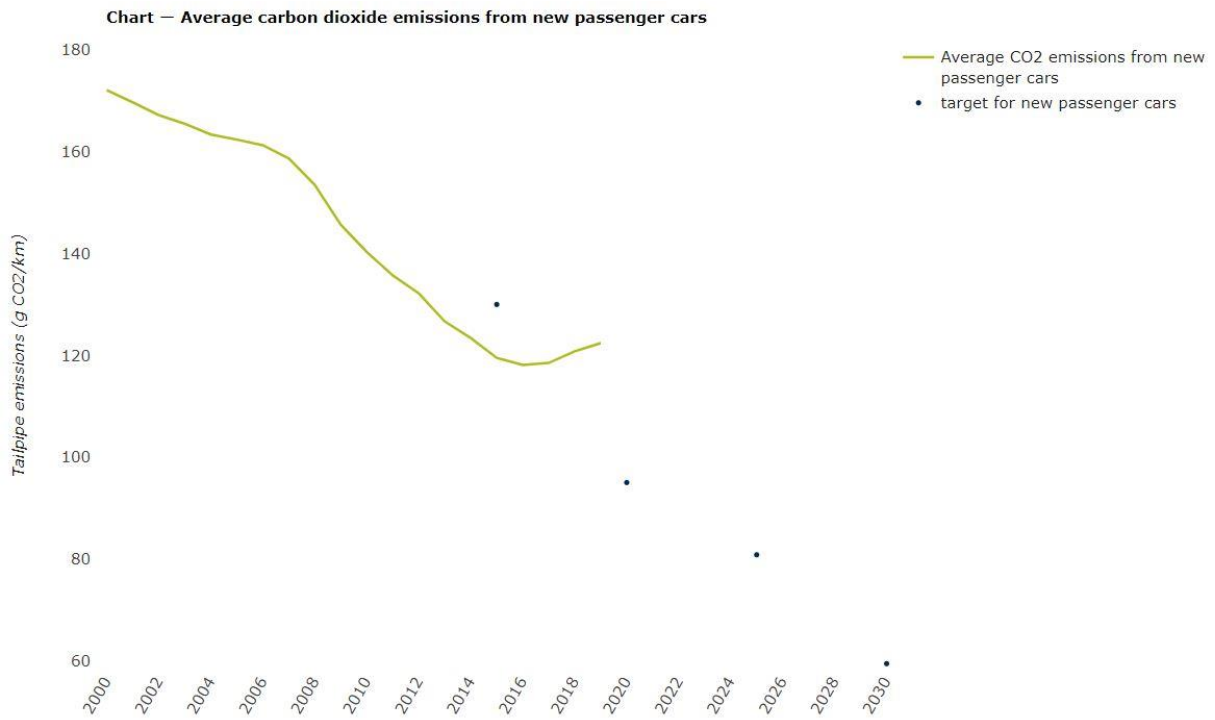


Figure 1 Average tailpipe emissions of passenger vehicles of the EU in g/km (EEA, 2020).

Using measured in cylinder pressure data of an engine, along with the accompanying values for air and fuel mass can reveal the characteristics of combustion for the engine in question. This understanding of an engine can be used to inform that of another configuration upon validation, hence why industry giants like MAHLE powertrain have turned to using various simulation tools for up to 70% of their development process, where there is no physical testing required until the end of the project. This use of thermodynamic principles, laws of physics and computational fluid dynamics is paving the way for a new generation of rapid development of ICE's that utilise; new technologies, materials, designs, and fuels, with the hope that we can reduce emissions effectively until we have a new alternative, sustainable and cost-effective propulsion method.

Project Objectives

- From first principles develop a correctly correlated **two-zone combustion model** of the 1500cc Ford Motor Company GTDI EcoBoost engine across varied load conditions and engine speeds within MathWorks MATLAB.
- Upon validation of the modelled in-cylinder pressures and mass fraction burnt (**MFB**) for these varied conditions, begin the development of a valid emissions model based on **chemical kinetics**, again in MATLAB.
- Having demonstrated the effectiveness of 1D combustion modelling, develop a 3D model using CFD software **Forte**, provided by ANSYS. Validating again against measured data.
- Achieving the adequate level of correlation for cylinder pressure, MFB and emission prediction, begin to adjust characteristics. Primarily the valve timing to change the cycle type from **Otto**, to either the **Atkinson** or **Miller** combustion cycles.
- Other characteristics would be the compression ratio, injection pulse width modulation and fuel type. However, these will only be sought after upon previous model validation and will be time dependent.

Although combustion simulations typically struggle to predict the exact erratic pressure profile due to the nature of combustion, as seen in the figure below, the definite trend can be modelled with a high level of accuracy. Hence the purpose of this research is to both show the importance and efficiency of simulation within the industry of today, and to demonstrate that the evolution of the operating cycles within internal combustion engines is still a viable option for reducing our greenhouse gas footprint.

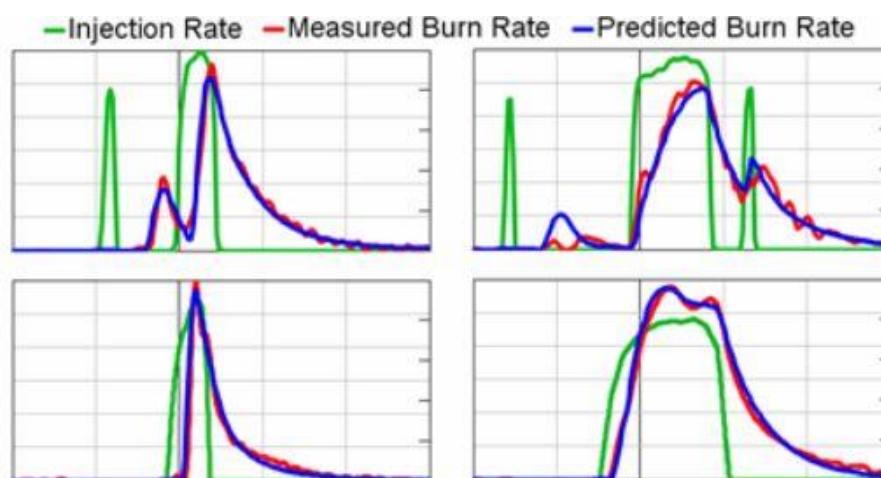


Figure 2 Capability and accuracy of simulation software GT-SUITE (Gamma Technologies LLC, 2021).

2. Literature Review.

1. History of the internal combustion engine – Four-Stroke.

The internal combustion engine owes itself to the extensive use of the steam engine during the 18th century because this allowed for a new stage of evolution for the iconic piston-in-cylinder system that is said to be traced back to 150BC and is still being utilised today. The first use of a steam “engine” in industrial application is accredited to one Jerónimo de Ayaz, who amongst many other things was regarded as a brilliant inventor who helped change the mining industry with his ideas of using the engine to drive a pump and remove excess water from the mines (Sandman, 2003). Despite its incredible range of application, issues pertaining to the steam engine were that the consumption of fuel was to happen externally, meaning even more time and surface contact where losses of heat energy that was being extracted could occur (Cromer & Proctor, 1999).

Because of this unfortunate problem, it was clear that to achieve higher efficiencies the two systems would have to become one, such that the combustion and expansion were to happen in the same cylinder. This concept was then theorised by Alphonse Beau de Rochas, in 1862, and this theory consisted of using of four consecutive cycles within a single cylinder to allow for the harmonious extraction of energy from a fuel. The four-stroke internal combustion engine was born.

