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Critical Evaluation of On-Engine Fuel Consumption Measurement

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ABSTRACT

To enable continued development and facilitate the adoption of new internal combustion engine technologies, the accuracy and repeatability of measurement methods used for verification need to be improved upon. A variety of methods are available for the measurement of fuel consumption based on volumetric or gravimetric principle or by equating carbon in the fuel to carbon in the exhaust flow. Measurements of fuel consumption from five different experimental campaigns with varying engine setups are presented, highlighting discrepancies between gravimetric fuel balance and exhaust feed gas carbon balance. Differences were larger for cold start tests and if all correction factors are neglected offsets can reach 7%.

The carbon balance and gravimetric methods have been considered independently to identify sources of inaccuracy and improvements have been suggested in the form of correction factors. The carbon balance estimate is dependent on a number of separate measurements, all taken at different conditions. To account for these, two correction factors were compared, the first proposed by British Standards Institute and the second derived from the experimental conditions of each of the measurements. The gravimetric measurement was affected by changes in fuel temperature within the fuelling circuit and a corrective method was proposed based on the change in fuel density.

When correction factors were applied to each of the measurement techniques for the five experimental campaigns, discrepancies were less than 1%, which in most cases was small enough for there to be no statistically significant difference between measurements. In addition, in some cases the scatter of results was reduced, contributing to improved test to test repeatability. The

improved performance when using correction factors was explained by including known disturbances such as fuel temperature and ambient humidity as inputs to the measurement system.

Key Words: Fuel consumption, Measurement Accuracy, Engine testing

1. INTRODUCTION

With the increasing focus on reducing fuel consumption and carbon dioxide (CO_2) emissions, the automotive industry is faced with the challenge of demonstrating all of the feasible options for reducing fuel consumption, no matter how small. The planned limits for CO_2 emissions [1] will require manufacturers to improve fuel economy to avoid large financial penalties in the European market. Recent reports from the Institution of Mechanical Engineers [2] and senior representatives from industry [3] have presented a commonly accepted road map for vehicle development. This predicts that benefits in fuel consumption will be achieved in small steps rather than any large leap in technology. However, automotive manufacturers will be reluctant to adopt new technologies in production if their cost effectiveness cannot be demonstrated. For example, small improvements in fuel consumption are achieved in areas such as engine friction, engine warm up [4] or transmission lubrication [5]. Improvements in these areas are often of the order of a few percent and in some cases less than 1% which can be hidden amongst measurement inaccuracies when carrying out proving trials. Novel engine designs will need to demonstrate statistically significant improvements to justify the additional production costs that will be incurred if they are to be adopted. However the performance of experimental and measurement systems may not allow these small differences to be detected. As a result, imprecise and inaccurate measurements are causing automotive manufacturers to miss opportunities for fuel consumption and CO_2 reductions which although small, cumulatively can result in significant benefits.

In addition, the emergence of new markets in developing countries means that these benefits in fuel consumption need to be demonstrated in different experimental facilities in very geographically

different regions [6]. An approach undertaken at the University of Bath has concentrated on improved precision by reducing test to test variability [7]. This reduces the number of tests required to achieve sufficient confidence in results, thus reducing experimental effort and costs. However, when considering measurements from different facilities or different setups, accuracy also needs to be considered. The difficulty arises in not knowing the *true value*: a particular system may have very good repeatability, but consistently measure the wrong value. As a consequence, test operators may not even be aware of these inaccuracies.

A variety of different methods and instruments are available to measure or estimate fuel consumption of an internal combustion engine. Each of the methods has individually received considerable attention and improvements in the form of international standards and sophisticated conditioning and control equipment. However, despite this choice and the challenges of improving measurement accuracy, to the authors' knowledge, there is no published comparison of these methods to assess their performance. These devices are typically accurate to within ±0.1% and include built in calibration procedures to ensure continued adherence to specification. However, the measurement device is only one component in the overall fuel system and the importance of the behaviour of the whole system is often overlooked. As a result, the majority of installations will exhibit effects which adversely affect the accuracy of their measurements. The work presented here aims to quantify some aspects affecting the accuracy of on-engine fuel consumption measurement and propose corrective or preventive actions to address these issues.

