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# Extreme Downsizing Technology and its Impact on Volumetric Flow, Brake Specific Fuel Consumption and Drivability of an Internal Combustion Engine.

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### **Abstract:**

There is an ever-increasing demand to increase the efficiency of a vehicle's engine. The pressure has resulted in car manufactures looking into different methods to future proof their cars engines. One method is the downsizing of their engines. This technology means that they take their bigger litre engines and decrease the overall capacity to a smaller litre such as a 1.0 litre car, while trying to maintain the performance and feeling of the larger engine. The industry has invested heavily in this technology but have still come across some drawbacks. The downsizing of a car increases the efficiency of the engine, in terms of more mileage per fuel burnt, but can have some effect on its performance when compared to the bigger engine. This report will investigate whether downsizing increases the efficiency of an engine, and how the technology effects the feel and performance of the vehicle. Calculations will be carried out to look at the air flow into the higher capacity engine and the downsized equivalent. Live data will be collected and processed using excel spreadsheets. From this a suitable system to improve the downsized engines performance can be selected and packaged. Research into this subject has highlighted that the downsizing of an internal combustion engine in various layouts can improve the overall efficiency of the engine, while maintaining the drivability for the driver, and the performance of its larger engine counterpart.

### **Technical Abstract:**

The fundamentals of the downsizing technology and the improvement of Brake Specific Fuel Consumption (BSFC) at part load operation is well known throughout the automotive industry. The automotive industry is continually developing the Internal combustion engines efficiency in relation to its Brake Specific Fuel Consumption (BSFC), its volumetric efficiency with combined fuel and air charge, and its volumetric flow. Downsizing of the internal combustion engines in vehicles has become a widely used technology by the automotive industry. A balance between increase in efficiency of the engine in relation to the BSFC, drivability and the performance of the vehicle must be ensured. Data collected using the Race-technologies DL1 data logger has be processed using an Excel spreadsheet and developed into a duty cycle to support the introduction of a forced induction system and demonstrate the effect on the Brake Specific Fuel Consumption for a downsized engine along the same cycle as the higher capacity engine. In conjunction with the data, calculations on the engines volumetric flow, its volumetric flow once a forced induction system has been applied and the overall conditioning of the charge will be carried out. This data can also be processed using a spreadsheet format. The data and calculations have been used to validate the credibility of a downsized engine in comparison to its larger capacity counterpart in relation to a BSFC map. The drivability and performance can then be looked at, a suitable electronic forced induction system utilising an E-supercharger can be introduced to ensure transient performance. This system will be evaluated and compared to an existing system such as a turbocharger. The information researched has proven its application can improve an internal combustion engines efficiency measure using analysis of the Brake Specific Fuel Consumption when compared to a larger capacity counterpart, while maintaining its drivability and performance when compared to the larger capacity unit it intends to replace. It also highlights the solution to the existing transient performance losses associated with an extreme downsized engine in the pursuit of increasing the efficiency of the Internal Combustion Engine.

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## **1.0: Introduction:**

The main issue for car manufactures regarding the internal combustion engines in a passenger vehicle is its efficiency, or lack of it. An engine has on average a 62.4 percent loss of its fuel energy during its internal combustion process (California energy commission, 2006). A modern internal combustion engine is becoming increasingly efficient, but on average a car only uses 10 to 15 percent of its installed horsepower performance (Cameron.K, 2014). Coupled with the size of the engines used, there is dramatic efficiency losses due many factors than need to be addressed to improve the internal combustion engines efficiency. The industries solution to these problems is engine downsizing, reducing losses associated with the larger engine sizes and help increase the efficiencies In relation to the Brake Specific Fuel Consumption (BSFC). The smaller engines reduce the losses through the bearings, piston ring friction and pumping losses (Cameron. K, 2014). This means compared to the larger capacity engines, there are less losses due to decreased overall surface areas.

Leading manufactures such as ford have utilised this technology and have set an example for one of the most successful downsized engines on the market. Fords Eco boost 1.0 litre engine is an example of such technologies. This 98-horsepower engine is capable of increasing the combined fuel economy by 6 percent according to (Matt Burt, 2016). Another example of a major part of the industry having success with downsized engine technology is MAHLE. This UK based company MAHLE powertrains has achieved a 50% downsizing from a 2.4L naturally aspirated to a 1.2L forced induction unit producing 120kw of peak power, all while maintaining a performance similar to the 2.4L engine. This means that the technology is effective in increasing the efficiency, while maintaining drivability through increasing volumetric flow. (Tran. H. et al, 2016).

Another major important factor that gives downsizing appeal to the industry is its ability to be able to deliver this technology without any major change to its manufacturing infrastructure, stated by (J.W.G Turner. Et al, 2015).

Although the downsizing of engines has many advantages when compared to their larger capacity counter parts. The main problem with a lower capacity engine is its drivability due to its lower volumetric flow rate. The higher the percentage of downsizing, the greater the need for increased volumetric flow to maintain the performance of the vehicle. This challenge is addressed using a forced induction system. Implementing this technology has allowed manufactures to achieve similar steady state performance to the larger capacity engines. Due to the engines smaller capacity there is less exhaust flow present to operate the turbo along the transient performance models. (Tran. H. et al, 2016) This phenomenon is known as turbo lag, a delay in the spooling of the turbine of the turbo charger due to reduced exhaust gas flow at lower engine speeds (Kazuhiro. N. et al, 2013).

A method for reducing this problematic transient performance would be to introduce an electric powered booster known as an "electric supercharger" (Tran. H. et al, 2016). This device when compared to a conventional supercharger is analogues as stated by (Michael. B. et al, 2016). This means that the device is powered by an electrical system, usually a 48-volt system rather than a 12 volt system, allowing it to operate independently of the exhaust gas flow. Meaning that the electric supercharger can have rapid transient response and provide steady state functionality, like the conventional turbocharger system. Using electrical control systems and clever packaging, this technology could provide the necessary volumetric flow rate for a downsized engine, while maintaining the increased efficiency the technology has to offer when compared to the larger capacity engines.

**Aims:**

- To evaluate and assess the efficiency of a Downsized engine in relation to the Brake Specific Fuel Consumption in an urban duty cycle, when compared to a larger capacity counterpart.
- To Evaluate and assess the volumetric flow of a Downsized engine in relation to its transient and steady state performance, when compared to a larger capacity naturally aspirated counterpart.

## **2.0: Literature Review:**

### **2.1- Volumetric flow:**

Volumetric flow can be defined as the mass of air flow, which is a measure of the effectiveness of the induction process. The industry uses Volumetric flow as an engines capability to intake a certain volume of air in a set time, this is the amount of air that can pass into a cylinder in a given time. The volumetric efficiency is defined as followed; it is desirable to maximise the volumetric flow and efficiency of an engine, due to the amount of fuel that can be burnt, and the power produced for a given displacement is maximised according to (Colin. R. Ferguson, 2014).

For a four-stroke engine the volumetric efficiency can be found using the formula as followed:

$$e_v = \frac{2(m_a + m_f)}{p_i V_d N}$$

- $m_f$  = Is the flow rate of the fuel inducted.  
(Colin. R. Ferguson, 2014).

### **2.2 Industry and its downsizing technologies:**

The industry has carried out millions of pounds worth of research and development on downsizing of their engine units, due to it being considered as an effective way of improving a vehicles powertrain efficiency (Oliver Lang, 2004). The definition of this technology is as a process where the operational load point of the engine is shifted to a higher, more efficient region utilising a reduction in swept volume of the unit (M. Bassett. Et al, 2016).

The analysis of the results by companies such as MAHLE have shown the degree of downsizing is defined as:

$$\text{Degree Of Downsizing} = \frac{SV_o - SV_{DS}}{SV_o}$$

(Bassett. Et al, 2016).

The term of which are also stated by (Bassett. Et al, 2016) where  $SV_o$  represents swept volume of the original engine and  $SV_{DS}$  represents the swept volume of the downsized engine.

The industry has developed the downsizing technology due to its key attributes in improving the efficiency of their internal combustion engines. Improvements such as overall reduction in CO2 and NO2 emissions due to decreased fuel consumption when compared to the larger engine units. (Chinmay Patil. Et al, 2017).

### 2.3 Forced induction systems:

Forced induction systems such as turbochargers and superchargers operate by introducing air (or air/ fuel mixture) known as a charge, into an engine's cylinder at a density greater than ambient. This allows a proportional increase in fuel that can be burnt hence raising the potential power output of an internal combustion engine, as defined by (N. Watson, 1986).

A Turbo charger is a specific method of supercharging. The energy of the hot exhaust gases that would usually be lost on a naturally aspirated engine are used to drive the compressor turbine of the turbocharger. This technology doesn't get something for nothing, but merely uses that energy that would usually be lost to compress the air above ambient pressure. The ideal available exhaust energy can be seen in 'figure 1' below. The energy consists of a 'blow down energy'. This energy is resulted from adiabatic expansion from condition 1 when the exhaust valve is opened, to ambient pressure at point 2. Points 3, 4, 5 and 6 display the work done by the piston within the cylinder in terms of displacing the remaining exhaust gases (N. Watson, 1986).

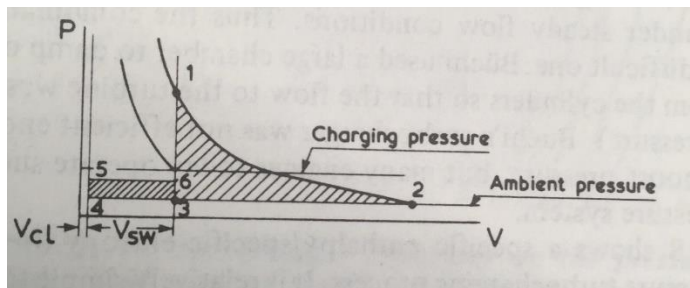


Figure 1: Work available from ideal exhaust process, (N. Watson, 1986).

A supercharger operates via a mechanical connection usually from the crankshaft. The principle is the same as the supercharger in the way it increases the pressure of the air above ambient pressure, which without the aid of a super charger would rely on the pumping action of the engine's pistons on intake stroke.

| Turbo charger Information                                                                                                            | Supercharger information                                                                                                                                        |
|--------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"><li>• Uses exhaust gas energy to operate the turbine which in turn spins the compressor.</li></ul> | <ul style="list-style-type: none"><li>• Uses crank-shaft for the energy to operate the compressor.</li></ul>                                                    |
| <ul style="list-style-type: none"><li>• The system is not directly connected to the engine.</li></ul>                                | <ul style="list-style-type: none"><li>• The system is mechanically connected to the engine.</li></ul>                                                           |
| <ul style="list-style-type: none"><li>• No parasitic drain to consider when calculating power increases.</li></ul>                   | <ul style="list-style-type: none"><li>• Due to the mechanical connection parasitic drain does have to be considered when calculating power increases.</li></ul> |

Table 1: Differences between a turbocharger and a supercharger, (Pro Car Mechanics, 2018).

#### **2.4- Available Alternative Forced Induction system:**

The companies MAHLE and Aeristech have pioneered a new development in the boosting of an internal combustion engine by hybridising the air intake systems, stated by (Aeristech, 2018).

Aeristech have been developing a compact and cost effective electric machine, for variable high-speed applications, for the past six years (Bassett, et al, 2016).



*Figure 2: e-supercharger development and packaging, (Aeristech, 2018).*

A conventional forced induction system such as a turbocharger or supercharger discussed in section '3.3' has inherent efficiency losses. This is due to the systems being measured by the amount of airflow the device creates after factoring out the power requirement to drive it, and the extent to which it heats up the air while creating the flow and pressure (Corky Bell, 1997). The power losses inherent with a turbocharger are much less than that of a supercharger. But the supercharger is driven by a belt which decreases its efficiency. The downside to both means it either comprises between turbo-lag and higher heat losses, or transient power gains but increased mechanical losses through a pulley system.

With these efficiency losses in mind, this is where the E-supercharger technology comes into its own. The E-supercharger can accelerate from an idle speed of  $30,000 \text{ mins}^{-1}$  to its maximum of  $120,000 \text{ mins}^{-1}$  in under 0.5 seconds. This allows it to address the low-speed turbo lag of a downsized engine (Bassett, et al, 2016). This technology also eliminates the belt driven system of a conventional supercharger, which requires brake horse power to run when the boosted pressure is needed to increase the volumetric flow due to it being powered by an electric motor (Aeristech, 2018).



*Figure 3: E-supercharger example (Aeristech, 2018).*

An electronic supercharger implemented in the industries downsizing of the internal combustion engine can introduce a net reduction in unit costs and the complexity of a forced induction system in the boosting of a heavily downsized engine. Adapted from (Bassett, et al, 2016).

## 2.5 Proposed vehicle:



Figure 4: Suzuki Swift Sport, (Daniel, Salathiel, 2018).

| <u>Specification:</u>        | <u>Information:</u> |
|------------------------------|---------------------|
| Capacity (Cubic Centimetres) | 1586 cc             |
| Bore x Stroke (mm)           | 78 x 83             |
| N/a efficiency %             | 78% (0.78)          |
| Maximum Rpm                  | 7000                |

Table 2: Suzuki Swift Sport specification, (En.wikipedia.com, 2018).

## **2.6- Brake Specific Fuel Consumption efficiency:**

Brake Specific Fuel Consumption (BSFC) is a measured perimeter that displays the efficiency of a combustion engine that burns fuel and produces rotational power at the crank shaft. The automotive industry uses BSFC mapping to evaluate the efficiency of the internal combustion engine.

The word 'brake' is related to the use of a dynamometer to measure the engines parameters such as fuel mass, flow rate, engine power and torque.

An internal combustion engine requires fuel and air to create energy. The amount of fuel used is a measure of an internal combustion engines efficiency. This is usually measured using a dynamometer, giving a measurement of the mass flow of fuel given in kg/Hour, kg/Minute or kg/second. This on its own isn't enough to analyse the efficiency of an engine because it doesn't take into consideration the amount of power produced from a specific quantity of fuel. The efficiency is obtained by dividing the fuel mass flow Kg/s by the engine output power (W). This equation can be seen in the equation below. (Extract Adapted from X-Engineer, 2019).

$$BSFC = \frac{m_f}{P_e}$$

$m_f$  – Kg/s

$P_e$  – Effective Power (W)

$BSFC$  – Kg/j

Power is usually measured in Kw, so BSFC can be displayed in g/Kw.h.

(X-Engineer, 2019).

### **2.7- Coast Down Testing:**

A coast down test is one the most frequently used tests utilised by the automotive and motorsport industry. The test consists in where the vehicle maintains a certain speed and then carries out the rest of the journey ungeared, simultaneously recording the speed, time and distance travelled until the vehicle reaches a complete stop. This process is carried out to obtain information about the general condition of the vehicle and the resistive forces interacting with the vehicle from its surrounding environment. (Ion Preda. et al, 2010).

The main aim of this test is to evaluate the resistant forces acting on the vehicle at a specific speed along its journey to allow the efficiency of a vehicle to be evaluated in regards to its fuel consumption, pollution and other variables. It is also used to establish the vehicles condition and resistive values of the drive train and various other components that control its motion. The requirements to perform a coast down test are standardised by the industry. The values of the coasting distance can then be compared to the values corresponding to similar or closely related types of vehicles. (Ion Preda. et al, 2010).

## **2.8 Volumetric flow formulas:**

In this case the investigation will look at a chosen donor car, for this donor car a Suzuki swift sport with a 1600cc engine will be used. From the specification of the donor cars engine, the volumetric flow can be calculated, which can then be compared to a four-cylinder 800cc engine.

The following formula can be used to calculate the volumetric flow of an engine. When  $v$  is given as volume of the cylinder,  $n$  is the naturally aspirated efficiency of the engine,  $N$  is denoted as the engine speed in Revolutions per minute.

$$V = \frac{v \times n \times N}{2 \times 60}$$

Please reference section '2.1' for the efficiency equation (Colin. R. Ferguson, 2014).

## **Cylinder volume formula:**

$$V_c = \text{Cylinder Area} \times \text{Stroke Length}$$

*Figure 5: Volume of chamber formula (Thecartech, 2018).*

## **2.9 Forced induction formula:**

The main thing to consider when calculating the increase in volumetric flow from a forced induction system on an engine is the Pressure ration when boosted. The pressure ratio is calculated using the absolute compressor output pressure in PSI, added to gauge pressure of 14.7 PSI, divided by the inlet pressure which is ambient equalling 14.7 PSI. This is the same as the gauge pressure, as a gauge factors into the ambient pressure as well as the pressure reading.

$$PR = \frac{\text{Compressor outlet required PSI} + 14.7 \text{ PSI}}{\text{Inlet Pressure at 14.7 PSI}}$$

*Equation 1: Pressure Ratio Equation, (Takemebeyondthehorizon.com, 2018)*

Once the pressure ratio is calculated for the forced induction system, this can be simply times by the volumetric flow calculated for the naturally aspirated engine you wish to apply the boost to.

### **3.0- Methodology Theoretical Calculations:**

To achieve a comparison between the current 1600cc M16a engine and its down sized equivalent, theoretical calculations can be carried out to calculate the volumetric flow of both engines naturally aspirated, to compare the performance losses. With these figures calculated theoretical calculations can be carried out to calculate the volumetric flow of the downsized engine when a forced induction system is introduced. These results will be analysed within the analysis section of this report to give an understanding of the requirements and demands needed to achieve the same performance in relation to transient flow as the higher capacity engine, while maintaining the efficiency advantages of the downsized engine.

#### **3.1 Suzuki Swift 1600cc Engine M16a Calculations:**

|                                           |                      |
|-------------------------------------------|----------------------|
| <b>Bore</b>                               | <b>78mm - 0.078m</b> |
| <b>Stroke</b>                             | <b>83mm – 0.083m</b> |
| <b>N/a Efficiency (<math>\eta</math>)</b> | <b>0.78</b>          |
| <b>Maximum Engine Speed (Rpm)</b>         | <b>7000</b>          |

*Table 3: M16a Suzuki Engine Specification (Parkers.co.uk, 2018) and (En.wikipedia.org, 2018).*

### **3.1.1- Volumetric Flow Equation:**

$$V = \frac{v \times \eta \times N}{2 \times 60}$$

*Equation 2: Volumetric Flow Equation, (C. R. Ferguson, et al. 2019).*

V- Volumetric Flow.

v- Volume of cylinder.

$\eta$ - Efficiency Of the engine.

N- Engine Speed (Rpm).

### **3.1.2- Calculations to achieve Volume of cylinder:**

$$v = \pi r^2 \times h$$

*Equation 3: Volume Equation, (C. R. Ferguson, et al. 2019).*

Where  $h$  is denoted as the stroke of the engine.

$$v = \pi \times 0.078^2 \times 0.083$$

$$v = 1.57 \times 10^{-4}$$

*Equation 4: M16a cylinder volume Calculations, (Daniel Salathiel, 2019).*

The volume above is the calculated volume for one cylinder. To achieve the total volume for the engine the volume above needs to be multiplied by the number of cylinders. In the case of the M16a, four cylinders.

$$v_t = 1.57 \times 10^{-4} \times 4$$

$$v_t = 6.28 \times 10^{-4}$$

*Equation 5: M16a total four-cylinder volume Calculations, (Daniel Salathiel, 2019).*

### **3.1.3- Calculating the Volumetric Flow for the 1600cc M16a naturally aspirated Engine:**

The volume from section 3.1.2 can now be placed into the equation shown in section 3.1. This will give the volumetric flow for the M16a 1600cc naturally aspirated engine from the donor car.

The calculations are as followed:

$$V = \frac{v \times \eta \times N}{2 \times 60}$$

$$V = \frac{6.28 \times 10^{-3} \times 0.78 \times 7000}{2 \times 60}$$

$$V = 0.286 \text{ m}^3/\text{s}$$

*Equation 6: M16a Volumetric Flow Calculations, (Daniel Salathiel, 2019).*

### **3.2 Calculating the Volumetric flow of the downsized 800cc engine:**

|                                           |                       |
|-------------------------------------------|-----------------------|
| <b>Bore</b>                               | <b>61mm - 0.0615m</b> |
| <b>Stroke</b>                             | <b>68mm – 0.0680m</b> |
| <b>N/a Efficiency (<math>\eta</math>)</b> | <b>0.78</b>           |
| <b>Maximum Engine Speed (Rpm)</b>         | <b>7000</b>           |

*Table 4: 800cc Specification (Parkers.co.uk, 2018) and (En.wikipedia.org, 2018).*

#### **3.2.1 Volumetric Flow Equation:**

$$V = \frac{v \times \eta \times N}{2 \times 60}$$

*Equation 7: Volumetric Flow Equation, (..., 2019).*

V- Volumetric Flow.

v- Volume of cylinder.

$\eta$ - Efficiency of the engine.

N- Engine Speed (Rpm).

#### **3.2.2- Calculations to achieve Volume of cylinder:**

$$v = \pi r^2 \times h$$

*Equation 8: Volume Equation, (C. R. Ferguson, et al. 2019).*

Where  $h$  is denoted as the stroke of the engine.

$$v = \pi \times 0.0615^2 \times 0.0680$$

$$v = 8.08 \times 10^{-4}$$

*Equation 9: 800cc cylinder volume Calculations, (Daniel Salathiel, 2019).*

The volume above is the calculated volume for one cylinder. To achieve the total volume for the engine the volume above needs to be multiplied by the number of cylinders. In the case of the downsized engine, four cylinders.

$$v_t = 8.08 \times 10^{-4} \times 4$$

$$v_t = 3.232 \times 10^{-3}$$

*Equation 10: 800cc total four-cylinder volume Calculations, (Daniel Salathiel, 2019).*

### **3.2.3- Calculating the Volumetric Flow for the 800cc downsized naturally aspirated Engine:**

The volume from section 3.2.2 can now be placed into the equation shown in section 3.2. This will give the volumetric flow for the 800cc naturally aspirated engine to replace the larger capacity 1600cc engine in the donor car.

The calculations are as followed:

$$V = \frac{v \times \eta \times N}{2 \times 60}$$

$$V = \frac{3.232 \times 10^{-3} \times 0.78 \times 7000}{2 \times 60}$$

$$V = 0.147 \text{ m}^3/\text{s}$$

*Equation 11: Volumetric flow calculation workings for the 800cc N/a, (Daniel Salathiel, 2019).*

### **3.3 Forced Induction System Calculations for the Downsized 800cc Engine:**

#### **3.3.1 Volumetric Flow Equation for a Forced Induction System:**

$$V = PR \times \frac{v \times \eta \times N}{2 \times 60}$$

*Equation 12: Forced Induction Volumetric Flow Equation, (N. Watson, et al. 2019).*

PR- Pressure Ratio

V- Volumetric Flow.

v- Volume of cylinder.

$\eta$ - Efficiency Of the engine.

N- Engine Speed (Rpm).

#### **3.3.2 Calculating Pressure Ratio**

For the engine to perform at a similar output as the higher 1600cc capacity, the pressure produced by the forced induction system needs to match that of the capacity of the cylinders. This equates to 2 bar of pressure, 29 PSI of boost pressure.

$$PR = \frac{29 + 14.7}{14.7}$$

$$PR = 2.97$$

*Equation 13: Pressure Ratio for Forced Induction System, (Daniel Salathiel, 2019).*

The following pressure ratio can be multiplied by the volumetric flow of the 800cc engine in its N/a state. The following Equation shows this process.

$$= 2.97 \times 0.147$$

$$= 0.437 \text{ m}^3/\text{s}$$

*Equation 14: Volumetric Flow Calculation for Forced Induction System, (Daniel Salathiel, 2019).*

### **3.4 Forced Induction System Temperature and efficiency Calculations for Downsized system:**

The following calculated temperatures assume no heat losses

#### **3.4.1 Compressor Outlet gas temperature:**

$$T_{out} = PR^{0.28} \times T_{in}$$

*Equation 15: Compressor Outlet Temperature Equation (K), (N. Watson, et al. 2019).*

$T_{out}$ - Compressor Outlet Temperature (K).

$PR$ - Pressure Ratio.

$T_{in}$ - Compressor Inlet Temperature (K).

And assuming the average temperature in the United Kingdom is 280.15 Kelvin, the following calculations can be made:

$$T_{out} = 2.97^{0.28} \times 280.15$$

$$T_{out} = 379.98 K$$

#### **3.5 Compressor Outlet Efficiency Calculations:**

The efficiency of the compressor being used for the forced induction system can be calculated using the following equation.

$$C\eta = \frac{(PR^{0.28} \times T_{in}) - T_{in}}{\text{Actual Temp Rise}}$$

*Equation 16: Compressor Efficiency Equation, (N. Watson, et al. 2019).*

$C\eta$ - Compressor Efficiency.