However, because of financial limitations, it wasn't developed past the point of being of a theorem by Alphonse. It took the intrigue of a German engineer; Nikolaus A. Otto to take the idea from paper to product and craft the first working engine in 1876. Upon its production it “rapidly” began to replace all other types of combustion engines, sparking the new revolution of propulsion and energy generation (Cromer & Proctor, 1999).

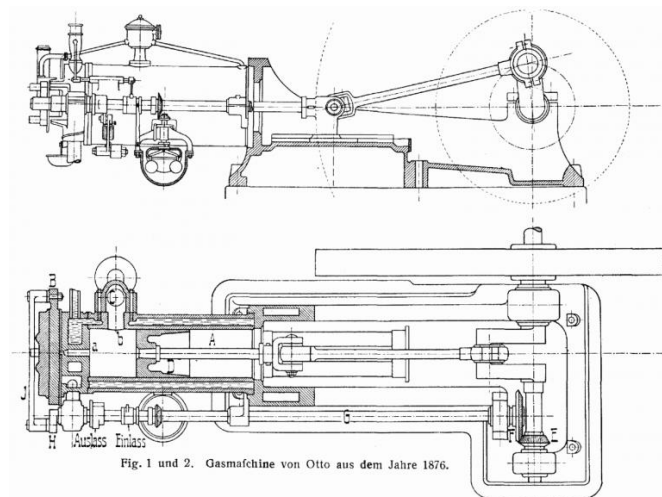


Figure 3 Diagram of Nikolaus A. Otto's first four-stroke ICE (Sack, 2019).

The standard operation of an internal combustion engine is renowned as the 'Otto' cycle. This cycle consists of four separate stages; intake, compression, combustion, and exhaust all of which are idealised across 180° of crankshaft rotation for each. The power stroke occurs once for every two revolutions of the crank, but most importantly the compression to expansion ratio is the same.

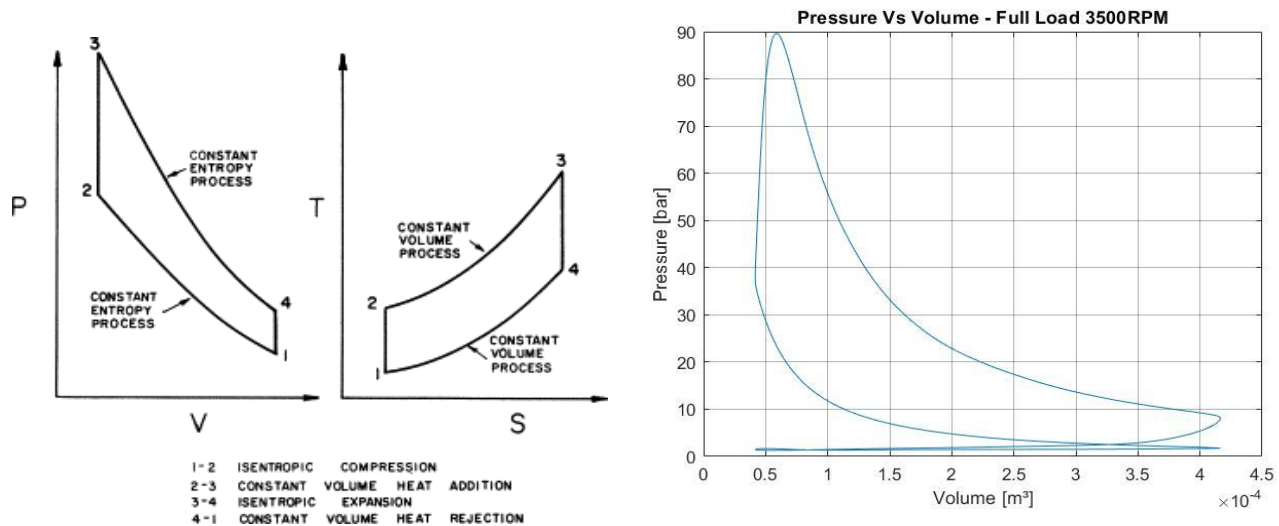


Figure 4 Idealised Otto cycle where the combustion process happens during constant volume (Isochoric) (Left) (Proctor, 2003); Real cycle pressure data highlighting the issue with assuming the process abides the constant volume process (Right).

2. Industry application and progression of the Atkinson cycle.

The Atkinson cycle is named unsurprisingly after its creator, James Atkinson (1864 – 1914). He was a British inventor that patented his design for an engine that operated over four-strokes, however the geometry of the engine allowed for longer time during the expansion cycle, increasing the time that work from the combusted fuel could be extracted and naturally increased the efficiency of the engine (Heywood, 1988). Advantages of Atkinson cycle were realised straight away, these can be categorised as;

- Higher thermal efficiency in comparison to the typical Otto cycle.
- Increased fuel efficiency.
- Potential for reduced pumping losses during operation.
- Ideal cycle to be used in harmony with an electric motor in hybrid applications.
- Potential for a reduction in emissions, without the addition of aftercare.

(Hou, 2007), (Li, et al., 2021), (Zhao, 2017), (Gahruei, et al., 2013).

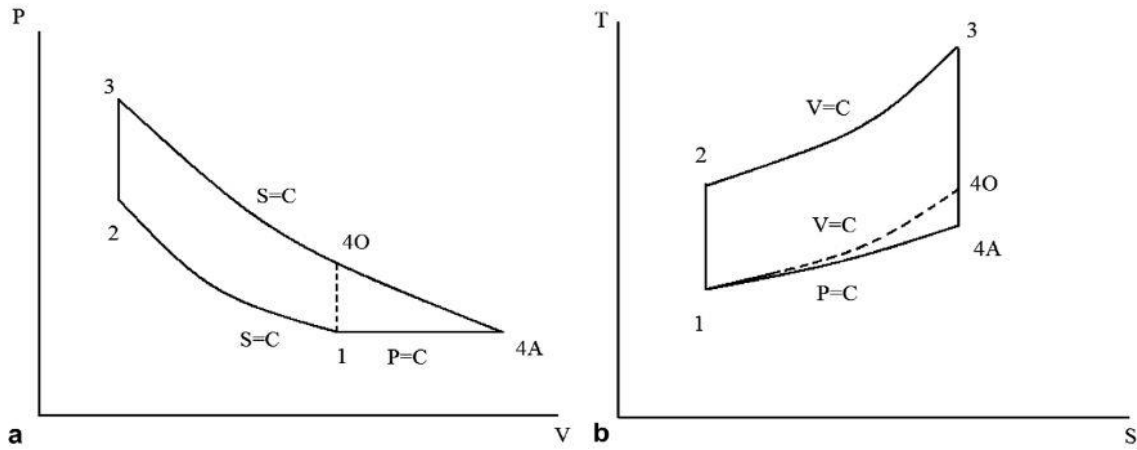


Figure 5 Comparison of the thermodynamic cycles, Otto (1-2-3-4O) and the Atkinson (1-2-3-4A). Where A is representing the pressure – volume [PV] diagram and B is representing the temperature – entropy diagram [TS] (Hou, 2007).