$PR$ - Pressure Ratio

$T_{in}$ - Temperature into Compressor (K)

##### **3.5.1 Calculating Temperature Rise:**

$$\text{Actual Temperature Rise} = \text{Outlet Temperature} - \Delta \text{Temperature}$$

$$\text{Actual Temperature Rise} = 379.98 k - 280.15 k$$

$$\text{Actual Temperature Rise} = 99.83 K$$

(Daniel Salathiel, 2019).

### **3.5.2 Calculating Actual Temperature rise using Compressor Efficiency:**

$$\text{Actual Temp Rise} = \frac{(PR^{0.28} \times T_{in}) - T_{in}}{C \eta}$$

$$\text{Actual Temp Rise} = \frac{(2.97^{0.28} \times 280.15) - 280.15}{0.78}$$

$$\text{Actual Temp Rise} = 127.98$$

The actual temperature rise equals 408.13 Kelvin

### **3.6- Conditioning of charge**

Before the charge can enter the engine, it has to be conditioned to reduce heat soak caused from the increase in temperature from the air passing through the compressor. The efficiency of a chosen intercooler of 78% can be used to calculate the inlet temperatures for the engine.

$$\text{Inter cooler } T_{out} = \eta \times \text{Compressor } T_{out}$$

*Equation 17: Intercooler outlet temperature Equation, (...,2019).*

Where,  $\eta$  is the thermal efficiency of the intercooler. The following Equation is derived:

$$\text{Inter cooler } T_{out} = 0.78 \times 379.98$$

$$\text{Inter cooler } T_{out} = 296.38 \text{ K}$$

Using the Actual Temperature rise:

$$\text{Inter cooler } T_{out} = 0.78 \times 408.13$$

$$\text{Inter cooler } T_{out} = 318.34 \text{ K}$$

These calculations can be used to design and package a suitable Intercooler system for the forced induction of the 800cc downsized engine.

### 3.7 Calculating Engine Speed from Duty Cycle Data:

| <b>Gear</b>           | <b>1600cc Ratio</b> | <b>800cc Ratio</b> |
|-----------------------|---------------------|--------------------|
| <b>1<sup>st</sup></b> | 3.25                | 4.98               |
| <b>2<sup>nd</sup></b> | 1.904               | 2.110              |
| <b>3<sup>rd</sup></b> | 1.407               | 1.780              |
| <b>4<sup>th</sup></b> | 1.064               | 1.310              |
| <b>5<sup>th</sup></b> | 0.855               | 1.150              |
| <b>Final Drive</b>    | 4.338               | 4.338              |

Figure 6: Gear Ratio Table, (CTC-Performance.com, 2019).

$$\text{Engine Speed RPM} = \frac{v \times G_r \times 336}{R_t}$$

Equation 18: Engine speed equation for Rpm using road speed and gear ratio, (Legacypic.uk/engineering, 2019) (Motortrend, 2017).

$v$ - Velocity (Mph)

$G_r$ - Gear Ratio

$R_t$ - Radius of Tyre (Inches)

#### **4.0 Methodology For data collection:**

The methodology for this project utilises techniques in the form of live data collection using a DL1 logger, the data collected will be processed using Race-technologies software. Further evaluation of the collected data will be carried out in an excel spreadsheet. From the processing of this data in the spreadsheet, a duty cycle for the route can be made to assist in the evaluation of the efficiency alongside a coast down test.



*Figure 7: DL1 Data logger, (Race-technologies.com, 2018).*

Alongside the data collection an excel spread sheet can be created to collate the data and help further analyse the data using various formula and look up functions that will be discussed.

These methods will evaluate the downsizing of an internal combustion engine and how it effects the efficiency, but also in reference to the improvement of volumetric flow and Brake Specific Fuel Consumption of the downsized engine to improve or match that of the high capacity original engine. Once the calculations for both the engines have been carried out, they can be used to determine the naturally aspirated volumetric flow of the higher capacity engine and the lower capacity engine. These formulas can be found in the sections below and will be used to look at the transient and steady state performance.

From the data and information gathered, a further evaluation of an electrified forced induction can be carried out. Evaluation of the Brake specific fuel consumption of the current larger capacity engine, which will allow for analysis when compared to the downsized equivalent suggested.

#### **4.1 DL1 Data duty cycle data collection Methodology:**

The DL1 data logger was selected to collect data for the duty cycle due to its adaptability in terms of using a built-in accelerometer and accurate GPS to track the route taken and gather the relevant data to carry out a duty cycle evaluation. This meant that there was no modification to the donor car required to collect the data streams required, saving time and cost.

For the duty cycle, a route was selected based on the geographical features it presented. These included low and high-speed sections, roundabouts, traffic, traffic lights and the typical features associated with urban driving. These features provide real life accuracy to the testing, allowing for a true reflection in urban driving in the data. The route selected can be seen in the figures below.



Figure 8: Race Technologies Duty Cycle Route plot from DL1 Data logger, (Racetechnologies, 2019).

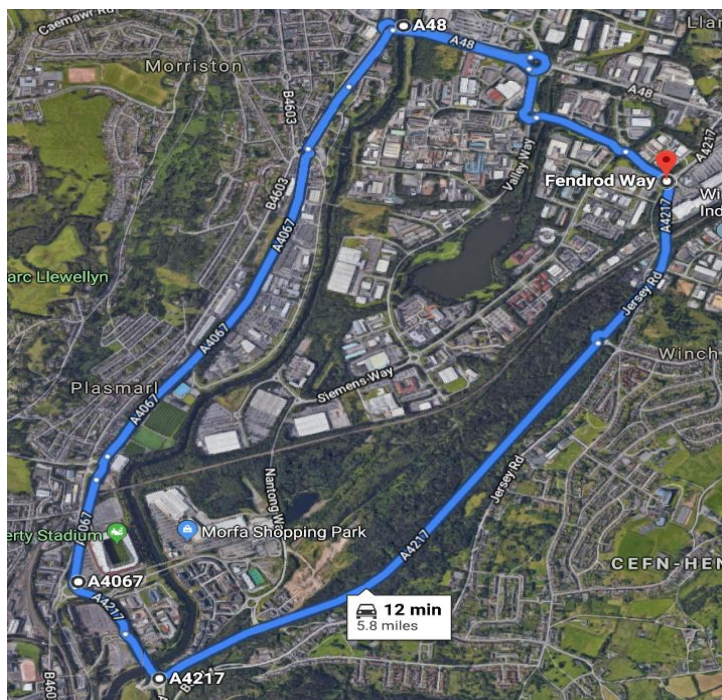


Figure 9: Satellite view of Duty Cycle route showing features, (Googlemaps.com, 2019).

#### **4.2- Coast Down Excel Spread Sheet Methodology:**

To establish results for the cars total resistive forces, a straight-line coast down test can be utilised. The test consists of the driver, driving up to the start line of the straight and proceeding to come to a complete stop. The driver is to then accelerate up to the maximum speed of 70 Miles per hour. The driver is to then hold the max speed for a minimum of 5 seconds to allow for the vehicle to settle.

The next step is critical to allow for the resistive forces acting upon the car to be calculated. The driver should put the vehicle into neutral, and When carrying out the coast down. To keep accuracy at its highest; keep steering inputs to a minimum and their foot away from Accelerator pedal and the brake pedal. If safety is compromised correct the car accordingly and reset the test if there is enough space left to do so.

The data from each run should be named and saved in a suitable location for future analysis. The route plot can be seen in the figure below.

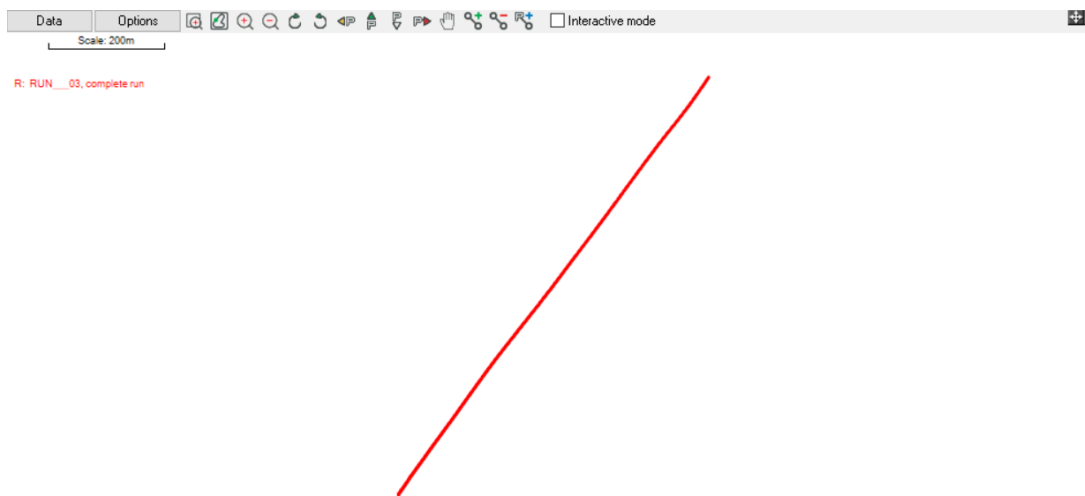


*Figure 10: Coast Down Racetechnologies GPS plot, (Daniel Salathiel, 2019).*

### 4.3 Excel Spreadsheet Formula for data processing for both collection processes:

#### 4.3.1- Aerodynamic Force (N) Formula:

A vehicle travelling at a particular speed in air encounters a resistive Force resisting its motion known as Aerodynamic Drag. It results from two main components; shape drag and skin friction. Skin friction results from when the air moves close to the skin of the vehicle, moving at the same velocity. The air moving further away from the body remains still. The difference in the velocity of the air molecules results in friction, thus results in the second component of aerodynamic Drag. Adapted from (M.Ehsani, 2012).

$$\text{Aerodynamic Force (N)} = A_f \times \rho \times Cd \times v^2$$

Equation 19 : Aerodynamic Force (N) Equation, (M.Ehsani, 2012).

$A_f$  – Frontal area ( $m^2$ )

$\rho$  - Density of Fluid

$Cd$  – Coefficient of Drag (N)

$V$  – Velocity (m/s)

The following Figure shows the Formula as it can be found in the spread sheet:

|         |          |             |                |                              |                            |                              |                        |                            |   |            |   |   |                       |                              |         |  |  |  |  |  |  |  |  |  |  |  |  |
|---------|----------|-------------|----------------|------------------------------|----------------------------|------------------------------|------------------------|----------------------------|---|------------|---|---|-----------------------|------------------------------|---------|--|--|--|--|--|--|--|--|--|--|--|--|
| VLOOKUP |          |             |                |                              |                            |                              |                        |                            |   |            |   |   |                       | =0.5*1.293*0.5*\$L\$3*(C2^2) |         |  |  |  |  |  |  |  |  |  |  |  |  |
|         | A        | B           | C              | D                            |                            | E                            | F                      | G                          | H |            | I | J | K                     | L                            | M       |  |  |  |  |  |  |  |  |  |  |  |  |
| 1       | Time [s] | Speed (MPH) | Velocity (m/s) | Change in Acceleration (m/s) | Change in Acceleration (N) | Aero Force (N)               | Rolling Resistance (N) | Total Resistive Forces (N) |   | Power (Kw) |   |   |                       |                              |         |  |  |  |  |  |  |  |  |  |  |  |  |
| 2       | 0        | 63.83       | 28.53          | 0.00                         | 0.00                       | =0.5*1.293*0.5*\$L\$3*(C2^2) |                        | 1209.17                    |   |            |   |   | Weight (Kg)           | 1105                         |         |  |  |  |  |  |  |  |  |  |  |  |  |
| 3       | 1        | 61.85       | 27.65          | -0.89                        | -978.92                    | 626.39                       | 542.00                 | 189.47                     |   |            |   |   | Frontal Area (m^2)    | 2.54                         |         |  |  |  |  |  |  |  |  |  |  |  |  |
| 4       | 2        | 60.62       | 27.10          | -0.55                        | -609.24                    | 601.65                       | 542.00                 | 534.41                     |   |            |   |   | Av. Incline (Degrees) |                              |         |  |  |  |  |  |  |  |  |  |  |  |  |
| 5       | 3        | 60.44       | 27.02          | -0.08                        | -86.70                     | 598.17                       | 542.00                 | 1053.48                    |   |            |   |   | Av. Decline (Degrees) |                              |         |  |  |  |  |  |  |  |  |  |  |  |  |
| 6       | 4        | 59.46       | 26.58          | -0.44                        | -483.70                    | 578.95                       | 542.00                 | 637.25                     |   |            |   |   | Av. Incline (Radians) |                              |         |  |  |  |  |  |  |  |  |  |  |  |  |
| 7       | 5        | 58.80       | 26.29          | -0.29                        | -325.32                    | 566.19                       | 542.00                 | 782.88                     |   |            |   |   | Av. Decline (Radians) |                              |         |  |  |  |  |  |  |  |  |  |  |  |  |
| 8       | 6        | 57.60       | 25.75          | -0.54                        | -593.84                    | 543.28                       | 542.00                 | 491.44                     |   |            |   |   |                       |                              |         |  |  |  |  |  |  |  |  |  |  |  |  |
| 9       | 7        | 56.68       | 25.34          | -0.41                        | -454.29                    | 526.07                       | 542.00                 | 613.78                     |   |            |   |   | Road Resistance       | 0.05                         | Macadam |  |  |  |  |  |  |  |  |  |  |  |  |
| 10      | 8        | 55.67       | 24.89          | -0.45                        | -498.19                    | 507.51                       | 542.00                 | 551.32                     |   |            |   |   |                       |                              |         |  |  |  |  |  |  |  |  |  |  |  |  |
| 11      | 9        | 55.33       | 24.73          | -0.15                        | -170.27                    | 501.25                       | 542.00                 | 872.98                     |   |            |   |   | Gravity (N/Kg)        | 9.81                         |         |  |  |  |  |  |  |  |  |  |  |  |  |
| 12      | 10       | 54.25       | 24.25          | -0.48                        | -529.44                    | 482.01                       | 542.00                 | 494.58                     |   |            |   |   |                       |                              |         |  |  |  |  |  |  |  |  |  |  |  |  |

Figure 11: Aerodynamic Force (N) Working formula example, (Daniel Salathiel, 2019).

Figure 11 above shows the Excel Spreadsheet requirements to utilise equation '18' to calculate the Aerodynamic Force acting upon the car during the two test stages. The formula shows the researched figures for coefficients for both drag and the density of air, multiplied by the frontal area shown in the blue box 'L3', and the velocity squared shown by the red box 'C2'. The dollar symbols are used to prevent the blue box from moving off the required weight when the formula is dragged down the column to calculate the aerodynamic drag for the entire testing session.

#### 4.3.2- Change in Acceleration (m/s):

The change in acceleration is required to calculate the change in acceleration force (N) in the Excel spread sheet. The following formula can be used to calculate the change in acceleration.

$$\text{Change in Acceleration (m/s)} = V_n - V_o$$

Equation 20: Change in Acceleration Formula, (Daniel Salathiel, 2019).

$V_n$  - New Velocity (m/s)

$V_o$  – Original Velocity (m/s)

The excel formula for the change in velocity can be seen in the figure below:

|   | A        | B           | C              | D                            |
|---|----------|-------------|----------------|------------------------------|
| 1 | Time [s] | Speed (MPH) | Velocity (m/s) | Change in Acceleration (m/s) |
| 2 | 0        | 63.83       | 28.53          |                              |
| 3 | 1        | 61.85       | 27.65          | =C3-C2                       |
| 4 | 2        | 60.62       | 27.10          | -0.55                        |

Figure 12: Change in Velocity Excel Spreadsheet Formula, (Daniel Salathiel, 2019).

The figure above shows the formula used in the Excel Spreadsheet to calculate the change in acceleration shown in equation 2. The formula uses the new speed shown in the blue box 'C3', and subtracts the original speed shown in the red box 'C2'. The resulting equation allowed the change in acceleration to be calculated for all the speeds in the two excel spread sheets to enable the spread sheet to calculate the change in Acceleration force in the next section of the report.

#### 4.3.3- Change in Acceleration Force (N) Formula:

The vehicles acceleration force comes from Newtons second law. Newtons second law states that the velocity of an object changes when it is subject to an external force. The law defines Force to be equal to the change in momentum (mass times velocity) per change in time. The following equation can be used. As stated by (Grc.nasa.gov, 2015).

$$F = m. a$$

Equation 21: Newtons second law (Grc.nasa.gov, 2015)

|                                          |          |             |                |                              |                            |                |                        |                            |            |   |                       |      |         |
|------------------------------------------|----------|-------------|----------------|------------------------------|----------------------------|----------------|------------------------|----------------------------|------------|---|-----------------------|------|---------|
| VLOOKUP    ✕    ✓    fx    = \$L\$2*--D3 |          |             |                |                              |                            |                |                        |                            |            |   |                       |      |         |
|                                          | A        | B           | C              | D                            | E                          | F              | G                      | H                          | I          | J | K                     | L    | M       |
| 1                                        | Time [s] | Speed (MPH) | Velocity (m/s) | Change in Acceleration (m/s) | Change in Acceleration (N) | Aero Force (N) | Rolling Resistance (N) | Total Resistive Forces (N) | Power (Kw) |   |                       |      |         |
| 2                                        | 0        | 63.83       | 28.53          | 0.00                         |                            | 667.17         | 542.00                 | 1209.17                    |            |   | Weight (Kg)           | 1105 |         |
| 3                                        | 1        | 61.85       | 27.65          | -0.89                        | = \$L\$2*--D3              | 626.39         | 542.00                 | 189.47                     |            |   | Frontal Area (m^2)    | 2.54 |         |
| 4                                        | 2        | 60.62       | 27.10          | -0.55                        | -609.24                    | 601.65         | 542.00                 | 534.41                     |            |   | Av. Incline (Degrees) |      |         |
| 5                                        | 3        | 60.44       | 27.02          | -0.08                        | -86.70                     | 598.17         | 542.00                 | 1053.48                    |            |   | Av. Decline (Degrees) |      |         |
| 6                                        | 4        | 59.46       | 26.58          | -0.44                        | -483.70                    | 578.95         | 542.00                 | 637.25                     |            |   | Av. Incline (Radians) |      |         |
| 7                                        | 5        | 58.80       | 26.29          | -0.29                        | -325.32                    | 566.19         | 542.00                 | 782.88                     |            |   | Av. Decline (Radians) |      |         |
| 8                                        | 6        | 57.60       | 25.75          | -0.54                        | -593.84                    | 543.28         | 542.00                 | 491.44                     |            |   |                       |      |         |
| 9                                        | 7        | 56.68       | 25.34          | -0.41                        | -454.29                    | 526.07         | 542.00                 | 613.78                     |            |   | Road Resistance       | 0.05 | Macadam |
| 10                                       | 8        | 55.67       | 24.89          | -0.45                        | -498.19                    | 507.51         | 542.00                 | 551.32                     |            |   |                       |      |         |
| 11                                       | 9        | 55.33       | 24.73          | -0.15                        | -170.27                    | 501.25         | 542.00                 | 872.98                     |            |   | Gravity (N/Kg)        | 9.81 |         |
| 12                                       | 10       | 54.25       | 24.25          | -0.48                        | -529.44                    | 482.01         | 542.00                 | 494.58                     |            |   |                       |      |         |

Equation 22: Acceleration Force (N) Excel Spreadsheet Formula, (Daniel Salathiel, 2019).

For the equation to produce the intended force results, the change in acceleration value was multiplied by a negative figure to achieve a positive force (N).

#### 4.3.4- Rolling Resistance Force (N) Formula:

Rolling resistance on a vehicles tyres is caused by hysteresis in the material itself. The pressure force is the area in contact between the tyre and the ground, and is symmetrically distributed through the centre line. Due to hysteresis in the deformation of the rubber material, the load at the loading point is larger than the unloading. To keep the wheel rolling, a force 'F' acting on the centre of the wheel is required to balance this rolling resistance moment. The force is expressed as followed by (M.Ehsani, 2012):

$$F = \frac{T_r}{r_d} = \frac{P_a}{r_d} = P f_r$$

Equation 23: Pressure Distrobution Equation, (M.Ehsani, 2012).

$$F = M \times g \times \mu_r$$

Equation 24: Rolling Resistance Force Equation, (Science Learning Hub, 2019).

$F$ - Rolling Resistance (N)

$M$ - Mass (Kg)

$g$ - gravity (N/kg)

$\mu_r$ - Coefficient of rolling resistance ( $\mu$ )

| VLOOKUP    X    ✓    f <sub>x</sub> =\$L\$2*\$L\$11*\$L\$9 |          |             |                |                              |                            |                |                        |                            |            |   |                       |      |         |
|------------------------------------------------------------|----------|-------------|----------------|------------------------------|----------------------------|----------------|------------------------|----------------------------|------------|---|-----------------------|------|---------|
|                                                            | A        | B           | C              | D                            | E                          | F              | G                      | H                          | I          | J | K                     | L    | M       |
| 1                                                          | Time [s] | Speed (MPH) | Velocity (m/s) | Change in Acceleration (m/s) | Change in Acceleration (N) | Aero Force (N) | Rolling Resistance (N) | Total Resistive Forces (N) | Power (Kw) |   |                       |      |         |
| 2                                                          | 0        | 63.83       | 28.53          | 0.00                         | 0.00                       | 667.17         | =S\$2*\$S\$11*\$S\$9   | 1209.17                    |            |   | Weight (Kg)           | 1105 |         |
| 3                                                          | 1        | 61.85       | 27.65          | -0.89                        | -978.92                    | 626.39         | 542.00                 | 189.47                     |            |   | Frontal Area (m^2)    | 2.54 |         |
| 4                                                          | 2        | 60.62       | 27.10          | -0.55                        | -609.24                    | 601.65         | 542.00                 | 534.41                     |            |   | Av. Incline (Degrees) |      |         |
| 5                                                          | 3        | 60.44       | 27.02          | -0.08                        | -86.70                     | 598.17         | 542.00                 | 1053.48                    |            |   | Av. Decline (Degrees) |      |         |
| 6                                                          | 4        | 59.46       | 26.58          | -0.44                        | -483.70                    | 578.95         | 542.00                 | 637.25                     |            |   | Av. Incline (Radians) |      |         |
| 7                                                          | 5        | 58.80       | 26.29          | -0.29                        | -325.32                    | 566.19         | 542.00                 | 782.88                     |            |   | Av. Decline (Radians) |      |         |
| 8                                                          | 6        | 57.60       | 25.75          | -0.54                        | -593.84                    | 543.28         | 542.00                 | 491.44                     |            |   |                       |      |         |
| 9                                                          | 7        | 56.68       | 25.34          | -0.41                        | -454.29                    | 526.07         | 542.00                 | 613.78                     |            |   | Road Resistance       | 0.05 | Macadam |
| 10                                                         | 8        | 55.67       | 24.89          | -0.45                        | -498.19                    | 507.51         | 542.00                 | 551.32                     |            |   |                       |      |         |
| 11                                                         | 9        | 55.33       | 24.73          | -0.15                        | -170.27                    | 501.25         | 542.00                 | 872.98                     |            |   | Gravity (N/Kg)        | 9.81 |         |
| 12                                                         | 10       | 54.25       | 24.25          | -0.48                        | -529.44                    | 482.01         | 542.00                 | 494.58                     |            |   |                       |      |         |

Equation 25: Excel Spreadsheet Rolling Resistance Formula Screenshot, (Daniel Salathiel, 2019).

The figure shows the formula required in the two Excel Spreadsheets for the calculation of the Rolling Resistance (N) at a given speed. The formula uses an adaptation of equation 23 to include the mass of the vehicle shown by the blue box 'L2', the gravity force in Red found in 'L11' and the coefficient of rolling resistance for Macadam Tarmac in purple box 'L9'. For each of these values the dollar signs were used to prevent the boxes from moving position when the formula in the Rolling Resistance column was dragged down to give the figure for each speed of the test session.