When James Atkinson first developed the cycle, his approach to cycle adjustment was to change the engines working geometry, meaning the compression ratio remained the same but the configuration allowed for further travel of the piston during the expansion cycle. This rather complicated system made the engine large and increased the mechanical losses through operation, hence why it was again adapted through the generations in such a way that now the valve timing is used to create the same effect. Late closing of the intake valve (LIVC) means that as the piston travels up the cylinder, there is less resistance (pumping losses) but does in turn reduce the compression ratio in doing so. This reduction is what then allows for the increase of expansion ratio (Li, et al., 2021).

$$OER = \frac{ER}{CR} = \frac{Vol_{\text{piston BDC after expansion}}}{Vol_{\text{piston BDC after intake}}}$$

(Yang, et al., 2020)

This adaptation of LIVC is used in industry engines today by manufactures such as; Ford Motor Company, Toyota, and Lexus. The most prominent of which is Toyota. They adopt the Atkinson cycle in many of their hybrid and some non-hybrid vehicles and in doing demonstrate effective use for a reduction in emissions and increased fuel efficiency (Clifford, 2015).

3. Industry application and progression of the Miller cycle.

The miller cycle is another adaptation of the traditional Otto cycle that Ralph Miller, an American engineer, filed a patent for on December 24th, 1957 (No. US2817322A). His approach was again to target an increase in thermal efficiency, achieved again with the use on an over-expansion type engine. The key difference between the Atkinson and Miller cycle is the idea for achieving this, being Atkinson initially used engine geometry and Miller targeted the valve timing (ATKINSON, 1886) (MILLER, 1957).

Miller choose initially to create the cycle to revolve around early intake valve closing (EIVC) on engines that utilised forced induction as not to impair the following combustion cycle because the volumetric efficiency could be kept high. As opposed to that of a naturally aspirated engine that requires that longest available opening time as possible, to increase volumetric efficiency to an adequate level, hence the typical association of cycles to that of Atkinson on NA engines, and Miller of FI engines (Jääskeläinen, 2019).

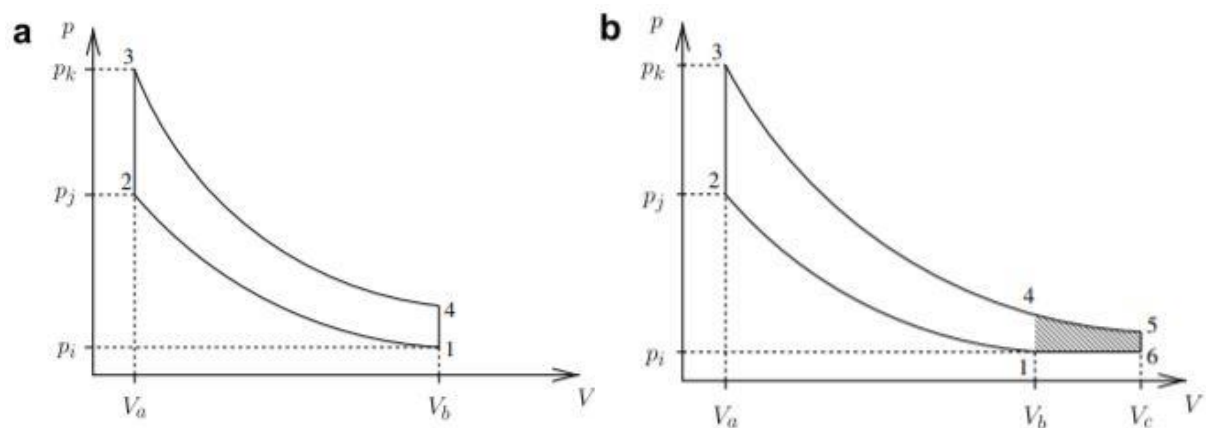


Figure 6 Comparison between the PV diagram of the typical Otto cycle (a) and the over-expansion Miller cycle (b) (Mikalsen, et al., 2009).

As can be seen, the cycle is very similar to that of the Atkinson with respect to the 'increased' volume during the expansion cycle. However, because Miller's target was to use EIVC instead of LIVC, his idea was there would be a reduction in charge temperature because the system should abide by the ideal gas law. Showing that with the change in volume without an increase in pressure, the temperature would have to decrease.

Miller's cycle is commonly used in diesel applications, on larger typical supercharged engines, where the loading condition can be kept relatively similar and not of high demand, because the limitation of both these cycles is known to be the reduced power output due to the common reduction in compression ratio (Gonca, et al., 2015) (Wang, et al., 2007) (Li, et al., 2019).

However, there is development in cases where the power output reduction can be offset with an increase in boost pressure to effectively increase charge density, whilst adjusting the effective exhaust gas recirculation ratio and equivalency ratio (Li, et al., 2014) (Chen, et al., 2019).

Typical uses of an engine utilising the miller cycle are larger off-road diesel applications throughout the marine industry and some power generation. Considering road applications, Mazda are the most notable manufacturer to have implemented the idea with their 2.25L KJ-ZEM V6 supercharged engine back in the late 1990's (Ashdown, 2018) and again for the later generation Mazda 2 MZR 1.3L DOHC (MAZDA, 2007). Although other's have tried, none were seemingly as effective as the Japanese manufacturer.

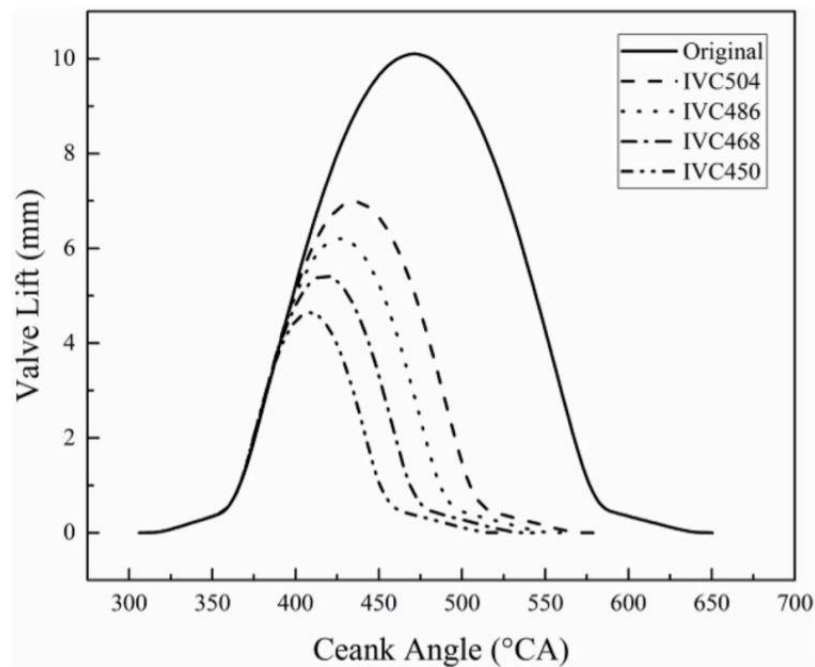


Figure 7 Visualisation of valve lift profiles when EIVC is utilised on an engine (Chen, et al., 2019).

4. Two-zone combustion & Emissions modelling.

Modelling combustion has become an integral part of technological, control and experimental advances for the internal combustion engine, because it “easily” allows for rapid development of knock, fuel consumption, and emissions modelling that can be used to influence how real-time control of the engine can be utilised (Guzzella & Onder, 2010). All of which are key targets for the industry at this point in history, given out current climate condition.

Two-zone combustion modelling is simply an advance from single-zone models, in which the combustion event isn't treated as a single entity. Because the combustion process pertains more to a burnt and unburnt zone as the flame propagates through the cylinder, hence the use of the more accurate model that allows the calculation of these two zones independently of one another.