#### 4.5- Duty Cycle Brake Specific Fuel Consumption Map:

A suitable Brake Specific Fuel Consumption Map was sourced from a credible source (Ford, 2012). The research BSFC map matches the specification of the 1600cc M16a engine regarding the capacity, engine speed range and the power figure. This meant that the Brake Specific Fuel Consumption Map could be adapted to reflect the performance and efficiency of the donor cars existing higher capacity engine.

|    | A  | B      | C      | D      | E      | F      | G     | H      | I      | J     | K      | L      | M      | N      | O     | P      | Q      | R |
|----|----|--------|--------|--------|--------|--------|-------|--------|--------|-------|--------|--------|--------|--------|-------|--------|--------|---|
| 1  |    | 800    | 1000   | 1250   | 1500   | 1750   | 2000  | 2250   | 2500   | 3000  | 3500   | 4000   | 4500   | 5000   | 5500  | 6000   | 6500   |   |
| 2  | Kw |        | 287.6  | 285.7  | 286.3  | 277.3  | 273.5 | 274    | 272.9  | 284.5 | 278.4  | 273.2  | 271.1  | 294.5  | 294.5 | 300    | 292.5  |   |
| 3  | 93 |        |        |        |        |        | 273.7 | 274.8  | 271.9  | 282.5 | 269.3  |        |        |        |       |        |        |   |
| 4  | 89 |        |        |        |        |        | 270.5 | 268.8  | 268.6  | 283.9 | 266.5  |        |        |        |       |        |        |   |
| 5  | 85 |        |        |        |        | 276.2  | 266.7 | 265.2  | 265.7  | 269.8 | 270.1  | 273.2  |        |        |       |        |        |   |
| 6  | 81 |        |        |        | 285.5  | 281.6  | 263.9 | 263    | 263    | 273.7 | 265.6  | 267.3  |        |        |       |        |        |   |
| 7  | 77 |        |        |        | 282.1  | 275.6  | 260.9 | 259.1  | 259.8  | 259.6 | 256.7  | 260.7  | 262.8  | 282.5  |       |        |        |   |
| 8  | 73 |        |        |        | 277.5  | 271.2  | 259.7 | 258    | 259.6  | 254.3 | 254.5  | 256.7  | 256.8  | 267.1  | 283.2 |        |        |   |
| 9  | 69 |        |        | 284.6  | 275.6  | 266.6  | 258.8 | 256.3  | 257.5  | 250.5 | 251.9  | 254.7  | 252.2  | 257.9  | 268.4 | 290.8  |        |   |
| 10 | 65 |        |        | 278.2  | 266.7  | 258.4  | 255.4 | 252.3  | 251.2  | 246   | 249.4  | 253.8  | 251.2  | 254.1  | 263.2 | 280.4  |        |   |
| 11 | 61 |        |        | 276.7  | 262.2  | 261.7  | 255.7 | 250.2  | 247.8  | 242.6 | 249    | 255.1  | 251.7  | 252.5  | 260.6 | 271.2  | 285.1  |   |
| 12 | 57 |        | 288.5  | 271.5  | 261    | 260.2  | 251   | 247.9  | 247.4  | 243.5 | 247.4  | 254    | 251.9  | 252.9  | 257.4 | 269.7  | 279    |   |
| 13 | 53 |        | 287.4  | 261.8  | 263    | 254.1  | 246.9 | 245    | 247.3  | 245.5 | 246.5  | 250.1  | 251.8  | 255.1  | 260.3 | 266.6  | 282    |   |
| 14 | 49 |        | 273.2  | 254.6  | 255    | 249.1  | 242.7 | 242.1  | 245.1  | 244.3 | 243.9  | 249.3  | 252.3  | 256.4  | 262.2 | 267.8  | 276.5  |   |
| 15 | 45 |        | 263.4  | 253.8  | 249.6  | 245.2  | 241.1 | 241.1  | 244.7  | 243.2 | 246.5  | 250.4  | 253.7  | 261.5  | 267.3 | 271    | 279.9  |   |
| 16 | 41 |        | 259.2  | 253    | 252.7  | 250.4  | 246   | 246.4  | 248.6  | 245.4 | 246.3  | 252.8  | 255.9  | 265.1  | 270.9 | 277    | 287    |   |
| 17 | 37 |        | 259.8  | 256.6  | 255.6  | 252.6  | 249.4 | 250.6  | 255.8  | 251.8 | 251.8  | 259.2  | 261.1  | 271    | 277.9 | 285.2  | 294.6  |   |
| 18 | 33 |        | 265    | 264    | 265.7  | 260.2  | 257.6 | 257.3  | 260.4  | 260   | 262    | 268.1  | 271.8  | 279.2  | 286.4 | 296.8  | 306.6  |   |
| 19 | 29 | 300.4  | 282.6  | 278.3  | 278    | 274.2  | 271.7 | 273.2  | 273.8  | 275.8 | 279.8  | 284.1  | 290.9  | 299.1  | 307.4 | 316.4  | 328.3  |   |
| 20 | 25 | 314.7  | 310.6  | 305    | 305.3  | 303    | 300.9 | 300.5  | 300.5  | 302.1 | 308.9  | 313.8  | 312.5  | 331.5  | 342.7 | 350.8  | 367.4  |   |
| 21 | 21 | 362.4  | 370    | 356    | 364.4  | 355.5  | 355.5 | 350.8  | 353.8  | 352   | 363.7  | 373.7  | 386.5  | 399.4  | 413.6 | 424.2  | 448.2  |   |
| 22 | 17 | 489.7  | 558.9  | 519.8  | 515.4  | 509.1  | 515.7 | 509.8  | 512.1  | 493.5 | 525.8  | 570.2  | 599.7  | 613.2  | 611.1 | 626.9  | 657.6  |   |
| 23 | 13 | 763.3  | 956.7  | 858.1  | 858    | 730.5  | 826.4 | 880.8  | 843.4  | 963.8 | 882.6  | 958    | 997.8  | 2188.9 | 976.4 | 1076.5 | 1088.2 |   |
| 24 | 9  | 1805.3 | 1462.4 | 3652.6 | 1772.2 | 1990.7 | 1617  | 1794.6 | 1779.4 | 1766  | 1988.3 | 2175.9 | 2188.9 |        |       |        |        |   |
| 25 |    |        |        |        |        |        |       |        |        |       |        |        |        |        |       |        |        |   |
| 26 |    |        |        |        |        |        |       |        |        |       |        |        |        |        |       |        |        |   |

Figure 14: Excel Spreadsheet Formatted Brake Specific Fuel Consumption Map, (Daniel Salathiel, 2019).

The BSFC map shows the amount of fuel being consumed by the car's engine at a given Engine power (Kw) and Engine speed (Rpm). From this the Fuel consumption in g/Kw.h can be further analysed to measure the efficiency of the engine along the duty cycle that has been created. This will give a true reflection of the engine's efficiency regarding the fuel being used as a higher capacity engine which can later be compared to a downsized equivalent.

#### 4.5.1 Brake Specific Fuel Consumption Map Excel Look-up Function:

For the Brake Specific Fuel Consumption to be easily analysed for a specific Engine power (Kw) and Engine Speed (Rpm), an Excel Look up function was created. The following figure shows the Formula used to create the look up function using two variables in an array, to pick out the specific data needed.

`=IFERROR(INDEX($B$3:$Q$24,MATCH(U3,$A$3:$A$24,0),MATCH(U2,$B$1:$Q$1,1)), "")`

Figure 15: Duty Cycle BSFC map Excel Spreadsheet Look-up function for g/Kw.h, (Daniel Salathiel, 2019).

The look-up function required the function to be set as the Engine power and Engine speed to find the data required. The array was set as the data content of the BSFC map and the index required an exact match when referencing both the required Engine power and speed figures when placed in the look up boxes.

#### 4.5.2- Brake Specific Fuel Consumption g/Kw.s Equation:

The data produced by the Look-up function can be further processed to obtain the grams of fuel being consumed per Kw.s, this will allow the specific fuel consumption in grams per second to be calculated. The equation and calculations can be seen in the next section '4.4.3'.

$$g/Kw.s = \frac{g/Kw.h}{(60 \times 60)}$$

Equation 26: G/Kw.h to g/Kw.s equation for conversion, (Daniel Salathiel, 2019).

| T                      | U           |
|------------------------|-------------|
| Engine Speed RPM       | 2000        |
| Kw                     | 93          |
| BSFC Value g/Kw.h      | 273.7       |
| BSFC Value g/Kw.s      | =U5/(60*60) |
| Fuel Consumption (g/s) | 7.07        |

Figure 16: Excel Spreadsheet g/Kw.h to g/Kw.s conversion fomula, (Daniel Salathiel, 2019).

Figure 17 shows the working formula in the Excel Spreadsheet for the conversion of grams per kilowatt hour to grams per kilowatt second.

#### 4.5.3- Fuel Consumption Equation:

To calculate the fuel consumption for the engine being tested the g/Kw.s need to be converted into grams per second to give a clearer understanding of the efficiency. This is in relation to volumetric flow, in this case the power of the engine at a given engine speed. The following equation was used, then inputted into the Excel Spreadsheets.

$$g/s = g/Kw.s \times Kw$$

Equation 27: Fuel consumption Equation for g/s, (Daniel Salathiel, 2019).

| T                      | U      |
|------------------------|--------|
| Engine Speed RPM       | 2000   |
| Kw                     | 93     |
| BSFC Value g/Kw.h      | 273.7  |
| BSFC Value g/Kw.s      | 0.076  |
| Fuel Consumption (g/s) | =U7*U3 |

Figure 17: Excel Spreadsheet g/s fuel consumption formula, (Daniel Salathiel, 2019).

The formula in the Excel Spreadsheet can be seen to multiply the current selected engine Power in Kilowatts, by the BSFC value in g/Kw.s.

#### 4.6- Coast Down Testing Theoretical and recorded data Methodology:

The DL1 data logger was used to record data for a Coast Down test. The data for the coast down test is required to analyse the parasitic losses through the previously discussed resistances acting on the car as it's in motion. The data collected was processed through the Racetechnologies software and imported into an Excel spreadsheet to be further extrapolated. The Formulas found in section '4.3' can be used to create formulas and look-up functions to give a clearer understating of the resistive forces acting on the car, and the efficiency of various factors associated with the motion of the vehicle. The Aerodynamic Drag Coefficient can be calculated for the car at the varying speeds during the coast down test, which can later be used to give an actual understanding of the forces acting on the vehicle during the duty cycle.

The following figure shows a sample of data from the coast down test in the Excel spreadsheet. The complete data set can be found in the appendix section.

|    |                     |             |                |                              |                            |                |                        |                            |            |   |                       |       |         |
|----|---------------------|-------------|----------------|------------------------------|----------------------------|----------------|------------------------|----------------------------|------------|---|-----------------------|-------|---------|
| G2 | =SL\$2*SL\$11*SL\$9 |             |                |                              |                            |                |                        |                            |            |   |                       |       |         |
|    | A                   | B           | C              | D                            | E                          | F              | G                      | H                          | I          | J | K                     | L     | M       |
| 1  | Time (s)            | Speed (MPH) | Velocity (m/s) | Change in Acceleration (m/s) | Change in Acceleration (N) | Aero Force (N) | Rolling Resistance (N) | Total Resistive Forces (N) | Power (Kw) |   |                       |       |         |
| 2  | 0                   | 63.83       | 28.53          | 0.00                         | 0.00                       | 667.17         | 542.00                 | 1209.17                    |            |   | Weight (Kg)           | 1105  |         |
| 3  | 1                   | 61.85       | 27.65          | -0.89                        | -978.92                    | 626.39         | 542.00                 | 189.47                     |            |   | Frontal Area (m^2)    | 2.535 |         |
| 4  | 2                   | 60.62       | 27.10          | -0.55                        | -609.24                    | 601.65         | 542.00                 | 534.41                     |            |   | Av. Incline (Degrees) |       |         |
| 5  | 3                   | 60.44       | 27.02          | -0.08                        | -86.70                     | 598.17         | 542.00                 | 1053.48                    |            |   | Av. Decline (Degrees) |       |         |
| 6  | 4                   | 59.46       | 26.58          | -0.44                        | -483.70                    | 578.95         | 542.00                 | 637.25                     |            |   | Av. Incline (Radians) |       |         |
| 7  | 5                   | 58.80       | 26.29          | -0.29                        | -325.32                    | 566.19         | 542.00                 | 782.88                     |            |   | Av. Decline (Radians) |       |         |
| 8  | 6                   | 57.60       | 25.75          | -0.54                        | -593.84                    | 543.28         | 542.00                 | 491.44                     |            |   |                       |       |         |
| 9  | 7                   | 56.68       | 25.34          | -0.41                        | -454.29                    | 526.07         | 542.00                 | 613.78                     |            |   | Road Resistance       | 0.05  | Macadam |
| 10 | 8                   | 55.67       | 24.89          | -0.45                        | -498.19                    | 507.51         | 542.00                 | 551.32                     |            |   |                       |       |         |
| 11 | 9                   | 55.33       | 24.73          | -0.15                        | -170.27                    | 501.25         | 542.00                 | 872.98                     |            |   | Gravity (N/Kg)        | 9.81  |         |
| 12 | 10                  | 54.25       | 24.25          | -0.48                        | -529.44                    | 482.01         | 542.00                 | 494.58                     |            |   |                       |       |         |
| 13 | 11                  | 53.29       | 23.82          | -0.43                        | -474.72                    | 465.09         | 542.00                 | 532.37                     |            |   |                       |       |         |
| 14 | 12                  | 51.79       | 23.15          | -0.67                        | -742.63                    | 439.22         | 542.00                 | 238.59                     |            |   |                       |       |         |
| 15 | 13                  | 50.80       | 22.71          | -0.44                        | -491.32                    | 422.51         | 542.00                 | 473.19                     |            |   |                       |       |         |
| 16 | 14                  | 49.95       | 22.33          | -0.38                        | -419.36                    | 408.51         | 542.00                 | 531.15                     |            |   |                       |       |         |
| 17 | 15                  | 48.40       | 21.64          | -0.69                        | -764.23                    | 383.59         | 542.00                 | 161.37                     |            |   |                       |       |         |
| 18 | 16                  | 47.28       | 21.13          | -0.50                        | -553.95                    | 366.02         | 542.00                 | 354.07                     |            |   |                       |       |         |
| 19 | 17                  | 46.26       | 20.68          | -0.45                        | -501.43                    | 350.47         | 542.00                 | 391.05                     |            |   |                       |       |         |
| 20 | 18                  | 45.14       | 20.18          | -0.50                        | -556.91                    | 333.60         | 542.00                 | 318.69                     |            |   |                       |       |         |
| 21 | 19                  | 44.42       | 19.86          | -0.32                        | -354.62                    | 323.07         | 542.00                 | 510.46                     |            |   |                       |       |         |
| 22 | 20                  | 43.54       | 19.46          | -0.39                        | -434.38                    | 310.40         | 542.00                 | 418.02                     |            |   |                       |       |         |
| 23 | 21                  | 42.83       | 19.15          | -0.32                        | -348.33                    | 300.43         | 542.00                 | 494.11                     |            |   |                       |       |         |
| 24 | 22                  | 42.50       | 19.00          | -0.15                        | -165.59                    | 295.75         | 542.00                 | 672.16                     |            |   |                       |       |         |
| 25 | 23                  | 41.98       | 18.77          | -0.23                        | -256.12                    | 288.57         | 542.00                 | 574.46                     |            |   |                       |       |         |
| 26 | 24                  | 41.44       | 18.52          | -0.24                        | -268.18                    | 281.16         | 542.00                 | 554.98                     |            |   |                       |       |         |
| 27 | 25                  | 40.05       | 17.90          | -0.62                        | -684.36                    | 262.67         | 542.00                 | 120.32                     |            |   |                       |       |         |
| 28 | 26                  | 38.69       | 17.30          | -0.61                        | -670.81                    | 245.16         | 542.00                 | 116.35                     |            |   |                       |       |         |

Figure 18: Excel Spreadsheet Coast Down Data Sample, (Daniel Salathiel, 2019).

#### 4.7- Drag Coefficient Excel Spreadsheet Look-up function:

The look-up function enables the Aerodynamic resistive force to be identified for a specific point along the coast down test. The look-up function uses a drop-down box which enables the user to select a speed the car is traveling at and provides an Aerodynamic Drag coefficient value for the selected speed. This will later be used to produce actual power values to analyse specific Brake Specific Fuel Consumption data.

|   | A           | B              | C                            | D                          | E | F | G           | H        |
|---|-------------|----------------|------------------------------|----------------------------|---|---|-------------|----------|
| 1 | Speed (MPH) | Velocity (m/s) | Change in Acceleration (m/s) | Change in Acceleration (N) |   |   |             |          |
| 2 | 63.83       | 28.53          | 0.00                         | 0.00                       |   |   | Weight (Kg) | 1105     |
| 3 | 61.85       | 27.65          | -0.89                        | -978.92                    |   |   |             |          |
| 4 | 60.62       | 27.10          | -0.55                        | -609.24                    |   |   | Speed       | 27.65    |
| 5 | 60.44       | 27.02          | -0.08                        | -86.70                     |   |   | Drag N      | -978.921 |

Figure 19: Excel Aerodynamic Force Look-up Function, (Daniel Salathiel, 2019).

## 5.0- Analysis

### 5.1 Coast Down Analysis:

The coast down test was required to test the cars resistive forces, which considered the resistive forces such as; Rolling resistance, aerodynamic drag and other parasitic resistances. The field test may show variations caused by wind speed and direction, as well as road surface irregularities causing varying effects on the coast down test (Villela, A. et al, 2017). The testing carried out took into considerations such as traffic volume due to the test being carried out on a public road This required the upmost safety and was carried out during a 'quiet' stage of the early morning to minimis the risk of both safety and interference with the data resulting from having to adjust the vehicles speed because of traffic obstructions.

The data from the DL1 Data logger was placed into an excel spread sheet to create a velocity curve for the coast down testing which can be seen in the figure below.

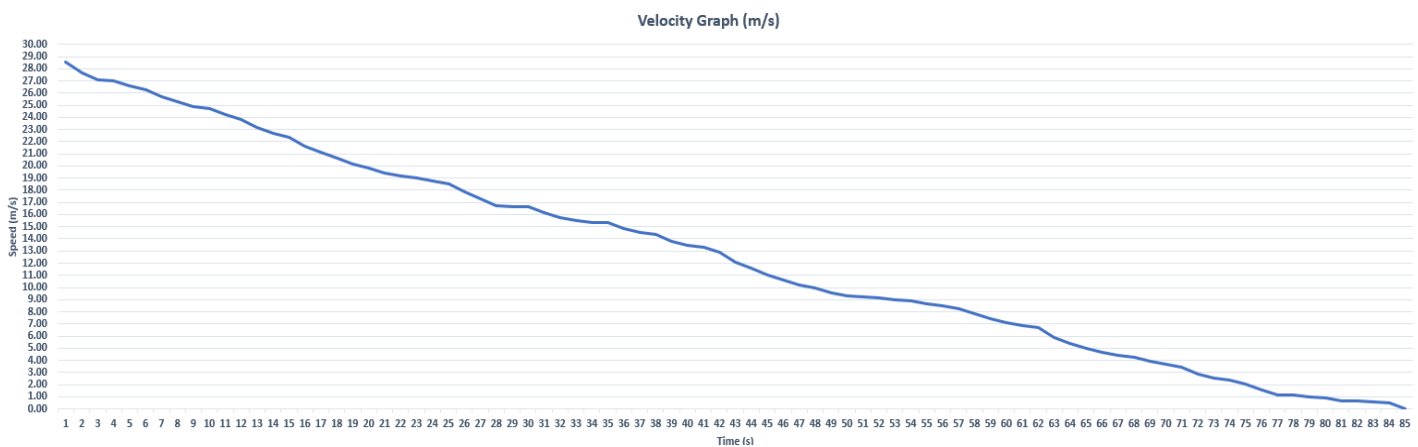


Figure 20: Coast Down Velocity Curve Graph, (Daniel Salathiel, 2019).

The Velocity curve shows the deceleration of the car over a period of 85 seconds. The data from the coast down data can be used to calculate the actual Aerodynamic resistance (N) for the car, which can be used to work out a more accurate Brake Specific Fuel Consumption value during points along the duty cycle. This process will allow for real life figures for the BSFC map to give a clearer understanding of the efficiency of the higher capacity internal combustion engine currently in the car, which can be compared with the downsized engine to give a clear understanding of how the technology relates to real life efficiency. (Villela, A. et al, 2017).

### 5.1.1 Rate of Deceleration Analysis:

The rate of deceleration for the coast down test is vital in giving an understanding of the resistive forces acting on a vehicle during its forward motion. The rate of deceleration was calculated from the coast down data using an equation in the Excel Spreadsheet previously discussed in this report. The rate of deceleration was calculated to allow for the data to be placed in a graph plotted against velocity. This data can be seen displayed graphically in the figure below.

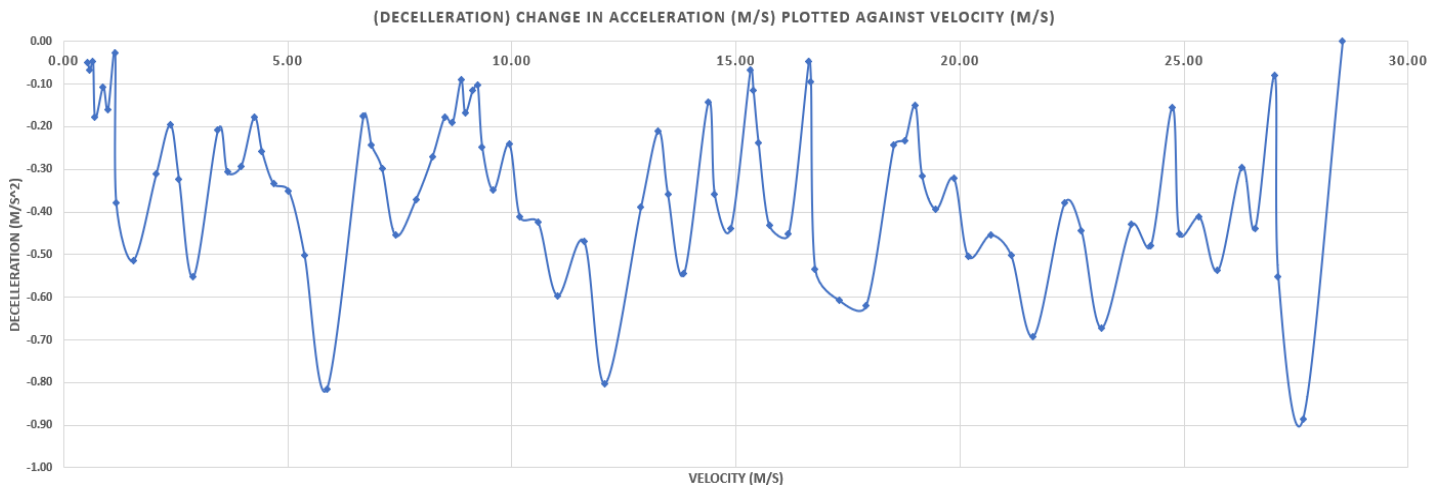


Figure 21: Coast Down Rate of Deceleration ( $m/s^2$ ) plotted against Velocity ( $m/s$ ), (Daniel Salathiel, 2019).

The highest rate of deceleration can be seen at the higher speeds of the coast down test. This suggests that the car is experiencing greater resistance at higher velocity than at the lower. The rate of acceleration can be seen to dramatically increase between 30 m/s and 15 m/s. This means that the data from the figure above shows the resistance acting on the vehicle that needs to be further analysed is the aerodynamic resistance. This is continuously changing variable, whereas the rolling resistance is assumed at staying the same for the entire coast down test due to the surface of the road or characteristics of tyre remaining consistent throughout the test. Section 5.1.2 will further analyse and compare these resistance values over the duration of the coast down test.

### 5.1.2 Resistive Forces analysis:

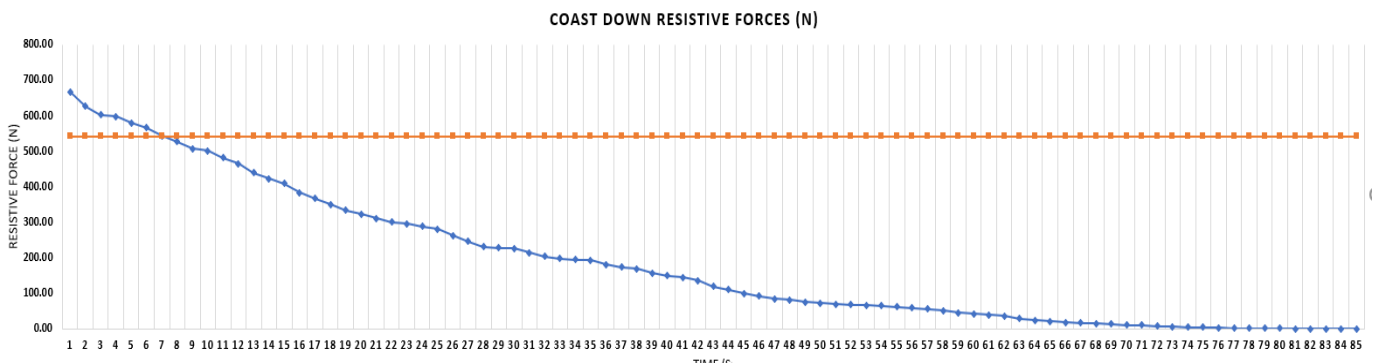


Figure 22: Coast Down Resistive Forces Comparison Graph, (Daniel Salathiel, 2019).

The Graph in figure 23 above shows both the Rolling resistance and the Aerodynamic resistance acting on the car during the coast down test. It can be noted that the Rolling resistance stays constant at 543 Newton's, whereas the Aerodynamic resistance has a positive correlation with the velocity graph seen in section 5.1. The data seen in the graph below for the aerodynamic resistance is required to accurately determine the efficiency of the higher capacity engine and the downsized equivalent. The data will be inserted into the duty cycle for the selected points for analysis, meaning a real-life Brake Specific Fuel Consumption value can be calculated, in turn giving a more accurate interpretation of the efficiency of the car's engine.

### 5.1.3- data required for Aerodynamic Resistance analysis Table:

| Speed (MPH) | Velocity (m/s) | Change in Acceleration (m/s) | Change in Acceleration (N) |
|-------------|----------------|------------------------------|----------------------------|
| 63.83       | 28.53          | 0.00                         | 0.00                       |
| 61.85       | 27.65          | -0.89                        | -978.92                    |
| 60.62       | 27.10          | -0.55                        | -609.24                    |
| 60.44       | 27.02          | -0.08                        | -86.70                     |
| 59.46       | 26.58          | -0.44                        | -483.70                    |
| 58.80       | 26.29          | -0.29                        | -325.32                    |
| 57.60       | 25.75          | -0.54                        | -593.84                    |
| 56.68       | 25.34          | -0.41                        | -454.29                    |
| 55.67       | 24.89          | -0.45                        | -498.19                    |
| 55.33       | 24.73          | -0.15                        | -170.27                    |
| 54.25       | 24.25          | -0.48                        | -529.44                    |
| 53.29       | 23.82          | -0.43                        | -474.72                    |
| 51.79       | 23.15          | -0.67                        | -742.63                    |
| 50.80       | 22.71          | -0.44                        | -491.32                    |
| 49.95       | 22.33          | -0.38                        | -419.36                    |
| 48.40       | 21.64          | -0.69                        | -764.23                    |
| 47.28       | 21.13          | -0.50                        | -553.95                    |
| 46.26       | 20.68          | -0.45                        | -501.43                    |
| 45.14       | 20.18          | -0.50                        | -556.91                    |
| 44.42       | 19.86          | -0.32                        | -354.62                    |
| 43.54       | 19.46          | -0.39                        | -434.38                    |
| 42.83       | 19.15          | -0.32                        | -348.33                    |
| 42.50       | 19.00          | -0.15                        | -165.59                    |
| 41.98       | 18.77          | -0.23                        | -256.12                    |
| 41.44       | 18.52          | -0.24                        | -268.18                    |
| 40.05       | 17.90          | -0.62                        | -684.36                    |
| 38.69       | 17.30          | -0.61                        | -670.81                    |
| 36.85       | 16.47          | -0.82                        | -910.48                    |
| 37.29       | 16.67          | 0.20                         | 217.70                     |
| 37.19       | 16.62          | -0.05                        | -50.77                     |
| 36.18       | 16.17          | -0.45                        | -499.42                    |
| 35.21       | 15.74          | -0.43                        | -477.36                    |
| 34.22       | 15.30          | -0.44                        | -488.42                    |
| 33.79       | 15.11          | -0.19                        | -212.99                    |
| 34.27       | 15.32          | 0.21                         | 236.87                     |
| 33.29       | 14.88          | -0.44                        | -483.63                    |
| 32.49       | 14.52          | -0.36                        | -396.82                    |
| 32.17       | 14.38          | -0.14                        | -157.54                    |
| 30.95       | 13.83          | -0.55                        | -602.60                    |
| 30.15       | 13.48          | -0.36                        | -395.34                    |
| 29.68       | 13.27          | -0.21                        | -232.01                    |
| 28.81       | 12.88          | -0.39                        | -430.00                    |
| 27.01       | 12.08          | -0.80                        | -886.94                    |
| 25.96       | 11.61          | -0.47                        | -517.87                    |
| 24.63       | 11.01          | -0.60                        | -659.06                    |
| 23.68       | 10.59          | -0.42                        | -469.27                    |
| 22.76       | 10.17          | -0.41                        | -454.45                    |
| 22.22       | 9.93           | -0.24                        | -265.12                    |
| 21.44       | 9.59           | -0.35                        | -384.60                    |
| 20.89       | 9.34           | -0.25                        | -274.89                    |
| 20.66       | 9.23           | -0.10                        | -113.38                    |
| 20.40       | 9.12           | -0.12                        | -127.35                    |
| 20.03       | 8.95           | -0.17                        | -184.07                    |
| 19.83       | 8.86           | -0.09                        | -99.84                     |
| 19.40       | 8.67           | -0.19                        | -209.47                    |
| 19.00       | 8.50           | -0.18                        | -196.34                    |
| 18.40       | 8.23           | -0.27                        | -297.66                    |

| Speed (MPH) | Velocity (m/s) | Change in Acceleration (m/s) | Change in Acceleration (N) |
|-------------|----------------|------------------------------|----------------------------|
| 17.57       | 7.86           | -0.37                        | -409.73                    |
| 16.55       | 7.40           | -0.46                        | -502.85                    |
| 15.89       | 7.10           | -0.30                        | -330.43                    |
| 15.34       | 6.86           | -0.24                        | -267.59                    |
| 14.95       | 6.68           | -0.18                        | -193.57                    |
| 13.13       | 5.87           | -0.81                        | -900.57                    |
| 12.01       | 5.37           | -0.50                        | -552.99                    |
| 11.23       | 5.02           | -0.35                        | -386.74                    |
| 10.48       | 4.68           | -0.33                        | -369.51                    |
| 9.90        | 4.43           | -0.26                        | -285.99                    |
| 9.50        | 4.25           | -0.18                        | -196.03                    |
| 8.85        | 3.96           | -0.29                        | -322.90                    |
| 8.16        | 3.65           | -0.31                        | -338.53                    |
| 7.70        | 3.44           | -0.21                        | -228.27                    |
| 6.47        | 2.89           | -0.55                        | -609.57                    |
| 5.75        | 2.57           | -0.32                        | -356.05                    |
| 5.31        | 2.37           | -0.20                        | -216.21                    |
| 4.61        | 2.06           | -0.31                        | -344.10                    |
| 3.46        | 1.55           | -0.51                        | -568.29                    |
| 2.61        | 1.17           | -0.38                        | -418.36                    |
| 2.56        | 1.14           | -0.03                        | -28.88                     |
| 2.20        | 0.98           | -0.16                        | -176.12                    |
| 1.96        | 0.88           | -0.11                        | -117.82                    |
| 1.56        | 0.70           | -0.18                        | -197.32                    |
| 1.46        | 0.65           | -0.05                        | -50.73                     |
| 1.53        | 0.68           | 0.03                         | 34.38                      |
| 1.20        | 0.54           | -0.15                        | -162.39                    |
| 0.00        | 0.00           | -0.54                        | -592.76                    |

Figure 23: Aerodynamic Resistance Values for each speed from Coast Down Test, (Daniel Salathiel, 2019).

## 5.2 Duty Cycle Analysis:

### 5.2.1 Duty Cycle Analysis- Velocity and Power graph (Kw)

The Brake Specific Fuel Consumption of an engine is determined by its frictional losses, pumping losses, fuel properties, thermal efficiencies and its combustion efficiency during operation. (B. Leach. Et al, 2014). Recent automotive internal combustion engines are introducing modernised architectures to reduce the Brake Specific Fuel Consumption (BSFC), without compromising the transient performance in relation to the engines volumetric flow, power and torque performance. (L. Teodosio. Et al, 2015).

The recorded data from the testing process will allow for the Brake Specific Fuel Consumption for the current higher capacity 1600cc engine to be analysed, then a comparison to the suggested downsized equivalent can be carried out to demonstrate the change in efficiencies for a downsized engine. This will give a reflection as to why the automotive industry is integrating this technology into their development of modern cars.

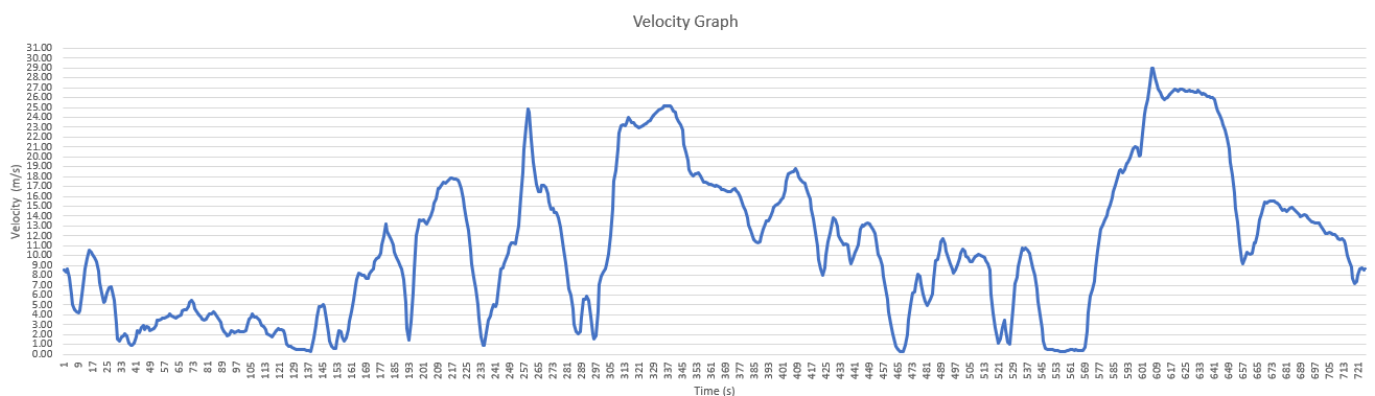


Figure 24: Duty Cycle Velocity (m/s) plotted against time (s) graph, (Daniel Salathiel, 2019).

Figure 25 shows the velocity of the car as it travels along the predetermined duty cycle. The velocity data can be clearly seen in a graphical format, this will allow for sections of data to be analysed to give a clear understanding of a cars Brake Specific Fuel (BSFC) economy along a typical urban duty cycle. The velocity data in relation to the position along the duty cycle can be used to determine the engine speed of the car and the gear selected. This information can be used alongside the look-up function to obtain a Brake specific fuel consumption value when allocated an engine power value (Kw) that can be determined from the data in figure 26 below. The Brake Specific Fuel consumption (BSFC) can be a direct measure of the car's efficiency in relation to its ability to burn fuel within a given power band and engine speed. The following will analyse the data from the higher capacity engine used to carry out the live data testing, giving a bench mark for the BSFC. This bench mark analysis will be used to then determine the efficiency of the downsized engine proposed in this report.

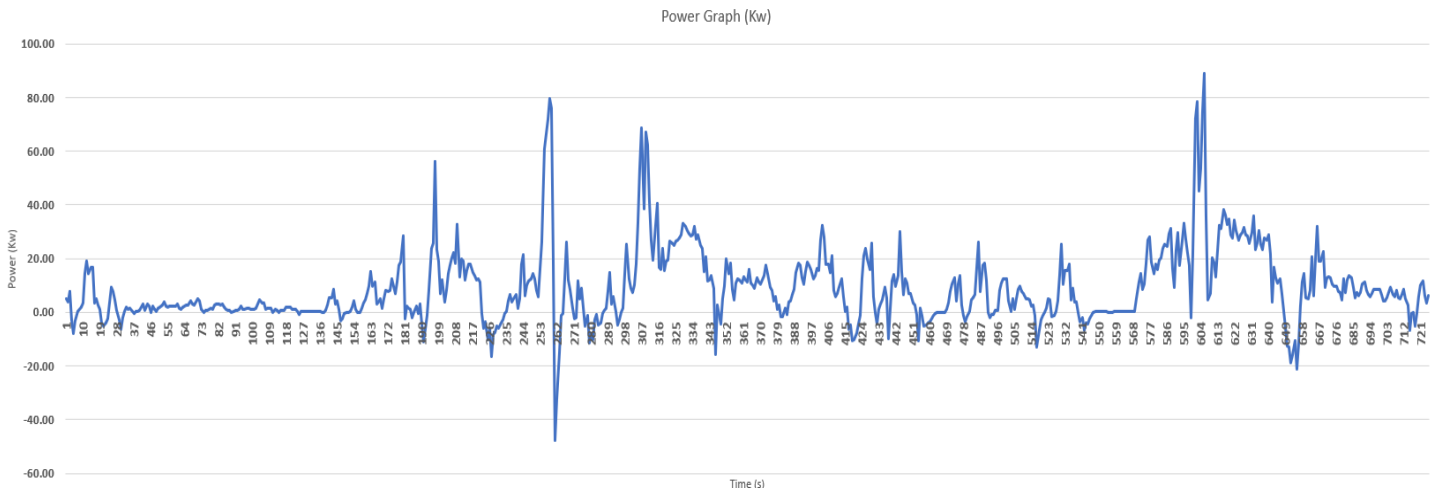


Figure 25: Duty Cycle Power (Kw) plotted against time (s) graph, (Daniel Salathiel, 2019).

The Power figure for a selected section of the Duty cycle can be chosen to give an accurate interpretation of the BSFC of the engine at a certain point in the drive cycle. This will allow both the data extrapolated from the velocity data shown in figure 25 to give the engine speed, and the power figure In Kw from the figure above to be placed in the look-up function to give the BSFC data from the map.

### 5.2.2 Duty Cycle BSFC analysis:

For the entire Duty cycle Brake Specific Fuel Consumption to be analysed the average Power (Kw) and average Road Speed (m/s), which was converted into Engine speed (Rpm), needed to be calculated. The resulting data can be seen in the average BSFC Table in section '5.2.2'.

The following figures shows the resulting Brake Specific Fuel Consumption value for the recorded Duty cycle of the higher capacity 1600cc engine.

|                       |       |                 |       |
|-----------------------|-------|-----------------|-------|
| AV. Power Total (Kw)  | 9.07  | Av. Speed (m/s) | 10.96 |
| AV. Power Total (BHP) | 12.15 | Av. Speed (Mph) | 24.53 |

Figure 26: Excel Spreadsheet Duty Cycle Av. Power (Kw) and speed (m/s) calculations, (Daniel Salathiel, 2019).

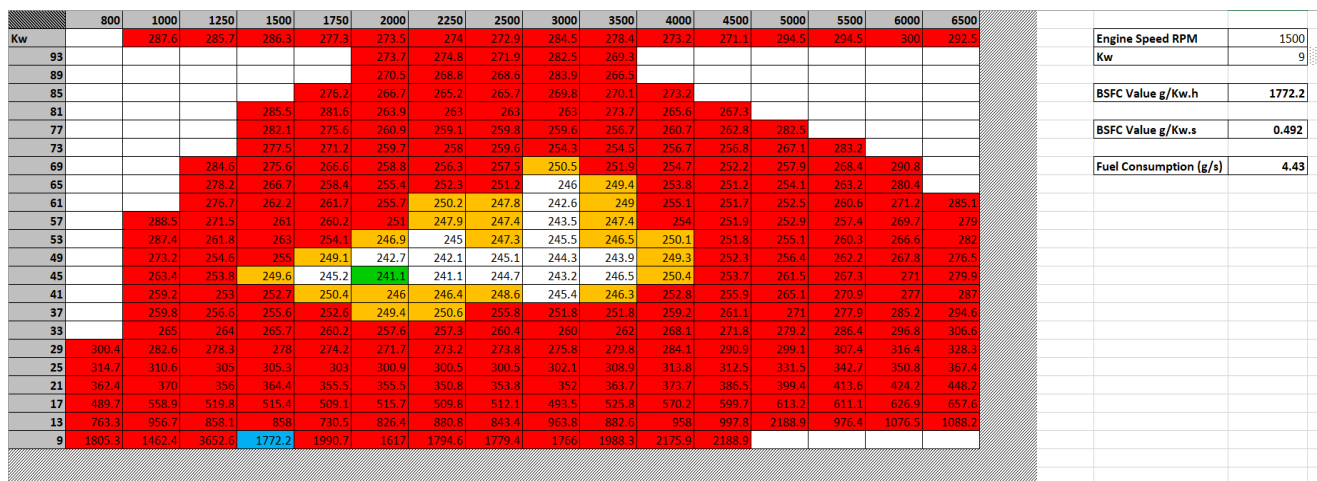


Figure 27: Av. BSFC Map values for Entire Duty Cycle for higher capacity engine, (Daniel Salathiel, 2019).

The Brake Specific Fuel Consumption efficiency of the higher capacity engine is measured as the cars tractive work against the amount of fuel energy required to travel that distance (Gao. Y. et al, 2007). The testing took into consideration average vehicle speed in traffic conditions, giving results that mirror real life driving in an urban area. This means that the Brake Specific Fuel Consumption calculated from the average duty cycle results gives a clear figure for the amount of fuel required to carry out the Duty Cycle route chosen. This data when compared to the downsized engine technologies values later in the report, will give an understanding of how the efficiency differs between the two different capacity engines.

The calculated Revolutions per second was 1509.97, using an average ratio of 1.064 for 4<sup>th</sup> gear. The map shows that the demand for fuel at the average Power (Kw) and road speeds (m/s), indicates that the car moving at the low demand average vehicle speed has a relatively high fuel consumption rate. This statement is also backed by (Gao. Y. et al, 2007) Technical report findings. The fuel is consumed at 1772.2 g/Kw.h, which is equal to 4.43 grams of fuel per second. The value shown in blue on the BSFC map above can be seen to be considerably higher than the optimum value indicated by the green box. The Fuel consumption in g/ kw.h is 1531.1 grams grater, meaning the higher capacity engine is using 82% percent more fuel per second, equating to 87% greater fuel consumption per g/Kw.h. This result for the higher capacity engine can be set as the bench mark for the Brake Specific Fuel Consumption efficiency over the course of the Duty cycle, which can be compared to the efficiency of the 800cc downsized engine proposed over the duration of the same Duty Cycle for the donor car.

|    | 800    | 1000   | 1250   | 1500   | 1750   | 2000  | 2250   | 2500   | 3000  | 3500   | 4000   | 4500   | 5000   | 5500  | 6000   | 6500   |       |                        |       |
|----|--------|--------|--------|--------|--------|-------|--------|--------|-------|--------|--------|--------|--------|-------|--------|--------|-------|------------------------|-------|
| Kw |        | 287.6  | 285.7  | 286.3  | 277.3  | 273.5 | 274    | 272.9  | 284.5 | 278.4  | 273.2  | 271.1  | 294.5  | 294.5 | 300    | 292.5  |       | Engine Speed RPM       | 2000  |
| 93 |        |        |        |        |        | 273.7 | 274.8  | 271.9  | 282.5 | 269.3  |        |        |        |       |        |        |       | Kw                     | 9     |
| 89 |        |        |        |        |        | 270.5 | 268.8  | 268.6  | 283.9 | 266.5  |        |        |        |       |        |        |       | BSFC Value g/Kw.h      | 1617  |
| 85 |        |        |        |        | 276.2  | 266.7 | 265.2  | 265.7  | 269.8 | 270.1  | 273.2  |        |        |       |        |        |       | BSFC Value g/Kw.s      | 0.449 |
| 81 |        |        |        | 285.5  | 281.6  | 263.9 | 263    | 263    | 263   | 273.7  | 265.6  | 267.9  |        |       |        |        |       | Fuel Consumption (g/s) | 4.04  |
| 77 |        |        |        | 282.1  | 275.6  | 260.9 | 259.1  | 259.8  | 259.6 | 256.7  | 260.7  | 262.8  | 282.5  |       |        |        |       |                        |       |
| 73 |        |        |        | 277.5  | 271.2  | 259.7 | 258    | 259.6  | 254.3 | 254.5  | 256.7  | 256.8  | 267.1  | 283.2 |        |        |       |                        |       |
| 69 |        |        | 284.6  | 275.6  | 266.6  | 258.8 | 256.3  | 257.5  | 250.5 | 251.9  | 254.7  | 252.2  | 257.9  | 268.4 | 290.8  |        |       |                        |       |
| 65 |        |        |        | 278.2  | 266.7  | 258.4 | 255.4  | 252.3  | 251.2 | 246    | 249.4  | 253.8  | 251.2  | 254.1 | 263.2  | 280.4  |       |                        |       |
| 61 |        |        |        | 276.7  | 262.2  | 261.7 | 255.7  | 250.2  | 247.8 | 242.6  | 249    | 255.1  | 251.7  | 252.5 | 260.6  | 271.2  | 285.1 |                        |       |
| 57 |        | 288.5  | 271.5  | 261    | 260.2  | 251   | 247.9  | 247.4  | 243.5 | 247.4  | 254    | 251.9  | 252.9  | 257.4 | 269.7  | 279    |       |                        |       |
| 53 |        | 287.4  | 261.8  | 263    | 254.1  | 246.9 | 245    | 247.3  | 245.5 | 246.5  | 250.1  | 251.8  | 255.1  | 260.3 | 266.6  | 282    |       |                        |       |
| 49 |        | 273.2  | 254.6  | 255    | 249.1  | 242.7 | 242.1  | 245.1  | 244.3 | 243.9  | 249.3  | 252.3  | 256.4  | 262.2 | 267.8  | 276.5  |       |                        |       |
| 45 |        | 263.4  | 253.8  | 249.6  | 245.2  | 241.1 | 241.1  | 244.7  | 243.2 | 246.5  | 250.4  | 253.7  | 261.5  | 267.3 | 271    | 279.9  |       |                        |       |
| 41 |        | 259.2  | 253    | 252.7  | 250.4  | 246   | 246.4  | 248.6  | 245.4 | 246.3  | 252.8  | 255.9  | 265.1  | 270.9 | 277    | 287    |       |                        |       |
| 37 |        | 259.8  | 256.6  | 255.6  | 252.6  | 249.4 | 250.6  | 255.8  | 251.8 | 251.8  | 259.2  | 261.1  | 271    | 277.9 | 285.2  | 294.6  |       |                        |       |
| 33 |        | 265    | 264    | 265.7  | 260.2  | 257.6 | 257.3  | 260.4  | 260   | 262    | 268.1  | 271.8  | 279.2  | 286.4 | 296.8  | 306.6  |       |                        |       |
| 29 | 300.4  | 282.6  | 278.3  | 278    | 274.2  | 271.7 | 273.2  | 273.8  | 275.8 | 279.8  | 284.1  | 290.9  | 299.1  | 307.4 | 316.4  | 328.3  |       |                        |       |
| 25 | 314.7  | 310.6  | 305    | 305.3  | 303    | 300.9 | 300.5  | 300.5  | 302.1 | 308.9  | 313.8  | 312.5  | 331.5  | 342.7 | 350.8  | 367.4  |       |                        |       |
| 21 | 362.4  | 370    | 356    | 364.4  | 355.5  | 355.5 | 350.8  | 353.8  | 352   | 363.7  | 373.7  | 386.5  | 399.4  | 413.6 | 424.2  | 448.2  |       |                        |       |
| 17 | 489.7  | 558.9  | 519.8  | 515.4  | 509.1  | 515.7 | 509.8  | 512.1  | 493.5 | 525.8  | 570.2  | 599.7  | 613.2  | 611.1 | 626.9  | 657.6  |       |                        |       |
| 13 | 763.3  | 956.7  | 858.1  | 858    | 730.5  | 826.4 | 880.8  | 843.4  | 963.8 | 882.6  | 958    | 997.8  | 2188.9 | 976.4 | 1076.5 | 1088.2 |       |                        |       |
| 9  | 1805.3 | 1462.4 | 3652.6 | 1772.2 | 1990.7 | 1617  | 1794.6 | 1779.4 | 1766  | 1988.3 | 2175.9 | 2188.9 |        |       |        |        |       |                        |       |

Figure 28: Average BSFC Value for the Duty Cycle, for the downsized engine, (Daniel Salathiel, 2019).