The advantage of using two-zone of single-zone modelling is identified in the following figures;

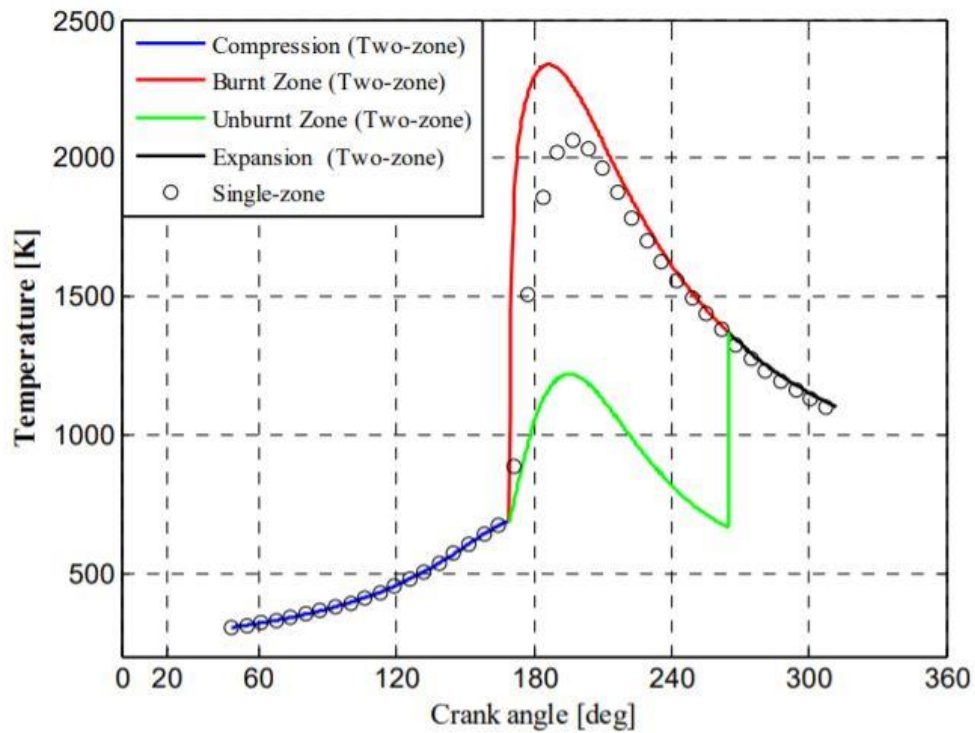


Figure 8 Predicted combustion in-cylinder temperatures using both single-zone and two-zone modelling techniques, identifying the potential difference, and reiterating what could be cause for concern given the models temperature dependency (Xiang, et al., 2018).

The fundamental equations used for this modelling format are those for mass conservation, energy conservation, and a pair of ideal gas equations;

$$M_b + M_u = M$$

$$V_b + V_u = V$$

$$\frac{d(m_u u_u)}{dt} = h_u \frac{dm_u}{dt} - P \frac{dV_u}{dt} - \dot{q}_u, L$$

$$\frac{d(m_b u_b)}{dt} = h_b \frac{dm_b}{dt} - P \frac{dV_b}{dt} - \dot{q}_b, L$$

Where M_b and M_u are the independent masses for the burnt and unburnt zones, h_b and h_u and the enthalpies of these zones respectively, and V_b & V_u are the volumes associated to the zones. It's proposed that the term for heat transfer to the walls, $\dot{q}_u, L$ & $\dot{q}_b, L$ are to be model by experimental correlations. As for the gas laws of the zones;

$$P = \frac{m_u R_u T_u}{V_u} = \frac{m_b R_b T_b}{V_b}$$

The pressure can be said to be equal across the burnt and unburnt zones, and it's also assumed that there is no heat transfer between the zones (McAllister, et al., 2011).

This can then effectively be used to model emissions production because of the significant influence of pressure and temperature on the calculation of species production using the idea of partial pressures.

Typical approach to combustion product modelling is based around the idea that the reaction can go both forward and backwards. Under the impression that combustion operates as a closed compressible system, it can be said that the increase in entropy must always be greater than, or equal to zero. Also, because the system is commonly treated as one that abides by constant temperature and pressure, that every change in chemical composition will reduce the value of Gibbs free energy, to the point where at chemical equilibrium the following condition is met (Merker, et al., 2006).

$$dG_{T,p} = 0$$

It can be said that the change in Gibbs free energy, at constant pressure and temperature, as the gas composition changes is;

$$(\Delta G)_{T,p} = \sum \tilde{\mu}_i \delta n_i$$

Where Δn_i is the change in the number of moles of the species denoted, i . $\tilde{\mu}_i$ is the chemical potential (Heywood, 2018).

Using the principle of chemical potential means that the solution for the concentrations of the various species will have to be an iterative process. So, to save time and money, the idea of partial pressures is introduced.

$$\sum_i v_i \tilde{g}_i^\circ + RT \ln \prod_i \left(\frac{P_i}{P^\circ} \right)^{v_i} = 0$$

$$K_p = \prod_i \left(\frac{P_i}{P^\circ} \right)^{v_i}$$

Where K_p is the equilibrium constant and it's now in relation to the partial pressures for the species ' i '. This constant is only dependent on the temperature of the system, and using published data, like the JANAF tables, the associated data between the constant and its associated temperature can be calculated and used to inform the model (Merker, et al., 2006). This is the method that'll lay the groundwork for emissions predictions throughout the research project.

The efficiency and validity of two-zone modelling can be seen across countless scholarly journals and papers; however, it should be noted that there is still assumptions to be made during this process that can lead to errors in predictions.

5. CFD combustion modelling.

Computational fluid dynamics is a world-renowned method of finite difference approximations that solve for fluid interactions of a system, be it externally across a vehicle body, or more intrinsically, internally for the combustion engine. Two infamous names are attributed to the "birth" of the mechanisms used today, Claude-Louis Navier and George Gabriel Stokes. The pair advanced the equations of one Leonhard Euler, to include transport of viscous fluids and as such the fundamental equations for CFD were made, and aptly named; the Navier-Stokes's equations (AMWEL Enterprises, 2008).

Advances through the years helped progress the equations to be more inclusive and refined, with many industries finding uses for the various software's that are available today. Utilising these systems has begun a new generation of both research and development, and simulation within the automotive industry. Although CFD models were commonly attributed to the external aerodynamics of the vehicle, it has been shown countless times that it can advance our understanding of the influence of geometrical, control, and fuelling changes on the combustion process. Research such as; (Baratta, et al., 2020), (Knop, et al., 2008), (Kosmadakis, et al., 2015), (Decan, et al., 2018).

This efficient, and very accurate modelling technique has progressed the automotive industry and will most likely continue to do so with constant advancements in computing technology helping to reduce computation time. Because the major downfall of the concept of CFD is simply the length of time that can be required to solve, hence why it's proposed that studies into the major contributing factors of a model will be conducted in the hope that computation can be reduce, without the expense of accuracy.

3. Methodology.

1. Mathematical Modelling.

Considering the approach for mathematical modelling, the traditional procedure of assessing the provided measured data for combustion characteristics will lay the groundwork for the investigations. All of which will be done with MathWorks MATLAB software.

Required characteristics are as follows;

- Polytropic index values for the order of change of pressure during compression and expansion.
- Starting position and delay of ignition helping to define the key point, the start of combustion.
- Duration time and end of combustion are also important for understanding the influence of the starting conditions; equivalency ratio, compression ratio, spark timing, etc.
- Volume and mass of the charge air and fuel mixture within the cylinder, to inform the chemical kinetics modelling.
- Burn rate of the mixture signifying the rate in which heat is added to the system.

(Merker, et al., 2006), (Heywood, 2018), (Heywood, 2018)

These characteristics will inform the following model fundamentals:

In-cylinder pressure trace profile predictions that follow the assumption it's an isentropic process. With respect to the ideal gas law the pressure will be found per degree using;

$$PV^n = \text{constant or,} \quad P_1 V_1^n = P_2 V_2^n$$

Where ' P ' is pressure, ' V ' is volume and ' n ' is the polytropic index (Heywood, 2018).

To find this polytropic value that is intrinsic of the compression and expansion process, typical approach is to use a logarithmic pressure – volume diagram and using the leading component of the polynomial fit to log-pressure. As seen in the following;

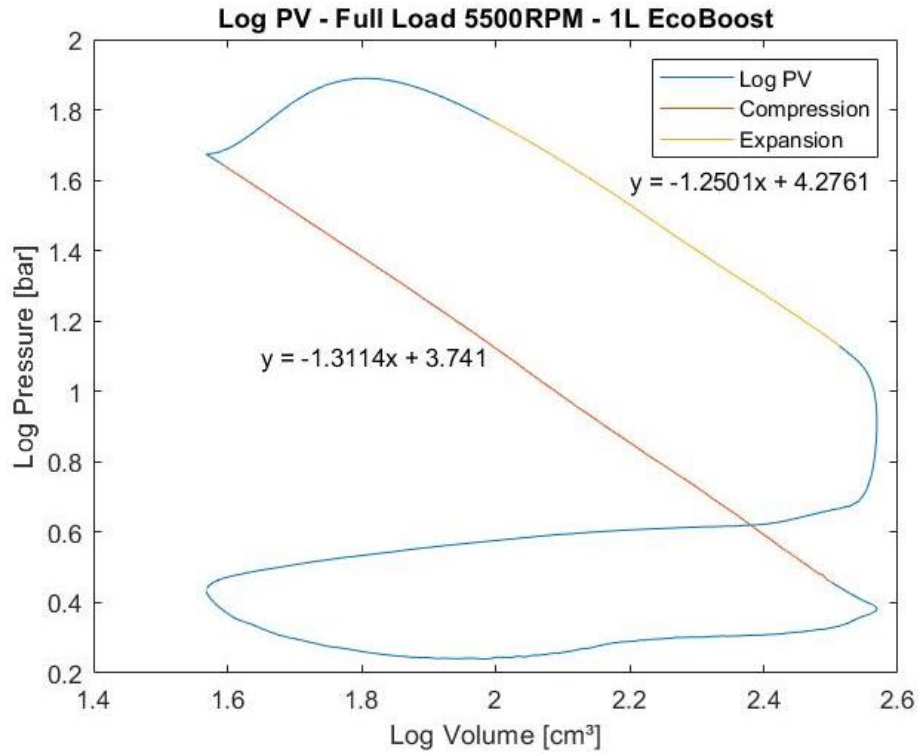


Figure 9 Log PV diagram showing the values for the polytropic values of full load condition for the 1L EcoBoost engine.

Considering the mass fraction burnt, this is modelled under the principal of a method proposed by the engineers Gerald M. Rassweiler and Lloyd Withrow after conduction an experiment to correlate the fraction of burnt mass to that or measured pressure data and photos of the combustion process (Rassweiler & Withrow, 1938).

$$\frac{V''_{tf}}{V_{tf}} = \frac{V'_t}{V_{tf}} \left(\frac{P_t}{P_{tf}} \right)^{\frac{1}{n''}}$$

Where 'V''' is the volume of the inflamed portion of the charge at the given time. "V" is the volume of the non-inflamed portion of the charge at the given time. 'P_t' is the absolute pressure (reduced to constant volume) at the given time and the notation of '._f' just defines the condition at EOC. Using this produces the MFB as shown in the following, but as can be seen in this, there is variation within each cylinder and this can cause discrepancies within modelling, if the averages were to be used. But this is not the intention, each cylinder will be calculated independently in the hope to retain errors to a minimum.

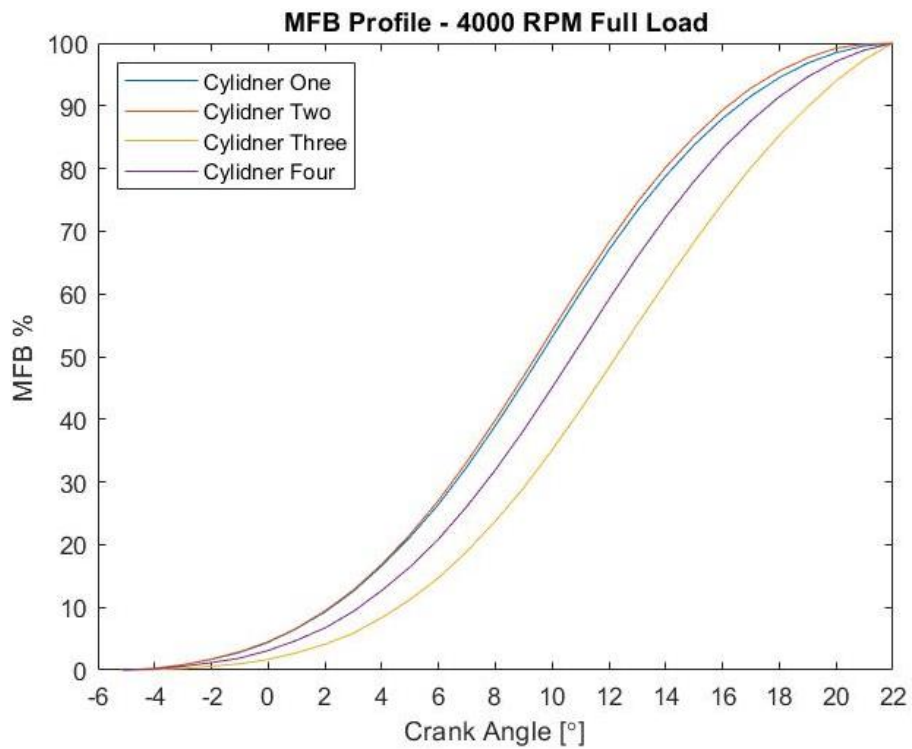


Figure 10 Mass Fraction Burn (MFB)% through combustion for the 1500cc EcoBoost GTDI engine at 4000RPM and 70% relative load.