The downsized equivalent uses a 4<sup>th</sup> gear ratio of 1.31, meaning its operation range for the same power output (Kw) increases up to 1910.27 Rpm. This means that the operation range is pushed towards a more efficient figure. The Brake Specific Fuel Consumption average for the total duty cycle for the downsized unit is 1617 g/Kw.h, 4.04 grams per second. This equates to an 8% saving in fuel over the higher capacity counterpart.

### 5.2.3 Duty Cycle Section 1 Analysis:

At lower engine loads, such as section one of the duty cycle, the biggest inefficiencies in relation to converting the fuels chemical energy into mechanical energy is due to the engine's friction and pumping losses (California energy commission, 2018). The average Power for section can be found in section 5.2.2 figure " measured at 2.07 Kw at a road speed of 3.72 m/s on average. This equates to an engine speed of 1250 Rpm calculated using a first gear 3.25 ratio and the average road speed for this section. The data can be seen inputted into the look-up function in the figure below. The slower road speeds shown in section one can be seen to increase the Brake Specific Fuel consumption to 3652.6 g/Kw.h highlighted by the blue indicator below. This means that the higher capacity engine used to carry out the Duty cycle uses 9.13 grams of fuel per second as seen in the figure below, due to the decrease in the engine efficiencies at low load cycle associated with decreased throttle position.

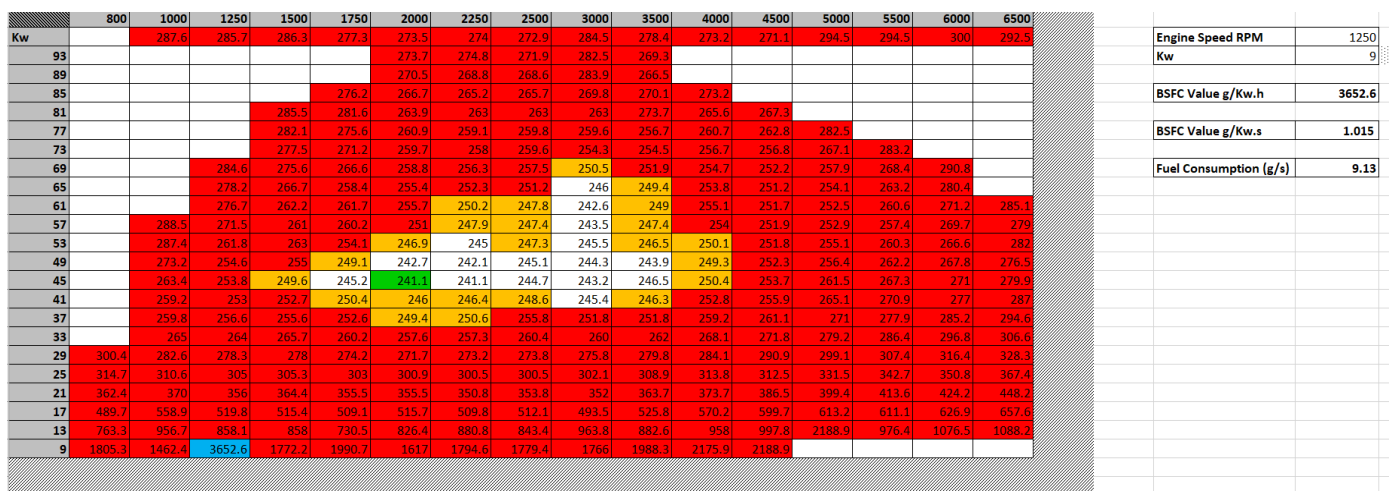


Figure 29: BSFC Map Section 1 1600cc Results, (Daniel Salathiel, 2019).

The downsized 800cc engine not only decreases the pumping losses which in turn can be seen to decrease the BSFC In figure 31 below, it increases the load required to produce the same performance as the higher capacity engine at the low load section of the duty cycle (California energy commission, 2018) . This means that the Brake Specific Fuel consumption can be decreased by up to 39% due to the increase in flow required to maintain the cars higher engine speed, for the same road speed requirement.

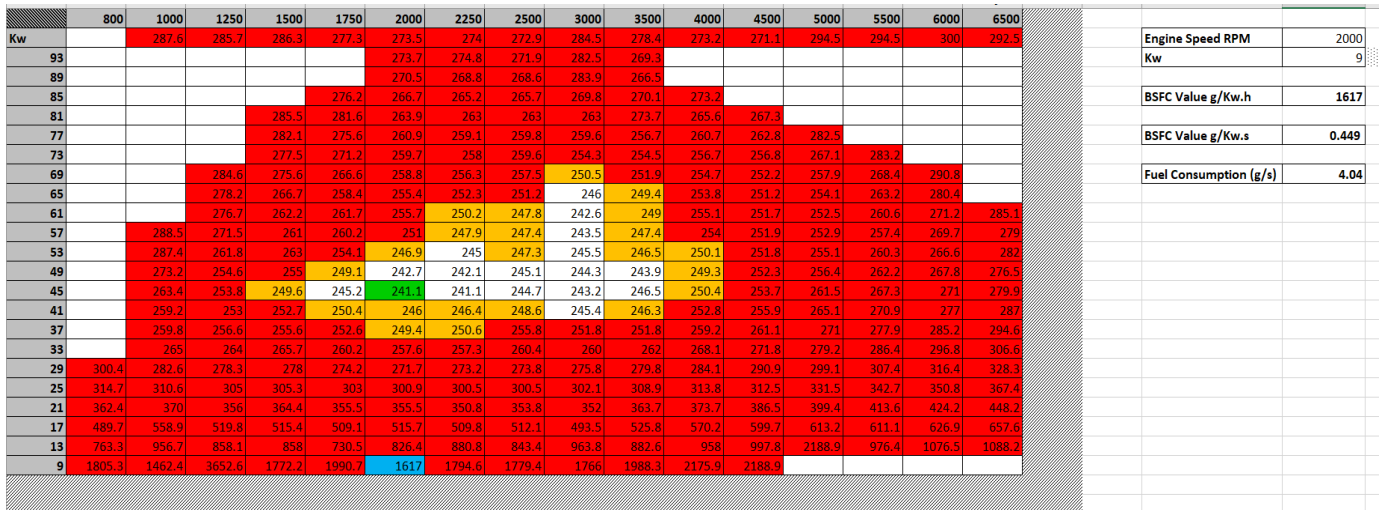


Figure 30: BSFC Map section 1 800cc Results, (Daniel Salathiel, 2019).

The resulting increase of fuel consumption can be reduced implementing the suggested downsizing technology. Using the gear ratio 4.98: 1, the Rpm for the same road speed and power was calculated for 1743Rpm, averaging up to 2000 Rpm. The Results for the 800cc downsized engine indicated in the blue box found in the figure shows a BSFC value of 1617 g/Kw.h, this means the lower capacity engine uses 4.04 grams of fuel per second. Meaning a decrease in grams of fuel per second of 5.09 which is a 55% increase in efficiency.

The increase in efficiency not only is attributed to the increase in partial load creating a closer BSFC to the optimum figure shown in green, but due to the decrease in pumping losses as result (Mechadyne, 2018). At part load the throttle restricts the air flow, decreasing the volumetric efficiency and causing the pressure in the manifold to fall below atmospheric pressure. It's due to these affects pumping losses occur, thus a lower capacity engine requiring higher throttle position for the same road speed during the duty cycle decreases the pumping losses occurring. (Mechadyne, 2018). Overall the efficiency can be seen to increase through the reduction in capacity of the donor cars engine, leading to greater fuel efficiency and volumetric efficiency.

### 5.2.4- Duty Cycle Section 5 Analysis:

Section 5 of the duty cycle displays the data for mid-range loads of the drive cycle. The figure below shows the Brake Specific Fuel Consumption values for the higher capacity 1600cc engine used to carry out the testing. The average power for section 5 was calculated at 12.80 Kw, and the average road speed (m/s) was calculated at 15.22. This meant that the car's engine speed was 1500 Rpm. From the Average power for the section and the engine speed the Brake Specific Fuel Consumption value can be found using the look-up function.

|    | 800    | 1000   | 1250   | 1500   | 1750   | 2000  | 2250   | 2500   | 3000  | 3500   | 4000   | 4500   | 5000   | 5500  | 6000   | 6500   |  |                        |       |
|----|--------|--------|--------|--------|--------|-------|--------|--------|-------|--------|--------|--------|--------|-------|--------|--------|--|------------------------|-------|
| Kw |        | 287.6  | 285.7  | 286.3  | 277.3  | 273.5 | 274    | 272.9  | 284.5 | 278.4  | 273.2  | 271.1  | 294.5  | 294.5 | 300    | 292.5  |  | Engine Speed RPM       | 1500  |
| 93 |        |        |        |        |        | 273.7 | 274.8  | 271.9  | 282.5 | 269.3  |        |        |        |       |        |        |  | Kw                     | 13    |
| 89 |        |        |        |        |        | 270.5 | 268.8  | 268.6  | 283.9 | 266.5  |        |        |        |       |        |        |  | BSFC Value g/Kw.h      | 858   |
| 85 |        |        |        |        | 276.2  | 266.7 | 265.2  | 265.7  | 269.8 | 270.1  | 273.2  |        |        |       |        |        |  | BSFC Value g/Kw.s      | 0.238 |
| 81 |        |        |        | 285.5  | 281.6  | 263.9 | 263    | 263    | 263   | 273.7  | 265.6  | 267.3  |        |       |        |        |  | Fuel Consumption (g/s) | 3.10  |
| 77 |        |        |        | 282.1  | 275.6  | 260.9 | 259.1  | 259.8  | 259.6 | 256.7  | 260.7  | 262.8  | 282.5  |       |        |        |  |                        |       |
| 73 |        |        |        | 277.5  | 271.2  | 259.7 | 258    | 259.6  | 254.3 | 254.5  | 256.7  | 256.8  | 267.1  | 283.2 |        |        |  |                        |       |
| 69 |        |        | 284.6  | 275.6  | 266.6  | 258.8 | 256.3  | 257.5  | 250.5 | 251.9  | 254.7  | 252.2  | 257.9  | 268.4 | 290.8  |        |  |                        |       |
| 65 |        |        | 278.2  | 266.7  | 258.4  | 255.4 | 252.3  | 251.2  | 246   | 249.4  | 253.8  | 251.2  | 254.1  | 263.2 | 280.4  |        |  |                        |       |
| 61 |        |        | 276.7  | 262.2  | 261.7  | 255.7 | 250.2  | 247.8  | 242.6 | 249    | 255.1  | 251.7  | 252.5  | 260.6 | 271.2  | 285.1  |  |                        |       |
| 57 |        | 288.5  | 271.5  | 261    | 260.2  | 254   | 247.9  | 247.4  | 243.5 | 247.4  | 254    | 251.9  | 252.9  | 257.4 | 269.7  | 279    |  |                        |       |
| 53 |        | 287.4  | 261.8  | 263    | 254.1  | 246.9 | 245    | 247.3  | 245.5 | 246.5  | 250.1  | 251.8  | 255.1  | 260.3 | 266.6  | 282    |  |                        |       |
| 49 |        | 273.2  | 254.6  | 255    | 249.1  | 242.7 | 242.1  | 245.1  | 244.3 | 243.9  | 249.3  | 252.3  | 256.4  | 262.2 | 267.8  | 276.5  |  |                        |       |
| 45 |        | 263.4  | 253.8  | 249.6  | 245.2  | 241.1 | 241.1  | 244.7  | 243.2 | 246.5  | 250.4  | 253.7  | 261.5  | 267.3 | 271    | 279.9  |  |                        |       |
| 41 |        | 259.2  | 253    | 252.7  | 250.4  | 246   | 246.4  | 248.6  | 245.4 | 246.3  | 252.8  | 255.9  | 265.1  | 270.9 | 277    | 287    |  |                        |       |
| 37 |        | 259.8  | 256.6  | 255.6  | 252.6  | 249.4 | 250.6  | 255.8  | 251.8 | 251.8  | 259.2  | 261.1  | 271    | 277.9 | 285.2  | 294.6  |  |                        |       |
| 33 |        | 265    | 264    | 265.7  | 260.2  | 257.6 | 257.3  | 260.4  | 260   | 262    | 268.1  | 271.8  | 279.2  | 286.4 | 296.8  | 306.6  |  |                        |       |
| 29 | 300.4  | 282.6  | 278.3  | 278    | 274.2  | 271.7 | 273.2  | 273.8  | 275.8 | 279.8  | 284.1  | 290.9  | 299.1  | 307.4 | 316.4  | 328.3  |  |                        |       |
| 25 | 314.7  | 310.6  | 305    | 305.3  | 303    | 300.9 | 300.5  | 300.5  | 302.1 | 308.9  | 313.8  | 312.5  | 331.5  | 342.7 | 350.8  | 367.4  |  |                        |       |
| 21 | 362.4  | 370    | 356    | 364.4  | 355.5  | 355.5 | 350.8  | 353.8  | 352   | 363.7  | 373.7  | 386.5  | 399.4  | 413.6 | 424.2  | 448.2  |  |                        |       |
| 17 | 489.7  | 558.9  | 519.8  | 515.4  | 509.1  | 515.7 | 509.8  | 512.1  | 493.5 | 525.8  | 570.2  | 599.7  | 613.2  | 611.1 | 626.9  | 657.6  |  |                        |       |
| 13 | 763.3  | 956.7  | 858.1  | 858    | 730.5  | 826.4 | 880.8  | 843.4  | 963.8 | 882.6  | 958    | 997.8  | 2188.9 | 976.4 | 1076.5 | 1088.2 |  |                        |       |
| 9  | 1805.3 | 1462.4 | 3652.6 | 1772.2 | 1990.7 | 1617  | 1794.6 | 1779.4 | 1766  | 1988.3 | 2175.9 | 2188.9 |        |       |        |        |  |                        |       |

Figure 31: Duty Cycle Section 5 1600cc BSFC value and data, (Daniel Salathiel, 2019).

The calculated Brake Specific Fuel Consumption value was that of 858 g/Kw.h, which was further processed to equal 3.10 grams of fuel being consumed per second. This is attributed to the fact that the car is using a greater power (Kw) due to a greater load, pushing the Brake Specific Fuel Consumption figure closer to the optimum BSFC efficiency of 241.1 g/Kw.h. The value for section 5 still shows an inefficiency of 71% greater fuel consumption in g/Kw.h than the idealised optimum BSFC figure. This equates to 0.9 grams of fuel per second.

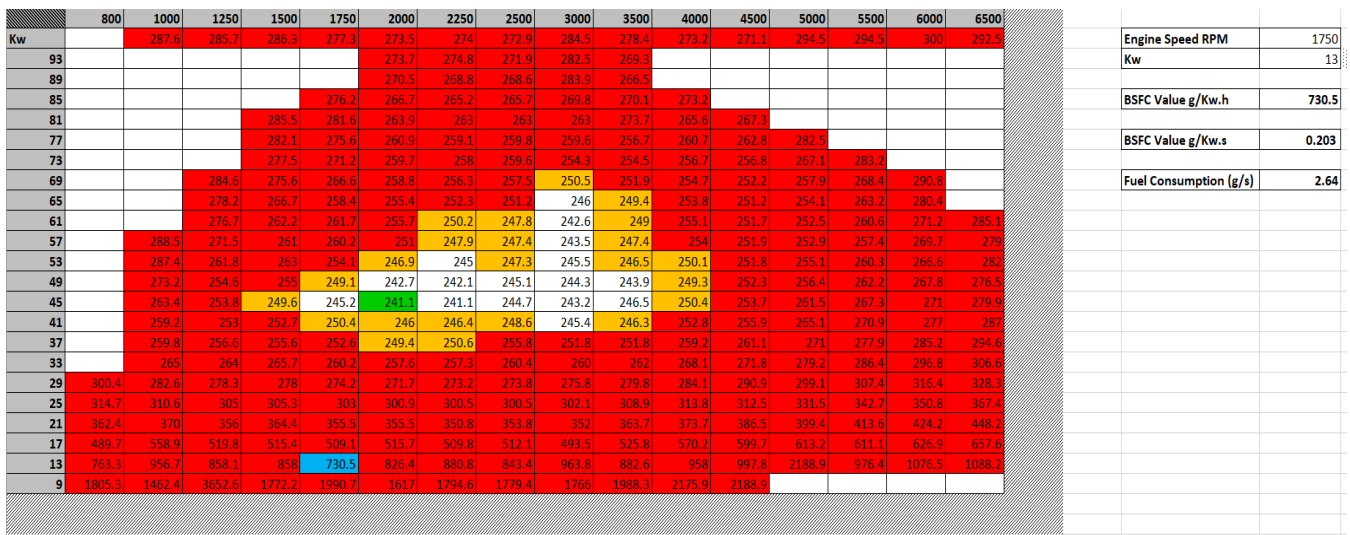


Figure 32: Duty Cycle Section 5 BSFC 800cc map, (Daniel Salathiel, 2019).

The downsized engine uses a 5<sup>th</sup> gear ratio of 1.15, meaning the engine speed is equal to 1750 rpm, at the same engine power and road speed. The figure shows the Brake Specific Fuel Consumption values for section 5 of the duty cycle when testing the 800cc downsized engine. The G/Kw.h can be seen to be 730.5, meaning a decrease in fuel consumption per hour of 14% when compared to the higher capacity engine. The downsized engine saves 0.64 grams of fuel per second when compared to its higher capacity counterpart, leading to a saving of 20% per second in terms of fuel used per second.

This saving in Brake Specific Fuel Consumption can be seen due to the higher duty cycle loads than section 1, pushing the downsized engines Brake Specific Fuel Consumption figures closer to the optimum range of consumption, due to the shifting on the engines operation map for a given road speed and engine speed, as seen in the results highlighted in blue on the BSFC map.

### 5.2.5- Duty Cycle Section 8 Analysis:

Section 8 of the duty cycle displays a high load, high road speed part of the duty cycle during data collection. The average power for this higher road speed section for the higher capacity 1600cc engine used for testing, is 21.07Kw, with an average road speed of 20.21 m/s (45.21 Mph). For this average speed to be achieved the vehicle must be using 4<sup>th</sup> gear at 2000 Rpm (for the higher capacity engine).

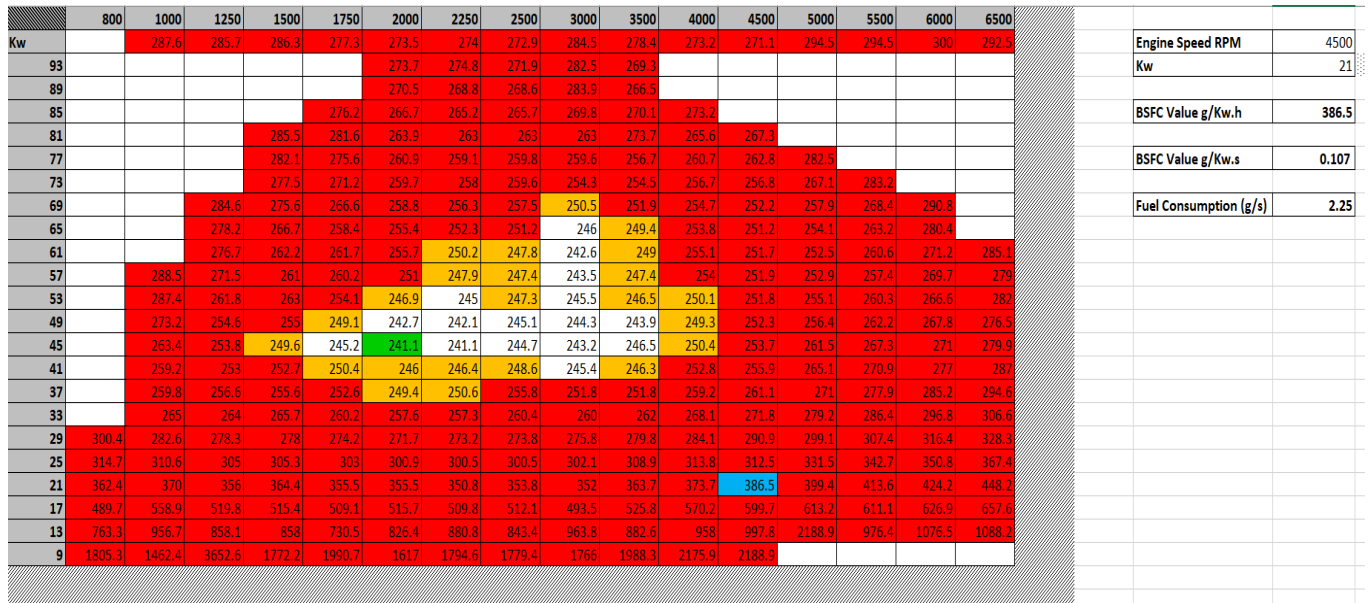


Figure 33: Duty Cycle section 8 BSFC map 1600cc results, (Daniel Salathiel 2019).

The higher capacity engine Brake Specific Fuel Consumption values when compared to the optimum value of the BSFC map in the figure above shows a decrease in efficiency of 32% due to the engine requiring higher engine speed and power request due to the higher demands of the duty cycle. This is considerably decreased over the lower loads and road speed due to the decreased pumping losses attributed to the higher throttle opening percentages required to maintain the power request of this duty cycle section (Mechadyne, 2018).

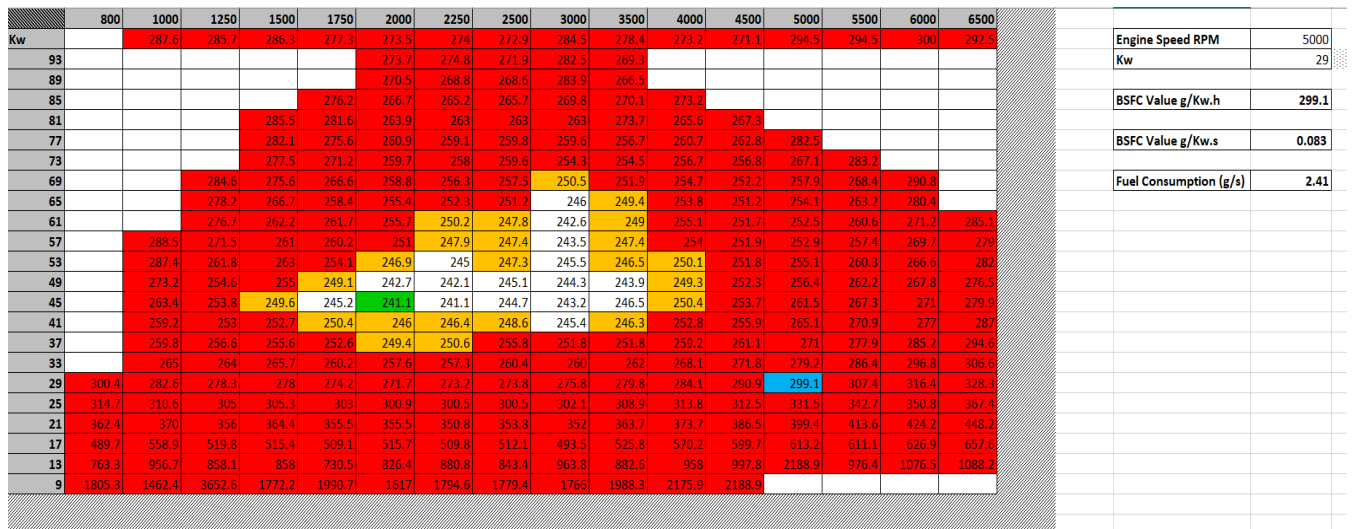


Figure 34: Duty Cycle Section 8 800cc BSFC map values, (Daniel Salathiel, 2019).

The downsized engine Brake Specific Fuel Consumption value for g/kw.h can be seen highlighted in blue in the figure above. The Brake Specific Fuel Consumption for the 800cc engine using a power of 29kw and an engine speed of 2500 rpm to match the load requirements is 353.8 g/Kw.h. This means that the downsized engine is 0.4% more efficient than the larger counterpart, but still shows a 31% increase in g/Kw.h when compared to the optimum Brake Specific Fuel Consumption value shown in green on the BSFC map, but still shows an 1% improvement over the 1600cc engine.

The decrease in consumption can be linked to the engine speed (Rpm) associated with the new 4<sup>th</sup> gear ratio designed for the downsized engine required to maintain the higher duty cycle loads, but having said this the shift in the range is required for the downsized engine to achieve the more efficiency g/Kw.h over a longer duration can achieve higher efficiencies (Mechadyne, 2018).

### 5.2.6 Duty Cycle specific points analysis Aerodynamic resistance values:

For each point selected from the duty cycle, a low load, mid load and high load, an Aerodynamic resistance value was found using the coast down data look-up value function in Excel. This value was inputted into the duty cycle to give a more accurate real-life figure for the power output (Kw) and engine speed. These values are inputted into the Brake Specific Fuel Consumption look-up function in the duty cycle Excel Spreadsheet to give an accurate consumption value for that specific point along the duty cycle. This is to measure and compare the efficiencies of the higher capacity 1600cc engine, and the proposed downsized 800cc engine.

The acquisition of the Aerodynamic figures from the coast down test, and the input into the duty cycle to analyse the efficiency of each engine unit can be seen in the figures below.

| 1  | Speed (MPH) | Velocity (m/s) | Change in Acceleration (m/s) | Change in Acceleration (N) |  |  |             |          |
|----|-------------|----------------|------------------------------|----------------------------|--|--|-------------|----------|
| 2  | 63.83       | 28.53          | 0.00                         | 0.00                       |  |  | Weight (Kg) | 1105     |
| 3  | 61.85       | 27.65          | -0.89                        | -978.92                    |  |  |             |          |
| 4  | 60.62       | 27.10          | -0.55                        | -609.24                    |  |  | Speed       | 3.96     |
| 5  | 60.44       | 27.02          | -0.08                        | -86.70                     |  |  | Drag N      | -322.898 |
| 6  | 59.46       | 26.58          | -0.44                        | -483.70                    |  |  |             |          |
| 7  | 58.80       | 26.29          | -0.29                        | -325.32                    |  |  |             |          |
| 8  | 57.60       | 25.75          | -0.54                        | -593.84                    |  |  |             |          |
| 9  | 56.68       | 25.34          | -0.41                        | -454.29                    |  |  |             |          |
| 10 | 55.67       | 24.89          | -0.45                        | -498.19                    |  |  |             |          |
| 11 | 55.33       | 24.73          | -0.15                        | -170.27                    |  |  |             |          |
| 12 | 54.25       | 24.25          | -0.48                        | -529.44                    |  |  |             |          |
| 13 | 53.29       | 23.82          | -0.43                        | -474.72                    |  |  |             |          |

Figure 35: Point 1 Aerodynamic Resistance look-up value for low load, (Daniel Salathiel, 2019)

| 1  | time [s] | Velocity in MPH | Velocity in (m/s) | Change in Acceleration (m/s) | Change Acceleration (N) | Aero Force (N) | Rolling Resistance (N) | Gradient Resistance (N) | Total Resistance (N) | Power (Kw) | Power (BHP) |
|----|----------|-----------------|-------------------|------------------------------|-------------------------|----------------|------------------------|-------------------------|----------------------|------------|-------------|
| 49 | 47       | 6.11            | 2.73              | -0.07                        | -74.93                  | 6.10           | 542.00                 | 0                       | 473.17               | 1.29       | 1.73        |
| 50 | 48       | 5.43            | 2.43              | -0.30                        | -335.55                 | 4.82           | 542.00                 | 0                       | 211.27               | 0.51       | 0.69        |
| 51 | 49       | 5.51            | 2.46              | 0.04                         | 41.06                   | 4.97           | 542.00                 | 0                       | 588.04               | 1.45       | 1.94        |
| 52 | 50       | 5.80            | 2.59              | 0.13                         | 141.90                  | 5.50           | 542.00                 | 0                       | 689.41               | 1.79       | 2.39        |
| 53 | 51       | 6.55            | 2.93              | 0.34                         | 371.70                  | 7.02           | 542.00                 | 0                       | 920.72               | 2.70       | 3.61        |
| 54 | 52       | 7.67            | 3.43              | 0.50                         | 555.70                  | 9.64           | 542.00                 | 0                       | 1107.35              | 3.80       | 5.09        |
| 55 | 53       | 7.86            | 3.51              | 0.08                         | 90.76                   | 10.11          | 542.00                 | 0                       | 642.87               | 2.26       | 3.03        |
| 56 | 54       | 7.90            | 3.53              | 0.02                         | 20.62                   | 10.22          | 542.00                 | 0                       | 572.84               | 2.02       | 2.71        |
| 57 | 55       | 8.17            | 3.65              | 0.12                         | 135.89                  | 10.94          | 542.00                 | 0                       | 688.84               | 2.52       | 3.37        |
| 58 | 56       | 8.33            | 3.72              | 0.07                         | 74.77                   | 11.35          | 542.00                 | 0                       | 628.13               | 2.34       | 3.13        |
| 59 | 57       | 8.52            | 3.81              | 0.09                         | 95.02                   | 12.23          | 542.00                 | 0                       | 959.92               | 3.66       | 4.90        |
| 60 | 58       | 8.64            | 3.86              | 0.06                         | 61.82                   | 12.23          | 542.00                 | 0                       | 616.06               | 2.38       | 3.19        |
| 61 | 59       | 9.06            | 4.05              | 0.19                         | 206.15                  | 13.44          | 542.00                 | 0                       | 761.60               | 3.08       | 4.13        |
| 62 | 60       | 8.78            | 3.93              | -0.12                        | -137.70                 | 12.63          | 542.00                 | 0                       | 416.94               | 1.64       | 2.19        |
| 63 | 61       | 8.34            | 3.73              | -0.20                        | -220.53                 | 11.38          | 542.00                 | 0                       | 332.85               | 1.24       | 1.66        |
| 64 | 62       | 8.29            | 3.71              | -0.02                        | -20.63                  | 11.26          | 542.00                 | 0                       | 532.64               | 1.97       | 2.65        |
| 65 | 63       | 8.36            | 3.74              | 0.03                         | 34.70                   | 11.46          | 542.00                 | 0                       | 588.15               | 2.20       | 2.95        |
| 66 | 64       | 8.70            | 3.89              | 0.15                         | 164.33                  | 12.39          | 542.00                 | 0                       | 718.72               | 2.79       | 3.74        |
| 67 | 65       | 8.94            | 4.00              | 0.11                         | 118.67                  | 13.08          | 542.00                 | 0                       | 673.75               | 2.69       | 3.61        |
| 68 | 66       | 9.76            | 4.36              | 0.37                         | 408.11                  | 15.61          | 542.00                 | 0                       | 965.72               | 4.21       | 5.65        |
| 69 | 67       | 10.10           | 4.51              | 0.15                         | 165.36                  | 16.70          | 542.00                 | 0                       | 724.06               | 3.27       | 4.38        |

Figure 36: Duty Cycle point 1 inputted Aerodynamic Resistance value to obtain actual Kw value, (Daniel Salathiel, 2019).

| 1  | Speed (MPH) | Velocity (m/s) | Change in Acceleration (m/s) | Change in Acceleration (N) |  |  |             |          |  |
|----|-------------|----------------|------------------------------|----------------------------|--|--|-------------|----------|--|
| 2  | 63.83       | 28.53          | 0.00                         | 0.00                       |  |  | Weight (Kg) | 1105     |  |
| 3  | 61.85       | 27.65          | -0.89                        | -978.92                    |  |  |             |          |  |
| 4  | 60.62       | 27.10          | -0.55                        | -609.24                    |  |  | Speed       | 9.34     |  |
| 5  | 60.44       | 27.02          | -0.08                        | -86.70                     |  |  | Drag N      | -274.887 |  |
| 6  | 59.46       | 26.58          | -0.44                        | -483.70                    |  |  |             |          |  |
| 7  | 58.80       | 26.29          | -0.29                        | -325.32                    |  |  |             |          |  |
| 8  | 57.60       | 25.75          | -0.54                        | -593.84                    |  |  |             |          |  |
| 9  | 56.68       | 25.34          | -0.41                        | -454.29                    |  |  |             |          |  |
| 10 | 55.67       | 24.89          | -0.45                        | -498.19                    |  |  |             |          |  |
| 11 | 55.33       | 24.73          | -0.15                        | -170.27                    |  |  |             |          |  |
| 12 | 54.25       | 24.25          | -0.48                        | -529.44                    |  |  |             |          |  |
| 13 | 53.29       | 23.82          | -0.43                        | -474.72                    |  |  |             |          |  |

Figure 37: Point 2 Aerodynamic Resistance look-up value for low load, (Daniel Salathiel, 2019)

|     | A        | B               | C                 | D                            | E                       | F              | G                      | H                       | I                    | J          | K           |
|-----|----------|-----------------|-------------------|------------------------------|-------------------------|----------------|------------------------|-------------------------|----------------------|------------|-------------|
| 1   | time [s] | Velocity in MPH | Velocity in (m/s) | Change in Acceleration (m/s) | Change Acceleration (N) | Aero Force (N) | Rolling Resistance (N) | Gradient Resistance (N) | Total Resistance (N) | Power (Kw) | Power (BHP) |
| 163 | 161      | 12.19           | 5.45              | 1.14                         | 1255.43                 | 24.33          | 542.00                 | 0                       | 1821.76              | 9.93       | 13.30       |
| 164 | 162      | 15.46           | 6.91              | 1.46                         | 1614.72                 | 39.13          | 542.00                 | 0                       | 2195.85              | 15.17      | 20.33       |
| 165 | 163      | 16.92           | 7.56              | 0.65                         | 721.78                  | 46.87          | 542.00                 | 0                       | 1310.65              | 9.91       | 13.28       |
| 166 | 164      | 18.51           | 8.27              | 0.71                         | 786.17                  | 56.11          | 542.00                 | 0                       | 1384.28              | 11.45      | 15.35       |
| 167 | 165      | 18.08           | 8.08              | -0.19                        | -214.67                 | 53.50          | 542.00                 | 0                       | 380.84               | 3.08       | 4.12        |
| 168 | 166      | 17.88           | 7.99              | -0.09                        | -96.24                  | 52.36          | 542.00                 | 0                       | 498.11               | 3.98       | 5.34        |
| 169 | 167      | 17.94           | 8.02              | 0.02                         | 27.08                   | 52.68          | 542.00                 | 0                       | 621.76               | 4.99       | 6.68        |
| 170 | 168      | 17.19           | 7.68              | -0.34                        | -370.62                 | 48.36          | 542.00                 | 0                       | 219.75               | 1.69       | 2.26        |
| 171 | 169      | 17.31           | 7.74              | 0.06                         | 62.82                   | 49.08          | 542.00                 | 0                       | 653.90               | 5.06       | 6.78        |
| 172 | 170      | 18.11           | 8.10              | 0.36                         | 394.25                  | 53.71          | 542.00                 | 0                       | 989.96               | 8.01       | 10.74       |
| 173 | 171      | 18.80           | 8.41              | 0.31                         | 342.35                  | 57.90          | 542.00                 | 0                       | 942.25               | 7.92       | 10.61       |
| 174 | 172      | 19.46           | 8.70              | 0.29                         | 324.65                  | 62.02          | 542.00                 | 0                       | 928.67               | 8.08       | 10.83       |
| 175 | 173      | 20.94           | 9.36              | 0.66                         | 730.53                  | 274.89         | 542.00                 | 0                       | 1547.43              | 14.49      | 19.41       |
| 176 | 174      | 21.72           | 9.71              | 0.35                         | 384.98                  | 77.25          | 542.00                 | 0                       | 1004.23              | 9.75       | 13.07       |
| 177 | 175      | 21.93           | 9.80              | 0.09                         | 104.02                  | 78.75          | 542.00                 | 0                       | 724.78               | 7.11       | 9.52        |
| 178 | 176      | 22.88           | 10.23             | 0.43                         | 470.67                  | 85.74          | 542.00                 | 0                       | 1098.42              | 11.24      | 15.06       |
| 179 | 177      | 24.81           | 11.09             | 0.86                         | 952.55                  | 100.80         | 542.00                 | 0                       | 1595.35              | 17.69      | 23.71       |
| 180 | 178      | 26.63           | 11.91             | 0.82                         | 900.63                  | 116.16         | 542.00                 | 0                       | 1558.80              | 18.56      | 24.87       |
| 181 | 179      | 29.58           | 13.22             | 1.32                         | 1454.47                 | 143.27         | 542.00                 | 0                       | 2139.74              | 28.29      | 37.91       |

Figure 38: Duty Cycle point 2 inputted Aerodynamic Resistance value to obtain actual Kw value, (Daniel Salathiel, 2019).

| Speed (MPH) | Velocity (m/s) | Change in Acceleration (m/s) | Change in Acceleration (N) |  |  |             |          |
|-------------|----------------|------------------------------|----------------------------|--|--|-------------|----------|
| 63.83       | 28.53          | 0.00                         | 0.00                       |  |  | Weight (Kg) | 1105     |
| 61.85       | 27.65          | -0.89                        | -978.92                    |  |  |             |          |
| 60.62       | 27.10          | -0.55                        | -609.24                    |  |  | Speed       | 24.89    |
| 60.44       | 27.02          | -0.08                        | -86.70                     |  |  | Drag N      | -498.192 |
| 59.46       | 26.58          | -0.44                        | -483.70                    |  |  |             |          |
| 58.80       | 26.29          | -0.29                        | -325.32                    |  |  |             |          |
| 57.60       | 25.75          | -0.54                        | -593.84                    |  |  |             |          |
| 56.68       | 25.34          | -0.41                        | -454.29                    |  |  |             |          |
| 55.67       | 24.89          | -0.45                        | -498.19                    |  |  |             |          |
| 55.33       | 24.73          | -0.15                        | -170.27                    |  |  |             |          |
| 54.25       | 24.25          | -0.48                        | -529.44                    |  |  |             |          |
| 53.29       | 23.82          | -0.43                        | -474.72                    |  |  |             |          |
| 51.79       | 23.15          | -0.67                        | -742.63                    |  |  |             |          |
| 50.80       | 22.71          | -0.44                        | -491.32                    |  |  |             |          |
| 49.95       | 22.33          | -0.38                        | -419.36                    |  |  |             |          |
| 48.40       | 21.64          | -0.69                        | -764.23                    |  |  |             |          |
| 47.28       | 21.13          | -0.50                        | -553.95                    |  |  |             |          |

Figure 39: Point 2 Aerodynamic Resistance look-up value for low load, (Daniel Salathiel, 2019).

| time [s] | Velocity in MPH | Velocity in (m/s) | Change in Acceleration (m/s) | Change Acceleration (N) | Aero Force (N) | Rolling Resistance (N) | Gradient Resistance (N) | Total Resistance (N) | Power (Kw) | Power (BHP) |
|----------|-----------------|-------------------|------------------------------|-------------------------|----------------|------------------------|-------------------------|----------------------|------------|-------------|
| 594      | 45.84           | 20.49             | 0.66                         | 727.70                  | 344.03         | 542.00                 | 0                       | 1613.73              | 33.07      | 44.31       |
| 595      | 46.66           | 20.86             | 0.37                         | 408.26                  | 356.55         | 542.00                 | 0                       | 1306.81              | 27.26      | 36.53       |
| 596      | 46.97           | 21.00             | 0.14                         | 150.40                  | 361.22         | 542.00                 | 0                       | 1053.63              | 22.12      | 29.64       |
| 597      | 46.84           | 20.94             | -0.06                        | -64.86                  | 359.20         | 542.00                 | 0                       | 836.35               | 17.51      | 23.46       |
| 598      | 44.87           | 20.06             | -0.88                        | -968.86                 | 329.75         | 542.00                 | 0                       | -97.11               | -1.95      | -2.61       |
| 599      | 45.24           | 20.23             | 0.17                         | 182.98                  | 335.21         | 542.00                 | 0                       | 1060.20              | 21.44      | 28.73       |
| 600      | 49.87           | 22.29             | 2.07                         | 2283.87                 | 407.23         | 542.00                 | 0                       | 3233.10              | 72.07      | 96.58       |
| 601      | 54.32           | 24.28             | 1.99                         | 2198.91                 | 483.17         | 542.00                 | 0                       | 3224.09              | 78.29      | 104.91      |
| 602      | 55.85           | 24.97             | 0.68                         | 755.18                  | 498.16         | 542.00                 | 0                       | 1795.34              | 44.82      | 60.06       |
| 603      | 57.82           | 25.85             | 0.88                         | 975.63                  | 547.52         | 542.00                 | 0                       | 2065.15              | 53.38      | 71.53       |
| 604      | 61.01           | 27.27             | 1.43                         | 1575.26                 | 609.57         | 542.00                 | 0                       | 2726.83              | 74.37      | 99.66       |
| 605      | 64.75           | 28.95             | 1.67                         | 1847.93                 | 686.62         | 542.00                 | 0                       | 3076.55              | 89.06      | 119.34      |
| 606      | 64.79           | 28.96             | 0.02                         | 20.09                   | 687.48         | 542.00                 | 0                       | 1249.57              | 36.19      | 48.50       |
| 607      | 62.72           | 28.04             | -0.93                        | -1022.53                | 644.26         | 542.00                 | 0                       | 163.73               | 4.59       | 6.15        |
| 608      | 60.91           | 27.23             | -0.81                        | -895.26                 | 607.56         | 542.00                 | 0                       | 254.31               | 6.92       | 9.28        |
| 609      | 60.14           | 26.88             | -0.35                        | -382.89                 | 592.20         | 542.00                 | 0                       | 751.31               | 20.20      | 27.06       |
| 610      | 59.31           | 26.51             | -0.37                        | -408.79                 | 576.01         | 542.00                 | 0                       | 709.23               | 18.80      | 25.20       |
| 611      | 58.14           | 25.99             | -0.52                        | -579.83                 | 553.44         | 542.00                 | 0                       | 515.61               | 13.40      | 17.96       |
| 612      | 57.70           | 25.79             | -0.19                        | -214.33                 | 545.21         | 542.00                 | 0                       | 872.88               | 22.52      | 30.17       |
| 613      | 58.02           | 25.94             | 0.14                         | 156.06                  | 551.19         | 542.00                 | 0                       | 1249.26              | 32.40      | 43.42       |
| 614      | 58.22           | 26.03             | 0.09                         | 99.85                   | 555.04         | 542.00                 | 0                       | 1196.90              | 31.15      | 41.74       |
| 615      | 58.91           | 26.33             | 0.31                         | 341.04                  | 568.28         | 542.00                 | 0                       | 1451.32              | 38.22      | 51.21       |
| 616      | 59.42           | 26.56             | 0.23                         | 251.00                  | 578.13         | 542.00                 | 0                       | 1371.13              | 36.42      | 48.80       |

Figure 40: Duty Cycle point 3 inputted Aerodynamic Resistance value to obtain actual Kw value, (Daniel Salathiel, 2019).

### 5.2.7- Duty Cycle Specific analysis:

The first point for analysis is a low load road speed to give a more in depth look at the efficiency of the two engines at a given point along the car's duty cycle. The road speed selected was 3.81 m/s at 2.47 Kw, meaning the power figure on the Brake Specific Fuel Consumption map was below 9 Kw.

The road speed for this point along duty cycle requires the car to use first gear, the standard ratio for the donor car is 3.25. Meaning the calculated engine speed is 1211.44 Rpm. This value was rounded to 1250 Rpm for compatibility with the Brake Specific Fuel Consumption map for the donor car used for testing.

|    | 800    | 1000   | 1250   | 1500   | 1750   | 2000  | 2250   | 2500   | 3000  | 3500   | 4000   | 4500   | 5000   | 5500  | 6000   | 6500   |                        |        |
|----|--------|--------|--------|--------|--------|-------|--------|--------|-------|--------|--------|--------|--------|-------|--------|--------|------------------------|--------|
| Kw |        | 287.6  | 285.7  | 286.3  | 277.3  | 273.5 | 274    | 272.9  | 284.5 | 278.4  | 273.2  | 271.1  | 294.5  | 294.5 | 300    | 292.5  | Engine Speed RPM       | 1250   |
| 93 |        |        |        |        |        | 273.7 | 274.8  | 271.9  | 282.5 | 269.3  |        |        |        |       |        |        | Kw                     | 9      |
| 89 |        |        |        |        |        | 270.5 | 268.8  | 268.6  | 283.9 | 266.5  |        |        |        |       |        |        | BSFC Value g/Kw.h      | 3652.6 |
| 85 |        |        |        |        | 276.2  | 266.7 | 265.2  | 265.7  | 269.8 | 270.1  | 273.2  |        |        |       |        |        | BSFC Value g/Kw.s      | 1.015  |
| 81 |        |        |        | 285.5  | 281.6  | 263.9 | 263    | 263    | 273.7 | 265.6  | 267.3  |        |        |       |        |        | Fuel Consumption (g/s) | 9.13   |
| 77 |        |        |        | 282.1  | 275.6  | 260.9 | 259.1  | 259.8  | 259.6 | 256.7  | 260.7  | 262.8  | 282.5  |       |        |        |                        |        |
| 73 |        |        |        | 277.5  | 271.2  | 259.7 | 258    | 259.6  | 254.3 | 254.5  | 256.7  | 256.8  | 267.1  | 283.2 |        |        |                        |        |
| 69 |        |        | 284.6  | 275.6  | 266.6  | 258.8 | 256.3  | 257.5  | 250.5 | 251.9  | 254.7  | 252.2  | 257.9  | 268.4 | 290.8  |        |                        |        |
| 65 |        |        | 278.2  | 266.7  | 258.4  | 255.4 | 252.3  | 251.2  | 246   | 249.4  | 253.8  | 251.2  | 254.1  | 263.2 | 280.4  |        |                        |        |
| 61 |        |        | 276.7  | 262.2  | 261.7  | 255.7 | 250.2  | 247.8  | 242.6 | 249    | 255.1  | 251.7  | 252.5  | 260.6 | 271.2  | 285.1  |                        |        |
| 57 |        | 288.5  | 271.5  | 261    | 260.2  | 251   | 247.9  | 247.4  | 243.5 | 247.4  | 254    | 251.9  | 252.9  | 257.4 | 269.7  | 279    |                        |        |
| 53 |        | 287.4  | 261.8  | 263    | 254.1  | 246.9 | 245    | 247.3  | 245.5 | 246.5  | 250.1  | 251.8  | 255.1  | 260.3 | 266.6  | 282    |                        |        |
| 49 |        | 273.2  | 254.6  | 255    | 249.1  | 242.7 | 242.1  | 245.1  | 244.3 | 243.9  | 249.3  | 252.3  | 256.4  | 262.2 | 267.8  | 276.5  |                        |        |
| 45 |        | 263.4  | 253.8  | 249.6  | 245.2  | 241.3 | 241.1  | 244.7  | 243.2 | 246.5  | 250.4  | 253.7  | 261.5  | 267.3 | 271    | 279.9  |                        |        |
| 41 |        | 259.2  | 253    | 252.7  | 250.4  | 246   | 246.4  | 248.6  | 245.4 | 246.3  | 252.8  | 255.9  | 265.1  | 270.9 | 277    | 287    |                        |        |
| 37 |        | 259.8  | 256.6  | 255.6  | 252.6  | 249.4 | 250.6  | 255.8  | 251.8 | 251.8  | 259.2  | 261.1  | 271    | 277.9 | 285.2  | 294.6  |                        |        |
| 33 |        | 265    | 264    | 265.7  | 260.2  | 257.6 | 257.3  | 260.4  | 260   | 262    | 268.1  | 271.8  | 279.2  | 286.4 | 296.8  | 306.6  |                        |        |
| 29 | 300.4  | 282.6  | 278.3  | 278    | 274.2  | 271.7 | 273.2  | 273.8  | 275.8 | 279.8  | 284.1  | 290.9  | 299.1  | 307.4 | 316.4  | 328.3  |                        |        |
| 25 | 314.7  | 310.6  | 305    | 305.3  | 303    | 300.9 | 300.5  | 300.5  | 302.1 | 308.9  | 313.8  | 312.5  | 331.5  | 342.7 | 350.8  | 367.4  |                        |        |
| 21 | 362.4  | 370    | 356    | 364.4  | 355.5  | 355.5 | 350.8  | 353.8  | 352   | 363.7  | 373.7  | 386.5  | 399.4  | 413.6 | 424.2  | 448.2  |                        |        |
| 17 | 489.7  | 558.9  | 519.8  | 515.4  | 509.1  | 515.7 | 509.8  | 512.1  | 493.5 | 525.8  | 570.2  | 599.7  | 613.2  | 611.1 | 626.9  | 657.6  |                        |        |
| 13 | 763.3  | 956.7  | 858.1  | 858    | 730.5  | 826.4 | 880.8  | 843.4  | 963.8 | 882.6  | 958    | 997.8  | 2188.9 | 976.4 | 1076.5 | 1088.2 |                        |        |
| 9  | 1805.3 | 1462.4 | 3652.6 | 1772.2 | 1990.7 | 1617  | 1794.6 | 1779.4 | 1766  | 1988.3 | 2175.9 | 2188.9 |        |       |        |        |                        |        |

Figure 41: Duty Cycle Point 1 1600cc BSFC value, (Daniel Salathiel, 2019).