As the for the unburnt zone, it's simply;

$$Unburnt = 1 - MFB$$

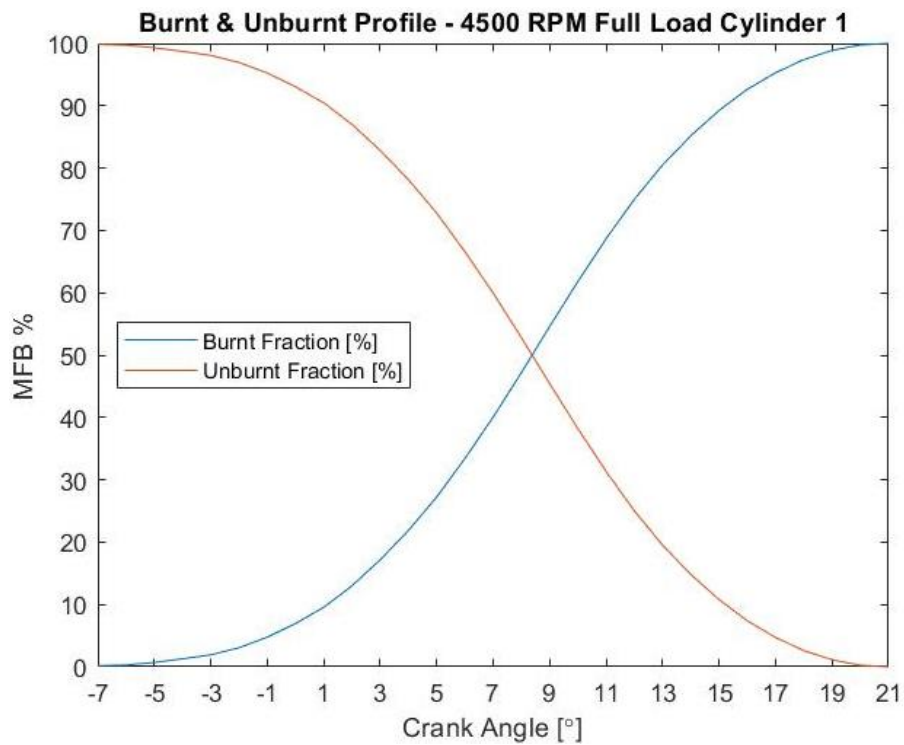


Figure 11 Burnt and Unburnt percentages through combustion for the 1500cc EcoBoost GTDI engine at 4500RPM and full load.

Following into the calculation of the species produced during the combustion phenomenon the calculations will be done under the principal of combustion equilibrium. This equilibrium is found using the known mass of fuel and air into the cylinder and this gives an initial value for the expected species of emissions that will be found following the idea mole fraction based on its partial pressure (McAllister, et al., 2011). Naturally, these equilibrium constants will change with variation in temperature, so considering the validity of the model, combustion temperature calculation is of the utmost importance.

The intention is to use the relationship of the effect of pressure on temperature during an isentropic thermodynamic process, such as;

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}$$

Where ‘ γ ’ is the ratio of specific heats;

$$\gamma = \frac{C_p}{C_v}$$

(McAllister, et al., 2011)

This ratio of specific heats will vary at each degree of crank rotation because of the change in temperature, as seen in the figure below. To account for this, the intention is to follow the process as described by John B. Heywood in his 2nd edition of Internal Combustion Engine Fundamentals, section 4.7.

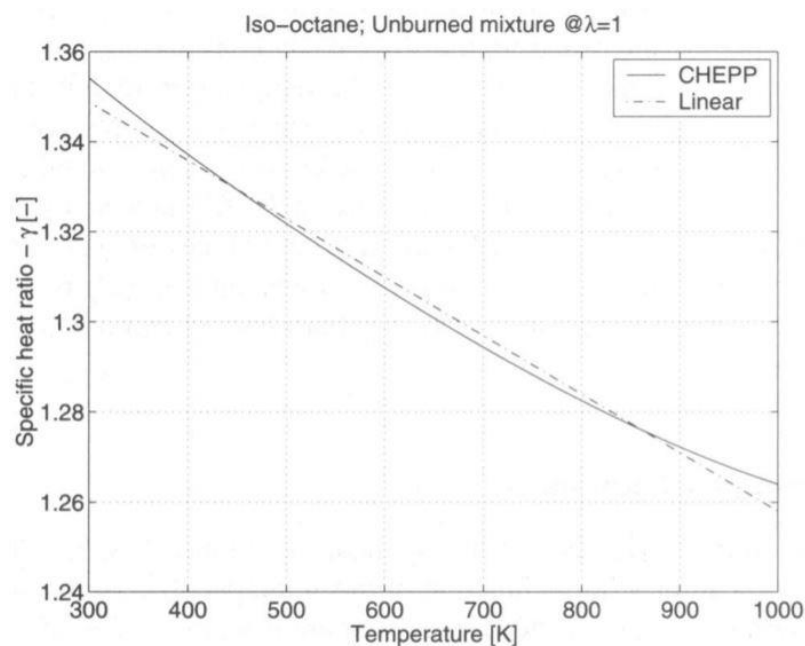


Figure 12 Specific heat ratio for an unburned stoichiometric mixture as a function of temperature (Klein & Eriksson, 2004).

Using this method of calculation increases the ability for the prediction of combustion product species, per degree or crank rotation, and this will in turn help to corroborate the modelling techniques and the ability to predict combustion. Although there is variations of the process for combustion modelling techniques, it's thought that from both previous experience and influence of resources that this process is the best approach to a valid research project in the sector of combustion modelling and emissions reduction.

2. CFD Combustion Modelling.

The intention for modelling combustion within the computational fluid dynamics package Forte, is that although the validity and accuracy of the model is of course going to be the target for the study. But it is important that these simulations are done efficiently with respect to time Vs error percentage. Across all industries its no secret that CFD simulations can take days, weeks even months to run, so to achieve the target of the study, the 'effect on combustion due to the change of thermodynamic cycle', the simulations will ideally be required to run across 3 days maximum.

To conduct the simulations, it is intended that the process will be as follows;

- Build a generic model that is representative of the engine's geometric characteristics.
- Conduct software studies on the major contributors; Turbulence models (FFM, LES), Mesh used in terms of; structure, shape, orthogonality, skewness, etc..., Domain and boundary conditions, Discretization control to reduce approximation errors.
- Conduct an analytic evaluation of the accuracy of models through changes of the above mention contributors to achieve efficiency and validity.
- Model for various load and speed conditions reflective of the WLTP cycle.
- After correlation of the modelling is achieved, begin adjustment of the combustion cycle properties, via a shift in valve timing.
- Compare results to measured data and demonstrate either the effectiveness, or its failure.

Decisions will be informed by journal articles, papers, and books, such as; (Netzer, et al., 2017), (Pasternak, et al., 2015), (Ge, et al., 2010), and (McAllister, et al., 2011).

There is multiple software's available for 3D simulation; GT-Power, Converge, SimScale, OpenFOAM and ANSYS Forte. The latter of which has been chosen simply because of accessibility and its relatively common use in industry. Although it's probable that converge would be the most effective package, it is clear ANSYS Forte is more than capable of accurately simulating combustion and chemical kinetic interactions.

4. Results Analysis.

Results collected during this research project will respectfully be quantitative because all data will be compared to externally measured data provided by Ford Motor company. The primary influencing results will be;

- In-cylinder pressure predictions as the piston travels through the full four-stroke cycle.
- Mass fraction of fuel burnt as the combustion process happens because this is fundamental to calculating the energy release during and influences the calculated temperature predictions.
- Temperature and flame propagation through cylinder because these are key to calculating the rate in which chemical reaction rates occur during the phenomenon.
- Masses of substances within cylinder, per degree of crank rotation, to enable comparison to the known measured specific emissions data.

During the process of analysis, starting from the initial modelling, the results of pressure prediction will be compared to that of the measured and will intern corroborate the modelling techniques and the predicted MFB that will then inform the independent zonal conditions of the burnt and unburnt fractions. This will inform the chemical kinetics model used for emissions predictions.

The values used to compare against are single state average measurements, and it's known that there can be a relatively large difference between modelled instant values and the measured averaged values. So, the trends across the engine may have to be compared to include a larger set of data accounting for more variation, meaning the data could require further post-processing that will extend the time allotted to this area of research.