Figure 41 above shows the Brake Specific Fuel Consumption for the higher capacity engine. The 1600cc engine used the highest possible g/Kw.h at 3652.6, meaning the engine used 9.13 grams of fuel. The higher capacity engine only uses three percent of its total power at this specific point of the duty cycle, showing that the losses are high due to the greater inefficiencies at lower loads due to the pumping losses experienced, associated with the low throttle percentages experienced at these loads during the duty cycle. Thus, causing a higher vacuum the piston must work against (Mechadyne, 2018).

|    | 800    | 1000   | 1250   | 1500   | 1750   | 2000  | 2250   | 2500   | 3000  | 3500   | 4000   | 4500   | 5000   | 5500  | 6000   | 6500   |  |                        |        |
|----|--------|--------|--------|--------|--------|-------|--------|--------|-------|--------|--------|--------|--------|-------|--------|--------|--|------------------------|--------|
| Kw |        | 287.6  | 285.7  | 286.3  | 277.3  | 273.5 | 274    | 272.9  | 284.5 | 278.4  | 273.2  | 271.1  | 294.5  | 294.5 | 300    | 292.5  |  | Engine Speed RPM       | 1750   |
| 93 |        |        |        |        |        | 273.7 | 274.8  | 271.9  | 282.5 | 269.3  |        |        |        |       |        |        |  | Kw                     | 9      |
| 89 |        |        |        |        |        | 270.5 | 268.8  | 268.6  | 283.9 | 266.5  |        |        |        |       |        |        |  | BSFC Value g/Kw.h      | 1990.7 |
| 85 |        |        |        |        | 276.2  | 266.7 | 265.2  | 265.7  | 269.8 | 270.1  | 273.2  |        |        |       |        |        |  | BSFC Value g/Kw.s      | 0.553  |
| 81 |        |        |        | 285.5  | 281.6  | 263.9 | 263    | 263    | 263   | 273.7  | 265.6  | 267.1  |        |       |        |        |  | Fuel Consumption (g/s) | 4.98   |
| 77 |        |        |        | 282.1  | 275.6  | 260.9 | 259.1  | 259.8  | 259.6 | 256.7  | 260.7  | 262.8  | 282.5  |       |        |        |  |                        |        |
| 73 |        |        |        | 277.5  | 271.2  | 259.7 | 258    | 259.6  | 254.3 | 254.5  | 256.7  | 256.8  | 267.1  | 283.2 |        |        |  |                        |        |
| 69 |        |        | 284.6  | 275.6  | 266.6  | 258.8 | 256.3  | 257.5  | 250.5 | 251.9  | 254.7  | 252.2  | 257.9  | 268.4 | 290.8  |        |  |                        |        |
| 65 |        |        | 278.2  | 266.7  | 258.4  | 255.4 | 252.3  | 251.2  | 246   | 249.4  | 253.8  | 251.2  | 254.1  | 263.2 | 280.4  |        |  |                        |        |
| 61 |        |        | 276.7  | 262.2  | 261.7  | 255.7 | 250.2  | 247.8  | 242.6 | 249    | 255.1  | 251.7  | 252.5  | 260.6 | 271.2  | 285.1  |  |                        |        |
| 57 |        | 288.5  | 271.5  | 261    | 260.2  | 251   | 247.9  | 247.4  | 243.5 | 247.4  | 254    | 251.9  | 252.9  | 257.4 | 269.7  | 279    |  |                        |        |
| 53 |        | 287.4  | 261.8  | 263    | 254.1  | 246.9 | 245    | 247.3  | 245.5 | 246.5  | 250.1  | 251.8  | 255.1  | 260.3 | 266.6  | 282    |  |                        |        |
| 49 |        | 273.2  | 254.6  | 255    | 249.1  | 242.7 | 242.1  | 245.1  | 244.3 | 243.9  | 249.3  | 252.3  | 256.4  | 262.2 | 267.8  | 276.5  |  |                        |        |
| 45 |        | 263.4  | 253.8  | 249.6  | 245.2  | 241.1 | 241.1  | 244.7  | 243.2 | 246.5  | 250.4  | 253.7  | 261.5  | 267.3 | 271    | 279.9  |  |                        |        |
| 41 |        | 259.2  | 253    | 252.7  | 250.4  | 246   | 246.4  | 248.6  | 245.4 | 246.3  | 252.8  | 255.9  | 265.1  | 270.9 | 277    | 287    |  |                        |        |
| 37 |        | 259.8  | 256.6  | 255.6  | 252.6  | 249.4 | 250.6  | 255.8  | 251.8 | 251.8  | 259.2  | 261.1  | 271    | 277.9 | 285.2  | 294.6  |  |                        |        |
| 33 |        | 265    | 264    | 265.7  | 260.2  | 257.6 | 257.3  | 260.4  | 260   | 262    | 268.1  | 271.8  | 279.2  | 286.4 | 296.8  | 306.6  |  |                        |        |
| 29 | 300.4  | 282.6  | 278.3  | 278    | 274.2  | 271.7 | 273.2  | 273.8  | 275.8 | 279.8  | 284.1  | 290.9  | 299.1  | 307.4 | 316.4  | 328.3  |  |                        |        |
| 25 | 314.7  | 310.6  | 305    | 305.3  | 303    | 300.9 | 300.5  | 300.5  | 302.1 | 308.9  | 313.8  | 312.5  | 331.5  | 342.7 | 350.8  | 367.4  |  |                        |        |
| 21 | 362.4  | 370    | 356    | 364.4  | 355.5  | 355.5 | 350.8  | 353.8  | 352   | 363.7  | 373.7  | 386.5  | 399.4  | 413.6 | 424.2  | 448.2  |  |                        |        |
| 17 | 489.7  | 558.9  | 519.8  | 515.4  | 509.1  | 515.7 | 509.8  | 512.1  | 493.5 | 525.8  | 570.2  | 599.7  | 613.2  | 611.1 | 626.9  | 657.6  |  |                        |        |
| 13 | 763.3  | 956.7  | 858.1  | 858    | 730.5  | 828.4 | 880.8  | 843.4  | 963.8 | 882.6  | 958    | 997.8  | 2188.9 | 976.4 | 1076.5 | 1088.2 |  |                        |        |
| 9  | 1805.3 | 1462.4 | 3652.6 | 1772.2 | 1990.7 | 1617  | 1794.6 | 1779.4 | 1766  | 1988.3 | 2175.9 | 2188.9 |        |       |        |        |  |                        |        |

Figure 42: Duty Cycle Point 1 800cc BSFC value, (Daniel Salathiel, 2019).

The proposed downsized engine achieved a higher engine speed (rpm) because of the new gear ratio of 4.98 1<sup>st</sup> gear meaning the load is pushed more towards the higher efficiency range of the Brake Specific Fuel Consumption range than the higher capacity engine. The Brake Specific Fuel Consumption value equalled 1990.7 g/Kw.h. Meaning the downsized engine is 45% more efficient and uses 4.15 grams of fuel per second less than its counterpart.

Point two along the duty cycle route reached a speed of 9.36 m/s and a max power of 12.58 Kw (13 Kw point on the BSFC map). For this road speed the car required 2<sup>nd</sup> gear, with a ratio of 1.904 achieving an engine speed of 1231.13 Rpm, rounded to 1250 Rpm for compatibility with the Brake Specific Fuel Map used to measure the efficiency for the two engines.

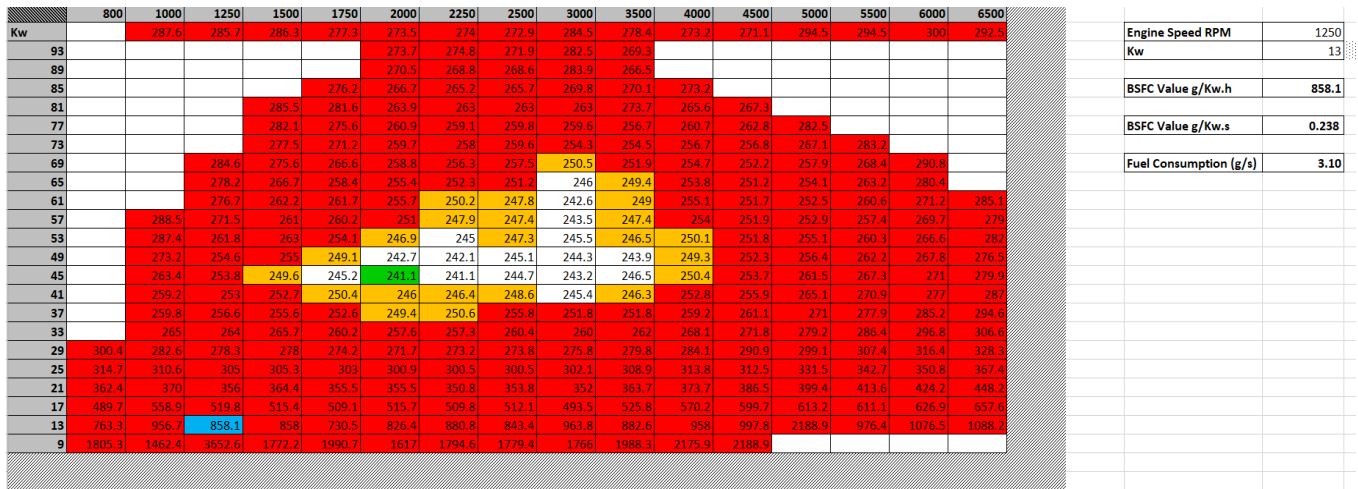


Figure 43: Duty Cycle Point 2 1600cc BSFC value, (Daniel Salathiel, 2019).

At the given engine speed and power for the 1600cc higher capacity engine, the efficiency in terms of g/Kw.h is 71% less efficient than the optimum Brake Specific Fuel Consumption value. The Brake Specific Fuel Consumption value for the engine used for testing is 858.1 g/Kw.h and 3.01 grams of fuel consumed per second.

|    | 800    | 1000   | 1250   | 1500   | 1750   | 2000  | 2250   | 2500   | 3000  | 3500   | 4000   | 4500   | 5000   | 5500  | 6000   | 6500   |       |                        |       |
|----|--------|--------|--------|--------|--------|-------|--------|--------|-------|--------|--------|--------|--------|-------|--------|--------|-------|------------------------|-------|
| Kw |        | 287.6  | 285.7  | 286.3  | 277.3  | 273.5 | 274    | 272.9  | 284.5 | 278.4  | 273.2  | 271.1  | 294.5  | 294.5 | 300    | 292.5  |       | Engine Speed RPM       | 1500  |
| 93 |        |        |        |        |        | 273.7 | 274.8  | 271.9  | 282.5 | 269.3  |        |        |        |       |        |        |       | Kw                     | 13    |
| 89 |        |        |        |        |        | 270.5 | 268.8  | 268.6  | 283.9 | 266.5  |        |        |        |       |        |        |       | BSFC Value g/Kw.h      | 858   |
| 85 |        |        |        |        | 276.2  | 266.7 | 265.2  | 265.7  | 269.8 | 270.1  | 273.2  |        |        |       |        |        |       | BSFC Value g/Kw.s      | 0.238 |
| 81 |        |        |        | 285.5  | 281.6  | 263.9 | 263    | 263    | 263   | 273.7  | 265.6  | 267.3  |        |       |        |        |       | Fuel Consumption (g/s) | 3.10  |
| 77 |        |        |        | 282.1  | 275.6  | 260.9 | 259.1  | 259.8  | 259.6 | 256.7  | 260.7  | 262.8  | 282.5  |       |        |        |       |                        |       |
| 73 |        |        |        | 277.5  | 271.2  | 259.7 | 258    | 259.6  | 254.3 | 254.5  | 256.7  | 256.8  | 267.1  | 283.2 |        |        |       |                        |       |
| 69 |        |        | 284.6  | 275.6  | 266.6  | 258.8 | 256.3  | 257.5  | 250.5 | 251.9  | 254.7  | 252.2  | 257.9  | 268.4 | 290.8  |        |       |                        |       |
| 65 |        |        | 278.2  | 266.7  | 258.4  | 255.4 | 252.3  | 251.2  | 246   | 249.4  | 253.8  | 251.2  | 254.1  | 263.2 | 280.4  |        |       |                        |       |
| 61 |        |        | 276.7  | 262.2  | 261.7  | 255.7 | 250.2  | 247.8  | 242.6 | 249    | 255.1  | 251.7  | 252.5  | 260.6 | 271.2  | 285.1  |       |                        |       |
| 57 |        | 288.5  | 271.5  | 261    | 260.2  | 251   | 247.9  | 247.4  | 243.5 | 247.4  | 254    | 251.9  | 252.9  | 257.4 | 269.7  | 279    |       |                        |       |
| 53 |        |        | 287.4  | 261.8  | 263    | 254.1 | 246.9  | 245    | 247.3 | 245.5  | 246.5  | 250.1  | 251.8  | 255.1 | 260.3  | 266.6  | 282   |                        |       |
| 49 |        |        | 273.2  | 254.6  | 255    | 249.1 | 242.7  | 242.1  | 245.1 | 244.3  | 243.9  | 249.3  | 252.3  | 256.4 | 262.2  | 267.8  | 276.5 |                        |       |
| 45 |        |        | 263.4  | 253.8  | 249.6  | 245.2 | 241.1  | 241.1  | 244.7 | 243.2  | 246.5  | 250.4  | 253.7  | 261.5 | 267.3  | 271    | 279.9 |                        |       |
| 41 |        |        | 259.2  | 253    | 252.7  | 250.4 | 246    | 246.4  | 248.6 | 245.4  | 246.3  | 252.8  | 255.9  | 265.1 | 270.9  | 277    | 287   |                        |       |
| 37 |        |        | 259.8  | 256.6  | 255.6  | 252.6 | 249.4  | 250.6  | 255.8 | 251.8  | 251.8  | 259.2  | 261.1  | 271   | 277.9  | 285.2  | 294.6 |                        |       |
| 33 |        |        | 265    | 264    | 265.7  | 260.2 | 257.6  | 257.3  | 260.4 | 260    | 262    | 268.1  | 271.8  | 279.2 | 286.4  | 296.8  | 306.6 |                        |       |
| 29 | 300.4  | 282.6  | 278.3  | 278    | 274.2  | 271.7 | 273.2  | 273.8  | 275.8 | 279.8  | 284.1  | 290.9  | 299.1  | 307.4 | 316.4  | 328.3  |       |                        |       |
| 25 | 314.7  | 310.6  | 305    | 305.3  | 303    | 300.9 | 300.5  | 300.5  | 302.1 | 308.9  | 313.8  | 312.5  | 331.5  | 342.7 | 350.8  | 367.4  |       |                        |       |
| 21 | 362.4  | 370    | 356    | 364.4  | 355.5  | 355.5 | 350.8  | 353.8  | 352   | 363.7  | 373.7  | 386.5  | 399.4  | 413.6 | 424.2  | 448.2  |       |                        |       |
| 17 | 489.7  | 558.9  | 519.8  | 515.4  | 509.1  | 515.7 | 509.8  | 512.1  | 493.5 | 525.8  | 570.2  | 599.7  | 613.2  | 611.1 | 626.9  | 657.6  |       |                        |       |
| 13 | 763.3  | 956.7  | 858.1  | 858    | 730.5  | 826.4 | 880.8  | 843.4  | 963.8 | 882.6  | 958    | 997.8  | 2188.9 | 976.4 | 1076.5 | 1088.2 |       |                        |       |
| 9  | 1805.3 | 1462.4 | 3652.6 | 1772.2 | 1990.7 | 1617  | 1794.6 | 1779.4 | 1766  | 1988.3 | 2175.9 | 2188.9 |        |       |        |        |       |                        |       |

Figure 44: Duty Cycle Point 2 800cc BSFC value, (Daniel Salathiel, 2019).

Along the same point of the duty cycle the downsized engine achieved an engine speed of 1557.5 Rpm (1500 rpm on BSFC Map), using a modified 1.78 ratio 2<sup>nd</sup> gear. The Brake Specific Fuel Consumption value is 858 g/Kw.h, meaning at this road speed for the higher capacity and downsized engine have the same efficiency when compare to the optimum value, even though on the other points and sections the higher operation loads associated with the downsized engine increase the efficiency. Meaning that this point and load on the duty cycle shows minimal efficiency gains from the downsized technology.

Point 3 shows a high load point on the car's duty cycle. The speed achieved was 24.97 m/s, at this speed there is 498.19 newtons of aerodynamic resistance acting upon the car with a max power of 45 Kw. This road speed required 4<sup>th</sup> gear in the test car, which uses a ratio of 1.064. At this ratio and speed the engine speed equalled 2599.82 Rpm (2500 Rpm on BSFC map).

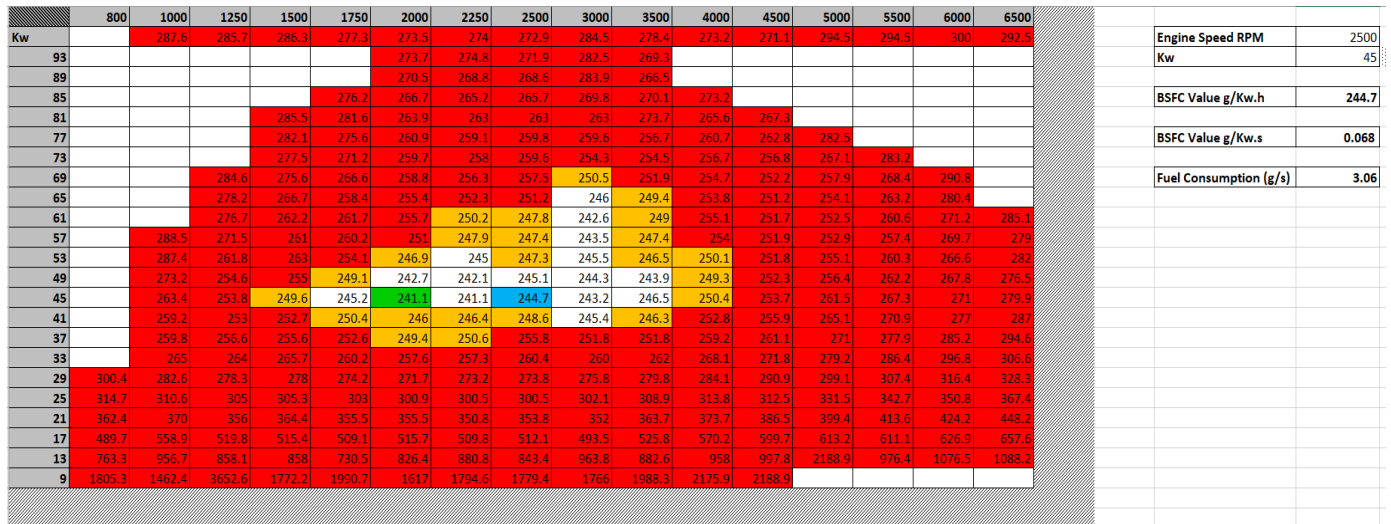


Figure 45: Duty Cycle Point 3 1600cc BSFC value, (Daniel Salathiel, 2019).

Figure 45 shows the Brake Specific Fuel Consumption if the 1600cc engine to be at a higher efficiency during high load sections. The load range has been pushed to a higher efficiency operating section of the map, meaning the engine used 244.7 g/Kw.h and 3.06 g/s. Due to the high increase in efficiency at this operation point associated with decreased pumping losses, and a greater affiliation for a better air to fuel ratio burn, in terms of energy produced per gram of fuel used, the engine achieved a 93% reduction in g/Kw.h when compared to the low load point at 2.47 Kw engine power. Adapted from (Mechadyne, 2018).

|    | 800    | 1000   | 1250   | 1500   | 1750   | 2000  | 2250   | 2500   | 3000  | 3500   | 4000   | 4500   | 5000   | 5500  | 6000   | 6500   |
|----|--------|--------|--------|--------|--------|-------|--------|--------|-------|--------|--------|--------|--------|-------|--------|--------|
| Kw |        | 287.6  | 285.7  | 286.3  | 277.3  | 273.5 | 274    | 272.9  | 284.5 | 278.4  | 273.2  | 271.1  | 294.5  | 294.5 | 300    | 292.5  |
| 93 |        |        |        |        |        | 273.7 | 274.8  | 271.9  | 282.5 | 269.3  |        |        |        |       |        |        |
| 89 |        |        |        |        |        | 270.5 | 268.8  | 268.6  | 283.9 | 266.5  |        |        |        |       |        |        |
| 85 |        |        |        |        | 276.2  | 266.7 | 265.2  | 265.7  | 269.8 | 270.1  | 273.2  |        |        |       |        |        |
| 81 |        |        |        | 285.5  | 281.6  | 263.9 | 263    | 263    | 273.7 | 265.6  | 287.3  |        |        |       |        |        |
| 77 |        |        |        | 282.1  | 275.6  | 260.9 | 259.1  | 259.8  | 259.6 | 260.7  | 262.8  | 282.5  |        |       |        |        |
| 73 |        |        |        | 277.5  | 271.2  | 259.7 | 258    | 259.6  | 254.3 | 254.5  | 256.7  | 256.8  | 267.1  | 283.3 |        |        |
| 69 |        |        | 284.6  | 275.6  | 266.6  | 258.8 | 256.3  | 257.5  | 250.5 | 251.9  | 254.7  | 252.2  | 257.9  | 268.4 | 290.8  |        |
| 65 |        |        | 278.2  | 266.7  | 258.4  | 255.4 | 252.3  | 251.2  | 246   | 249.4  | 253.8  | 251.2  | 254.1  | 263.2 | 280.4  |        |
| 61 |        |        | 276.7  | 262.2  | 261.7  | 255.7 | 250.2  | 247.8  | 242.6 | 249    | 255.1  | 251.7  | 252.5  | 260.6 | 271.2  | 285.1  |
| 57 |        | 288.5  | 271.5  | 261    | 260.2  | 251   | 247.9  | 247.4  | 243.5 | 247.4  | 254    | 251.9  | 252.9  | 257.4 | 269.7  | 279    |
| 53 |        | 287.4  | 261.8  | 263    | 254.1  | 246.9 | 245    | 247.3  | 245.5 | 246.5  | 250.1  | 251.8  | 255.1  | 260.3 | 266.6  | 282    |
| 49 |        | 273.2  | 254.6  | 255    | 249.1  | 242.7 | 242.1  | 245.1  | 244.3 | 243.9  | 249.3  | 252.3  | 256.4  | 262.2 | 267.8  | 276.5  |
| 45 |        | 263.4  | 253.8  | 249.6  | 245.2  | 241.1 | 241.1  | 244.7  | 243.2 | 246.5  | 250.4  | 253.7  | 261.5  | 267.3 | 271    | 279.9  |
| 41 |        | 259.2  | 253    | 252.7  | 250.4  | 246   | 246.4  | 248.6  | 245.4 | 246.3  | 252.8  | 255.9  | 265.1  | 270.9 | 277    | 282    |
| 37 |        | 259.8  | 256.6  | 255.6  | 252.6  | 249.4 | 250.6  | 255.8  | 251.8 | 251.8  | 259.2  | 261.1  | 271    | 277.9 | 285.2  | 294.6  |
| 33 |        | 265    | 264    | 265.7  | 260.2  | 257.6 | 257.3  | 260.4  | 260   | 262    | 268.1  | 271.8  | 279.2  | 286.4 | 296.8  | 306.6  |
| 29 | 300.4  | 282.6  | 278.3  | 278    | 274.2  | 271.7 | 273.2  | 273.8  | 275.8 | 279.8  | 284.1  | 290.9  | 299.1  | 307.4 | 316.4  | 328.3  |
| 25 | 314.7  | 310.6  | 305    | 305.3  | 303    | 300.9 | 300.5  | 300.5  | 302.1 | 308.9  | 313.8  | 312.5  | 331.5  | 342.7 | 350.8  | 367.4  |
| 21 | 362.4  | 370    | 356    | 364.4  | 355.5  | 350.8 | 353.8  | 352    | 363.7 | 373.7  | 386.5  | 399.4  | 413.6  | 424.2 | 448.2  |        |
| 17 | 489.7  | 558.9  | 519.8  | 515.4  | 509.1  | 515.7 | 509.8  | 512.1  | 493.5 | 525.8  | 570.2  | 599.7  | 613.2  | 611.1 | 626.9  | 657.6  |
| 13 | 763.3  | 956.7  | 858.1  | 858    | 730.5  | 826.4 | 880.8  | 843.4  | 963.8 | 882.6  | 958    | 997.8  | 2188.9 | 976.4 | 1076.5 | 1088.2 |
| 9  | 1805.3 | 1462.4 | 3652.6 | 1772.2 | 1990.7 | 1617  | 1794.6 | 1779.4 | 1766  | 1988.3 | 2175.9 | 2188.9 |        |       |        |        |

|                        |       |
|------------------------|-------|
| Engine Speed RPM       | 3000  |
| Kw                     | 45    |
| BSFC Value g/Kw.h      | 243.2 |
| BSFC Value g/Kw.s      | 0.068 |
| Fuel Consumption (g/s) | 3.04  |

Figure 46: Duty Cycle Point 3 800cc BSFC value, (Daniel Salathiel, 2019).