To reiterate this point, it can be seen in the following figure that the maximum cylinder pressure from the provided data is at 15.8 bar of pressure occurring in cylinder two. However, when comparing to the averaged cycle tabulated data during this collection event, it's seen that cylinder two reads a maximum pressure of 19.13 bar. This is a difference of 3.33 bar, and this level of discrepancy will have to be accounted for so that this research can progress through on time (FoMoCo, 2013).

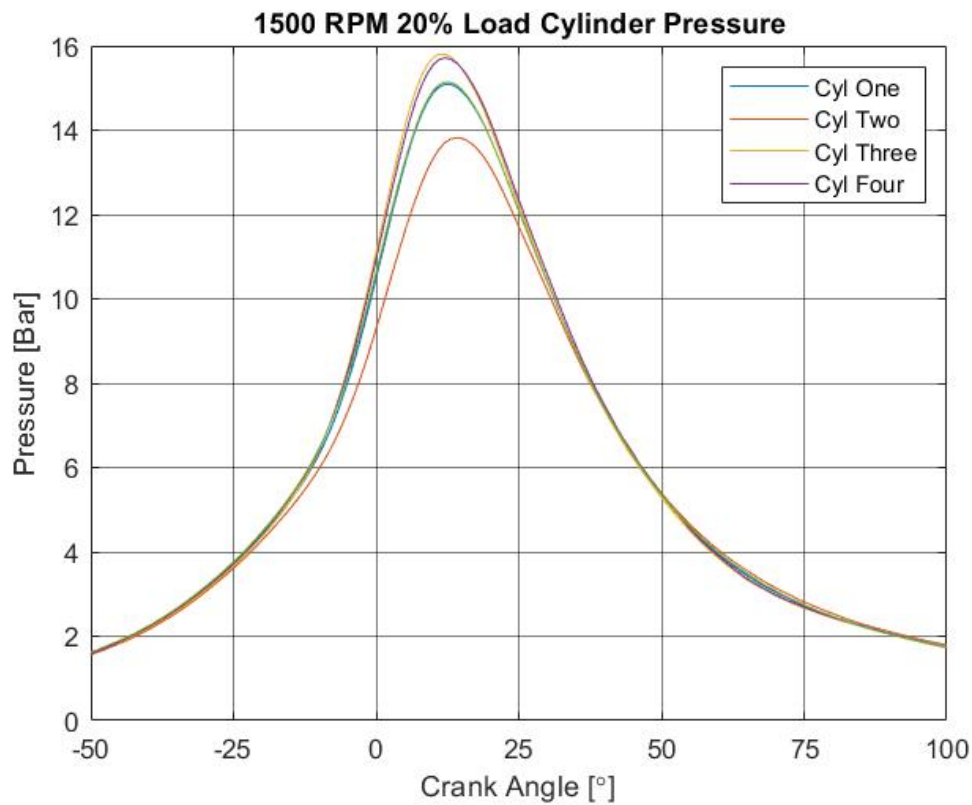


Figure 13 Measured in-cylinder pressure traces of the 1.5L EcoBoost engine, showing the variation of maximum pressures from cylinder to cylinder.

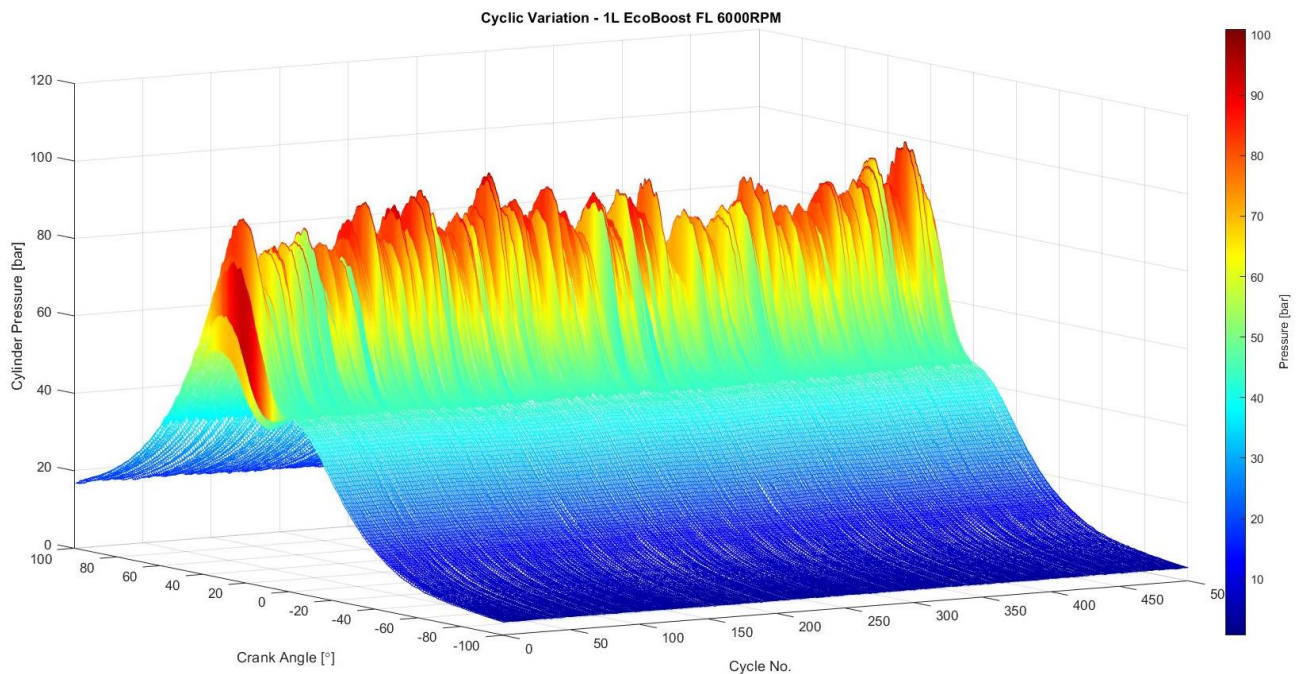


Figure 14 Visualisation of the severity for cycle – to – cycle (cyclic) variation considering the same load and engine speed conditions - 1L EcoBoost GTDI FoMoCo engine cylinder 1 6000RPM.

As made evident from the above figures, cylinder to cylinder variation isn't the only issue regarding the potential for difference between predicted simulation results and measured data. The cylinder pressure data for the 1L EcoBoost FoMoCo engine, with all the traces being only from cylinder one, bringing a brilliant representation of the chaotic nature of combustion in engines and demonstrates that the key point of simulation is to demonstrate the trends, more so than the exact values.

Upon validation of the two-zone model, the intent is to use ANSYS Forte to begin including reactions around more axis within the space in the cylinder, hopefully increasing the prediction ability. The results will be justified regarding the accuracy and time taken because one of the key parameters of simulation is that it can be achieved efficiently.

One of the crucial results obtained from the 3D modelling is the values for turbulence within the cylinder when operating under the standard conditions. This is because adjusting the valve timing to either remain open longer, or shorter, will adjust the turbulence within the cylinder and this will have a knock-on effect of whether the mixture will be homogenous by the point of combustion because of the swirl ratio (Shu, et al., 2019) (Kaplan, 2019).

With all the modelling completed and effectively validated, changes to the model's external factors will be studied, and results of these will be compared to that of measured and published data of previously conducted studies, to show if the expected trends are being followed.

5. Project planning.

The following Gantt chart shows the progression of definite tasks throughout the proposed research project, with the preferred start date, length of task, and the availability to include delays and any prolonging of tasks. This plan is based upon the start of the project to occur on the 1st of May 2021 and continue until the end of August 2021, covering an expected total of 123 days. Using the Gantt chart will help to keep the project on time and ensure that the research and results analysis will be completed on schedule.

Project Planner

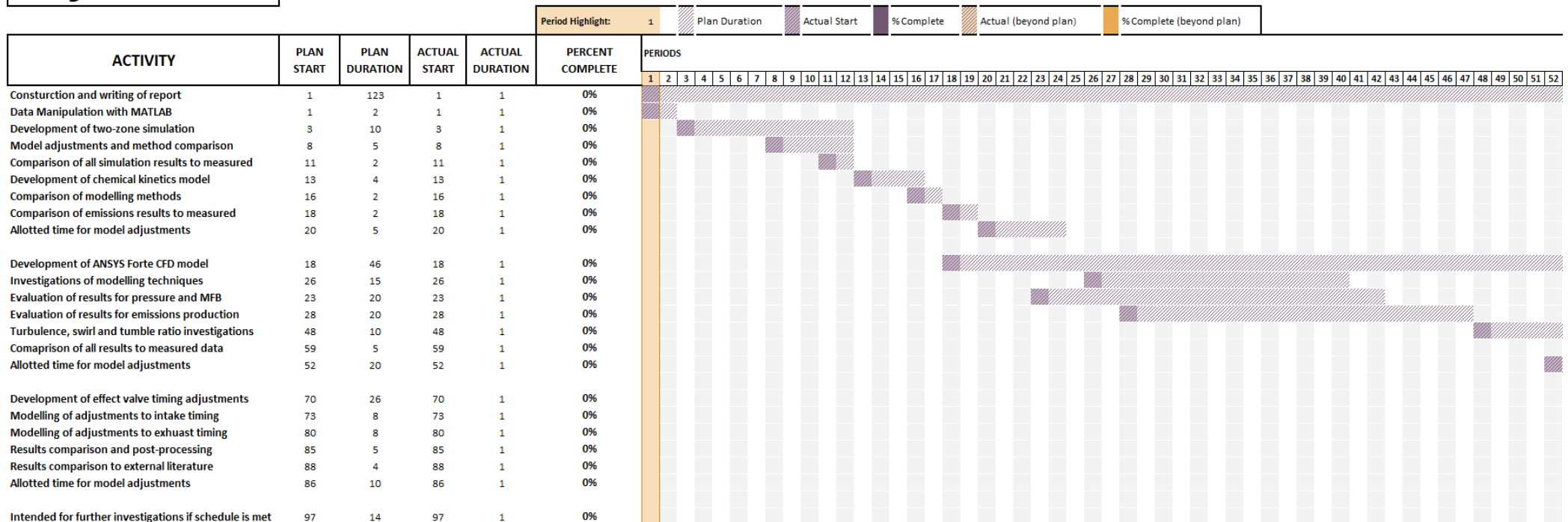


Figure 15 Plan, time scale, and map of progression of tasks during the research project – Gantt chart (1).

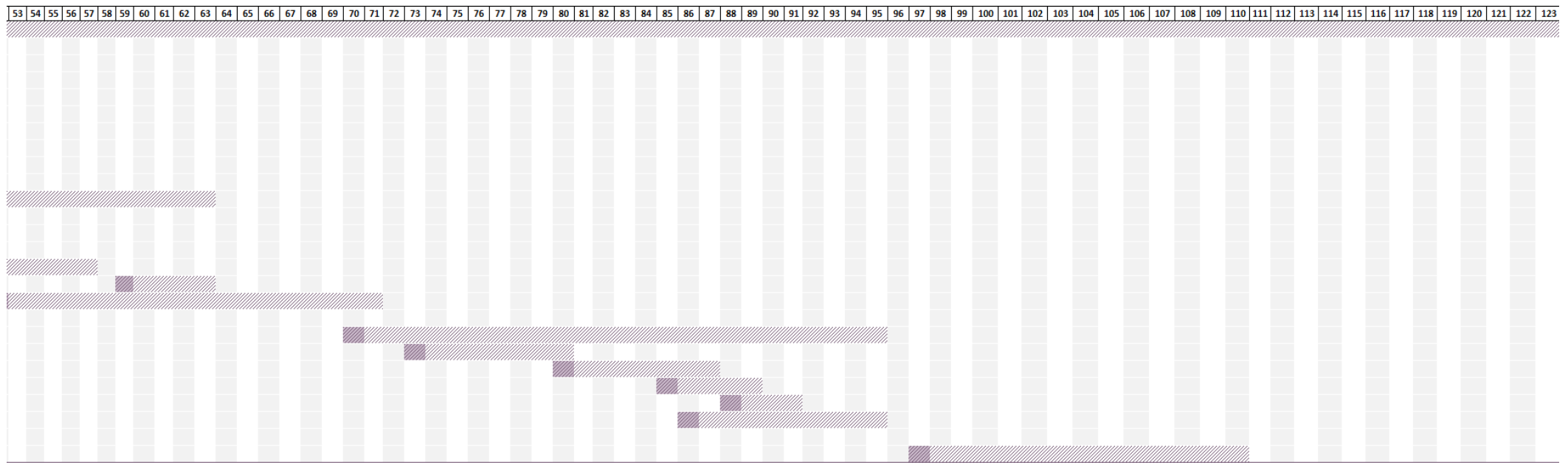


Figure 16 Plan, time scale, and map of progression of tasks during the research project – Gantt chart (2).

The key gateways through the project will be the development and validation of the two-zone combustion model because it shows a good understanding to the characteristics of combustion for this engine. But also, that the fundamental values can be found from manipulation of real measured data. The second gateway of the project is effective and correlative modelling of emissions production during the combustion event because this is the target of the study. The third and final gateway task of the project, will be development and validation of the CFD model created within ANSYS Forte, because this is the focal point of the study allowing for combustion cycle changes to be evaluated and the research project to prove successful.

6. Evaluation.

The proposed research project is thought to be significant for both personal development, and industry development. Considering the very real issue us humans are facing, in that we are teetering on the edge of no return regarding our net output of harmful emissions and greenhouse gases, we must make serious improves across the board to reduce our impact.

Considering the technologies readily available to engineers today allows us to simulate phenomenon, like combustion, without adding to the problem. The common approach to simulation of combustion have been outlined here and it's clear that the techniques can be refined for the independent applications when considering the multitude of literature detailing the effectiveness and accuracy of the models described within this proposal.

It's felt that the research targets are achievable within the timescale detailed above, and given the reviewed literature throughout it's thought that the hypothesis of implementing these cycles can reduce the NO_x emissions created from the engine significantly because of their ability to reduce in-cylinder temperatures, whilst allowing for longer combustion time, meaning there's more chance of reverse reactions of NO_x to occur (Shen, et al., 2021).

As with any simulation there is typical assumptions that must be made, and this is not a new idea, hence there is previous research on how to maintain errors that can occur to a minimum. As was explained, there must be consideration for the effects of cyclic and cylinder variations within the modelling and therefore it is believed that the modelling may not be exact when compared to tabulated data, but the trend will most definitely reflect the engines characteristics.

Given the potential impact of the global pandemic, the exact modelling of the internal geometry of the 1500cc EcoBoost may be limited, and this could show to be an area of concern considering that the project is theoretical, so the effectiveness of the model would require real-world testing. However, because of resource and other limiting factors this isn't possible.

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