Even at higher operating loads the downsized engine shows a higher efficiency in relation to the amount of fuel consumed for the same engine power. The downsized engine with a gear ratio of 1.31 4<sup>th</sup> gear can achieve a greater engine speed of 3200.90 Rpm, increasing the operation load range further saving 1% of fuel in relation to g/Kw.h. A closer Brake Specific Fuel Consumption value to the optimum, meaning at all load points analysed, the downsized engine technology saved greater amounts of fuel per g/Kw.h and g/s than the higher capacity counterpart, indicating the technology is more efficient in relation to BSFC.

### 5.3- Efficiency of Downsizing Technology:

The downsizing of a petrol engine has long been recognised as an affective technology not only to reduce emissions but decreasing the fuel consumption combined. Engine downsizing is the process whereby the engines operating load range is shifted to a higher point along the Brake Specific Fuel consumption and performance map, closer to the more efficient region, utilising the reduction in engine swept volume in relation to its capacity. (Bassett. Et al, 2016).

Further improvements in Brake Specific Fuel consumption and performance are made possible through increased levels of downsizing. In the case of the car being tested for this report, a 50% decrease in swept volume. The higher compression ratio of this engine also leads to a part-load fuel economy benefit in relation to the Brake Specific Fuel consumption, which can be seen in the figure below highlighting a typical BSFC map for a downsized engine.

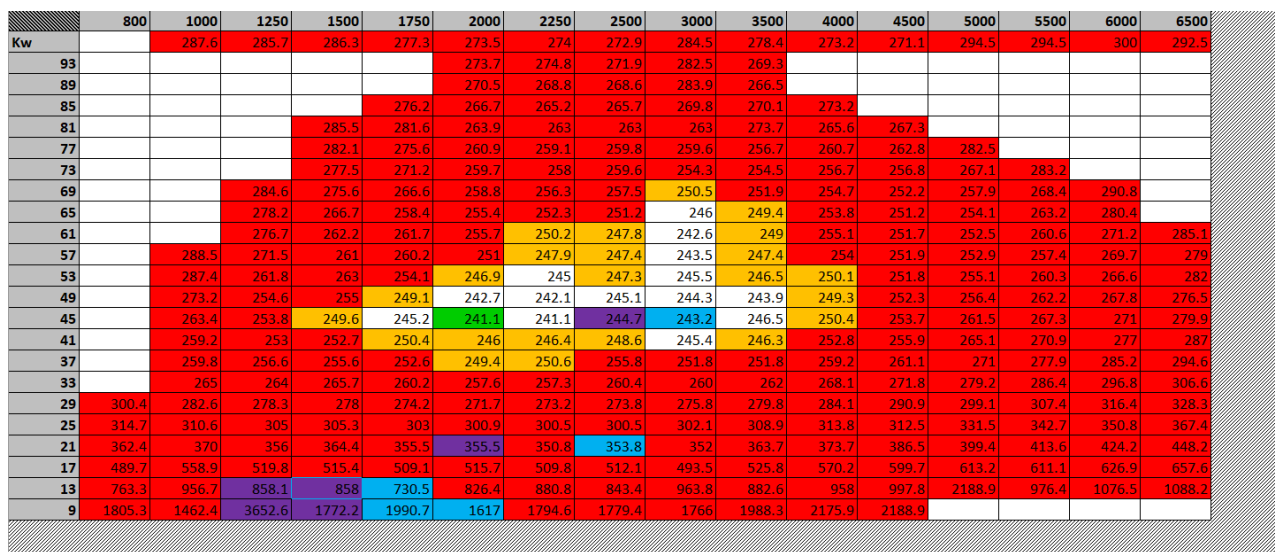


Figure 47: BSFC map with indicated 800cc values and 1600cc values, (Daniel Salathiel, 2019)

The values highlighted on the map above in blue indicate the discussed Brake Specific Fuel consumption data for the 800cc downsized engine, whereas the purple values represent the higher capacity 1600cc engine used to gather the duty cycle data. The values plotted for the downsized engine can clearly be seen to be closer to the optimum operating range for fuel consumption. This clearly indicated that the downsized engine is more efficient at part-load duty cycle operation. As supported by (Bassett. Et al, 2016) findings. The high capacity engine can be seen to operate in the highly inefficient range and can be seen to use only 90 percent of its available power in an urban environment.

The Fuel consumption savings for the downsized engine could also be attributed to the reduction in frictional, pumping and thermodynamic losses. The smaller engine means there is a reduction in friction due to the smaller moving parts, thus reducing the losses responsible for up to 8% loss of the total fuel energy (Mechadyne, 2018). A downsized engine can achieve up to 50% less friction resulting in a minimum of 11% reduction in fuel consumption (nap.edu, 2019). At part load the throttle restricts the air flow, decreasing the volumetric efficiency and causing the pressure in the manifold to fall below atmospheric pressure. Its due to the is affect pumping losses occur, thus a lower capacity engine requiring higher throttle position for the same road speed during the duty cycle decreases the pumping losses occurring. (Mechadyne, 2018).

The thermodynamic factors affect indicates the thermal efficiency. The reduction in losses within the downsized engine when compared to the higher capacity engine is a result of the higher compression ratio. The increase in pressure can provide an increase in cycle efficiency when used in relation to pressure assist systems and valve timings, maintaining the higher compression while increasing the expansion ratio. Also, the decrease in capacity means there is a reduction in heat being produced associated with the Otto Combustion Process. This reduction In volumetric flow can present transient performance issues. Technologies to improve the performance of a downsized engine to equal that of the higher naturally aspirated engine will be discussed in the following section (nap.edu, 2019).

This means that the downsizing technology provides a solution for the poor Brake Specific Fuel consumption values of the higher capacity counter parts.

The figure below shows a typical Brake Specific Fuel Consumption Map for a downsized engine used to cross reference the findings in this report.

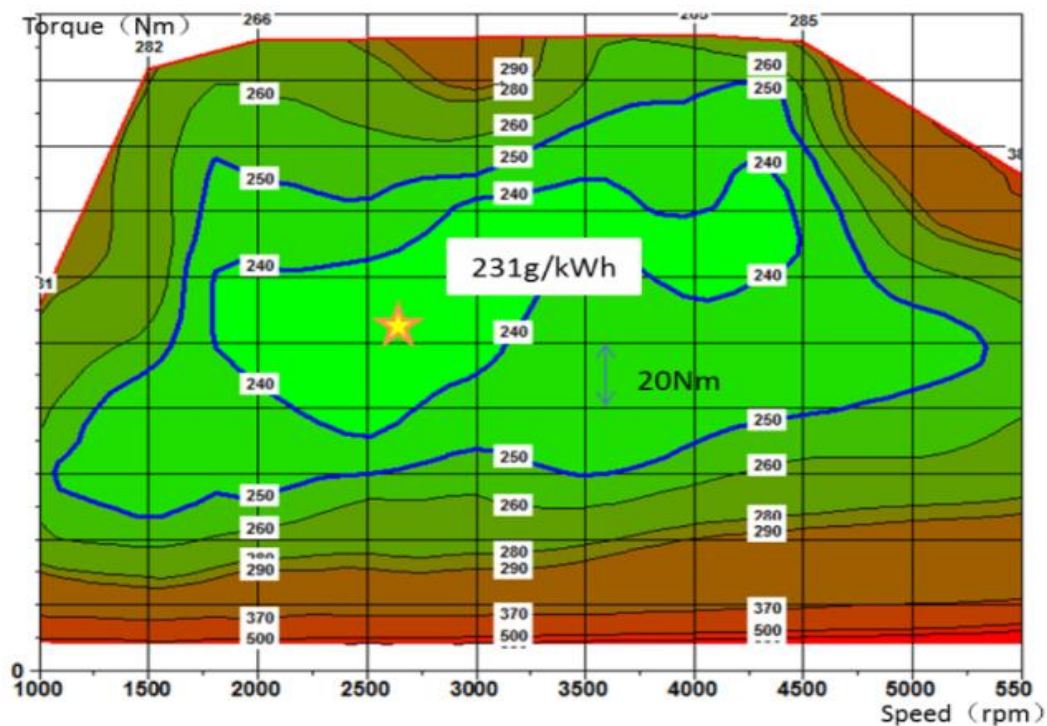


Figure 48: Typical Downsized Engine BSFC Map, (S. Zhang.Et al, 2017).

#### **5.4- Volumetric Flow Transient Performance Analysis:**

##### **5.4.1- Calculated Volumetric Flow for Naturally Aspirated performance:**

| <b><u>1600cc N/a:</u></b>                                             | <b><u>800cc N/a</u></b>                                                |
|-----------------------------------------------------------------------|------------------------------------------------------------------------|
| $V = \frac{v \times \eta \times N}{2 \times 60}$                      | $V = \frac{v \times \eta \times N}{2 \times 60}$                       |
| $V = \frac{6.28 \times 10^{-3} \times 0.78 \times 7000}{2 \times 60}$ | $V = \frac{3.232 \times 10^{-3} \times 0.78 \times 7000}{2 \times 60}$ |
| $V = 0.286 \text{ m}^3/\text{s}$                                      | $V = 0.147 \text{ m}^3/\text{s}$                                       |

*Figure 49: Volumetric Flow Equation comparison, (Daniel Salathiel, 2019).*

The figure above shows the calculated volumetric flow rates for both the higher capacity engine and the downsized engine. Assume the efficiency for both engines is 78% for accuracy for comparison.

The total swept volume of the original 1600cc engine in the donor car is  $6.28 \times 10^{-3}$ . The volume for the 800cc engine is  $3.232 \times 10^{-3}$ . A comparison of the flow rate showed that the volumetric flow for the downsized engine is  $0.139 \text{ m}^3/\text{s}$  less, meaning that both the volumetric flow and total cylinder volume in  $\text{mm}^3$  is 49% less than the higher capacity counterpart. Thus, the downsized engine has 49% less performance in terms of volumetric flow, this would lead to drastic transient performance losses if the downsized unit was left naturally aspirated.

#### **5.4.2- Forced induction calculations for the downsized Engine:**

For Downsized engines to be comparable to their larger counterparts, the specific output performance must be increased by a percentage equal to the reduction in engine size and performance resulting (W.Attard. Et al, 2006). The higher specific output can only be achieved through increased engine speeds which isn't viable for this situation, or forced induction systems such as turbochargers, superchargers or electronically assisted technology, to help enable the downsized engine be improved to match its larger counterpart (W.Attard. Et al, 2006).

The concept of replacing larger capacity naturally aspirated engines with smaller forced induction engines in order to achieve improved fuel economy is not new. Significant technology applications of turbocharging with downsized engine units have led to the combinations being more prevalent within the industry as a technique for obtaining specific torque and power targets for the engine (B.leach, 2014).

The Boost pressure required to match the downsized engines performance to the higher capacity counterpart, is 2 bar. This is required to match the volumetric performance of the bigger engine because its double atmospheric pressure a naturally aspirated (N/a) engine runs at. The 800cc engine is 48% down of volumetric flow, meaning double atmospheric pressure is required to achieve similar volumetric flow to that of the 1600cc engine. The forced induction system calculations based on this means a pressure ratio of 2.97 is to be used. This gives a volumetric flow of  $0.437 \text{ m}^3/\text{s}$ , which is  $0.150 \text{ m}^3/\text{s}$  more than the higher capacity engine (N/a), thus a 34% increase in performance from the induction system proposed.

From the forced induction boost values, a formula can be used to calculate the theoretical power of the downsized engine. The following equation was used:

$$\text{Lower BHP value} = 0.052 \times CI \times (PSI + 14.7)$$

$$\text{Higher BHP value} = 0.077 \times CI \times (PSI + 14.7)$$

*Equation 28: BHP calculations for forced induction systems, (Corky Bell, 2006).*

The 0.052 and 0.077 values come from the BHP/CID PSI values from a variety of turbocharged systems on a variety of engines to allow for an estimated figure to be calculated for all forced induction systems (Corky Bell, 2006). The CI value for the downsized engine as referenced by the source is 48.82.

From these two equations using 29 PSI Boost pressure and the 48.82 CI value the lower Brake Horse Power figure for the downsized engine equalled 111 BHP, and the upper equalled 164.27 BHP. So the average power for the downsized unit is 137.63 BHP, 12.63 horse power more than the 1600cc N/a engine originally found in the car.

#### **5.4.3- Technology For Improving Transient Performance:**

The most obvious path to enable a downsized engine to increase the pressure of air flow in is through various forced air-charging technologies. The industry has exclusively adopted to harvest the exhaust gas energy that would otherwise be wasted to increase the volumetric flow rate available for the combustion process, resulting in high power and thermal efficiency. Turbocharged downsized engines however, present two undesirable performance characteristics; mainly low boost pressure and poor transient performance due to low gas flow resulting in turbo lag. (X. Xingyu. Et al, 2017). Turbo lag is caused by the time it takes for the pressure for the exhaust gases to build enough pressure in the exhaust system to build to the required level needed to spin the turbine inside the turbo to produce the compression needed for the required power request (Aet-turbos, 2019).

The transient performance in relation to the load step of a higher boost system at lower engine loads and engine speeds is a current issue faced by the downsizing technology when using a conventional forced induction system. Aeristech, previously discussed in the literature section of this report, have developed an electric supercharger system to be used to boost a N/a downsized engine or be used in conjunction with a conventional turbocharger to create a new type of two stage forced induction system. As stated by (M. Bassett. Et al, 2016).

Most electric assist pressure charging systems can produce transient volumetric flow pressure to help reduce turbo lag found in a downsized engine. The Aeristech Electric Supercharger system is capable of also producing steady-state air delivery, making it a dual-purpose system (M. Bassett. Et al, 2016). Thus, ideal for improving the volumetric flow and performance of the selected downsized unit in this report. This system combines the technologies of a conventional mechanical supercharger in producing the required steady state flow for the higher engine speeds, and the electronic assist systems in eliminating the lag time improving the steady state performance of the engine unit. This means that the system selected above will not only aid in the improvement of the efficiency of the engine via reductions in pumping losses, leading to BSFC benefits, it can also increase the drivability of the car due to its performance advantages over a transient scale (X. Xingyu. Et al, 2017).

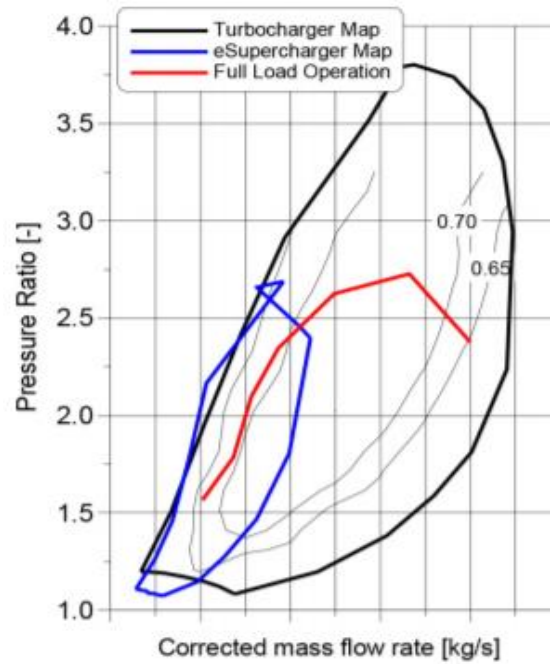


Figure 50: MAHLE Forced induction systems comparison for the Aeristech System, (M. Bassett. Et al, 2016).

The figure above shows the efficiency in relation to the pressure range the technologies can produce. It can be noted that the E-supercharger system is well within the full load operation of the engine, and produces air flow rate in Kg/s at a much lower pressure ratio, thus reducing the lag time for boost pressure to be present to increase the volumetric flow of the engine. The peak pressure isn't as high as the turbocharger, but the system will increase the drivability and efficiency within the urban duty cycle tested in this report.

#### 5.4.4 Control Systems for Electronic Supercharger:

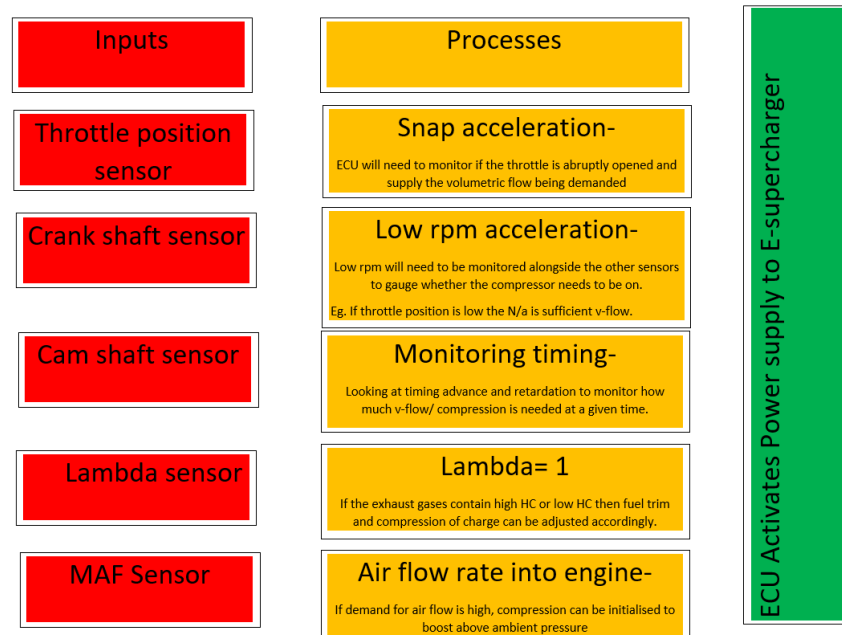


Figure 51: Electronic Supercharger Control System Overview, (Daniel Salathiel, 2019).

The average speed for the duty cycle was 10.96 m/s (24.53 Mph), meaning that most of the time the engine was running at low loads, with low engine speeds. The power request for this period in relation to performance requirements is low. This means that the Electronic supercharger system can be deactivated to further increase the efficiency of the engine. The system will need to take into consideration different factors to determine if the system should be activated to improve the transient performance or efficiency. The system can monitor the sensors in the diagram above to determine the road speed, engine speed and throttle position, this information in turn is processed by a control module that will either supply the system with voltage or not. The system will need to be programmed to take into consideration snap acceleration, which usually is associated with overtaking, therefore the system will need to look into the power request from the driver to help maintain the efficiency of the system, but also the transient response to maintain the cars drivability and feel the drivers used to with the higher capacity counterpart.

The figure above displayed all the variables the Control module will need to look at as minimum to gather an understanding of the requirements in relation to BSFC and Volumetric Flow.

### **5.5 Limitations of Downsizing Technology:**

Downsizing technology, although increasingly beneficial to the automotive industry, does pose some limitations that need to be addressed to maximise the technologies potential. The increased specific power requirements place greater strain on the internal components of the engine, due to the increased strains associated with increased combustion loads and inertia loads that are inherent with introducing a forced induction system and increase the engine speed (W. Attard. Et al, 2006).

The technology also increases the cost and complexity of the redesign of the internal combustion engine components. This is due to the requirement to use improved materials and manufacturing processes, such as new tooling or design work. The introduction of more complex control systems also increases the costing of developing and manufacturing a downsized equivalent engine. These measures are required to prevent premature failure or wear of components due to the higher stresses experienced by a boosted downsized engine. As stated by (W. Attard. Et al, 2006).

The higher temperatures associated with the boost pressures used to increase the performance of a downsized engine can cause uncontrolled combustion known as knock (W. Attard. Et al, 2006).

Knock mainly occurs in the end-gas region, which in turn would deteriorate the engines performance, efficiency and reliability. Knock is characterised by the sound of the abnormal combustion resulting from auto ignition of the fuel ahead of the advanced flame (Nap.edu, 2019). This causes high frequency pressure oscillations inside the cylinder that produces the sharp metallic noise called knock. The phenomena are governed by engine variables such as control systems and the anti-knock quality of the fuel, defined as the octane number rating (Nap.edu, 2019).

All this said, if the limitations are addresses with the solutions provided by the industry such as engine cycling for stress testing, the appropriate control systems and the use of a higher Ron rated fuel, downsizing technology shows great potential.

## **6.0- Conclusion:**

This paper reports the theoretical and numerical data showing the effects downsizing technology has on efficiency in relation to Brake Specific Fuel Consumption, and volumetric flow. A model for both coast down data and duty cycle data that was collected was created to determine the actual forces acting on the test vehicle, and the effects an urban route has on the cars efficiency, and the various factors effecting the efficiency of the engine in both capacity layouts.

The efficiency for both the engine used for testing and the downsized engine were measured using a Brake Specific Fuel Consumption map. Comparisons between the optimum efficiency consumption and the efficiency of the proposed downsized engine were made. The conclusion made from the analysis of these data sets were shown to favour the downsized technology in terms of efficiency gains, meaning the smaller capacity engine proposed with the relevant gear ratios pushed the operation load in relation to engine speed, to a more efficient Brake Specific Fuel Consumption value at the same engine power (Kw) and road speed (m/s) as the higher capacity engine counterpart. As supported by various sourced technical papers such as 'Fuel economy improvements and knock tendency reduction of a downsized engine (L. Teodosio. Et al, 2015).

The performance analysis also considered the constraints of the naturally aspirated and conventional turbocharger system in relation to transient flow associated with the volumetric flow. This analysis section offered alternative researched technologies that provide a solution to the inherent problems with the conventional system, which increased volumetric flow and efficiency, along with increased drivability. These factors are a measure of the technologies viability at replacing the larger capacity counterpart. The proposed technology in fact allow the technology to be a viable, more efficient solution to the internal combustion engines efficiency issues faced by the industry. These researched proven technologies and constraints are validated by the analysis of the theoretical calculations, showing the naturally aspirated 800cc engine is  $0.139 \text{ m}^3/\text{s}$  less in terms of volumetric flow rate than the higher capacity engine. But, when a forced induction system is introduced using the specifications of a modernised forced induction system on the proposed 800cc engine in this report, the downsized unit showed a greater volumetric flow, at  $0.150 \text{ m}^3/\text{s}$  more. This analysis shows that the downsized technology proposed as an alternative for the existing 1600cc engine, is a viable alternative and a technology that can provide many advantages in relation to the efficiency of the internal combustion engine.

The performance analysis also took into account the limitations of the technology in relation to manufacturing, development and performance aspects that will need to be addressed. These performance aspects include compression ignition events at low speeds as discussed. The analysis suggests strategized solutions that could be implemented in the report if there weren't time constraints.

The best Brake Specific Fuel Consumption reduction using the downsized unit was at low load sections of the duty cycle, the greatest seen for the parts analysed was 55 percent at section 1. These reductions were achieved through shifting the operation load using modified gear ratios, with relation to engine speed (Rpm) at the same engine power (Kw) as the higher capacity unit.

Although the definitive efficiency increases have not been confirmed by further practical testing of the 800cc proposed engine due to economical and time constraints. The presented results in this report are both quantitatively and qualitatively comparable, and backed up by published and trusted academically accredited technical reports, sources and assessed data sets. With this in mind the

testing process, data processing and modelling techniques in this report are shown to be reliable at describing the efficiency and performance characteristics affecting the Brake Specific Fuel Consumption and volumetric flow of downsized internal combustion engine when compared to its proposed predecessor.

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## **8.0 Appendices:**

- Excel Spread sheets and data One Drive Link: [https://uowtsd-my.sharepoint.com/:f:/g/personal/dsalathiel\\_149609\\_student\\_uwtsd\\_ac\\_uk/EmciXCvlnwxGsa-R4kXgSZ0BQIMvYPSs\\_cN162WHfVu1A?e=afSuSK](https://uowtsd-my.sharepoint.com/:f:/g/personal/dsalathiel_149609_student_uwtsd_ac_uk/EmciXCvlnwxGsa-R4kXgSZ0BQIMvYPSs_cN162WHfVu1A?e=afSuSK)