2. APPROACH

2.1 Fuel consumption measurement methods

A number of well established measurement methods are available commercially for direct or indirect measurement of fuel consumption [8]. Descriptions of each of the methods will now be presented:

- **Gravimetric**: the mass of fuel flowing to the engine is measured directly either on a cumulative basis or as a rate. Cumulative meters or fuel balance measure the weight of fuel in a supply beaker; fuel flows from the beaker to the engine and the resultant change in weight is the measured fuel consumption. As the fuel beaker is of discrete capacity, unless a well controlled system using two fuel balances is used, this is a discontinuous measurement method. Refilling the fuel beaker is required at constant intervals and is therefore not appropriate for extended high load testing. Gravimetric rate measurements use a Wheatstone bridge layout, where mass flow rate is proportional to a measured pressure drop; or a vibrating tube design based on the Coriolis effect.

- **Volumetric**: similar to the gravimetric measurement, the volume of fuel flowing to the engine is measured, again either on a cumulative basis or as a flow rate. Cumulative meters measure a change in volume within a vessel or beaker and are discontinuous measurements. Volumetric flow rate devices are often positive displacement devices that measure a rotational output signal to deduce flow rate, however these devices must compensate for pressure drops and leakages. Fuel density estimate is required which is often based on the fuel suppliers' data and fuel temperature measurement.

- **Carbon Balance**: indirect estimate of fuel consumption can be obtained by equating the mass of carbon in the exhaust to the carbon concentration of the fuel. The mass of carbon in the exhaust is estimated from exhaust concentrations of CO_2, carbon monoxide (CO) and unburned hydrocarbons (THC). The carbon content of the fuel is obtained from the fuel supplier or measured using chemical analysis. The emissions can be sampled at different points in the exhaust system on a continuous basis [9, 10] or collected and analysed post test. Whilst the latter will not give detailed fuel consumption over a testing sequence, it is the adopted standard for homologation tests.

- **Engine Control Unit (ECU) Data**: the control system's fuelling demand signal may be used as a fuel consumption estimate. Depending on the engine strategy, subsequent density

estimates may be required. This signal is not a measure but a demand signal and requires calibration for each particular engine to yield accurate results. However, ECU data is good for assessing repeatability and is available on a cyclic basis allowing in depth analysis, notably during transient events.

A previous study at the University of Bath (partly presented in [7]) compared these methods. A gravimetric fuel balance (AVL 733s), a positive displacement volumetric rate device (Pierburg PLU 116H), engine exhaust emissions carbon balance and ECU data were compared to the homologation standard bag test. Consistent with manufacturers' specifications, the gravimetric fuel balance gave better agreement with the bag method, however, it was not clear if this was due to the volumetric principle or the measurement of a rate rather than a cumulative difference.

The carbon balance method is the only measure of burnt fuel, since both the gravimetric and volumetric methods measure fuel supplied to the fuelling circuit, and ECU represents the requested fuel injection rate, as calibrated by the engine calibration. Despite this, the carbon balance method is dependant on a number of measures (emissions concentration, exhaust mass flow rate, etc.) for which the combined accuracy is worse than the measurements of the gravimetric or volumetric devices. The carbon balance also offers lower response time, compromising the detailed analysis of transient events [11]. To measure a fuel consumption by mass, volumetric measurements always require the additional measure of fuel density, which is temperature dependant and introduces additional uncertainty. Cumulative devices tend to offer the most accurate results and are reliant on a single measurement (mass of fuel in beaker, time to consume a known volume, etc.), however they are compromised by their measurement principles, requiring a refilling during which measurement is suspended. Rate meters usually require multiple measures of pressure ("Flowtron" Hydraulic Wheatstone Bridge), rotational speed (Turbine flowmeters, positive displacement devices) or force (Coriolis effect) and can be sensitive to fuel viscosity [8, 12].

Ultimately the choice between volumetric or gravimetric devices will depend on the application, required accuracy, duty cycle and operational environment. For example, a fuel balance may not be compatible with vehicles fitted with an ECU controlled lift pump. Conversely, for on vehicle applications the Coriolis rate sensor will be sensitive to external vibrations. Rate devices measure on a continuous basis allowing for better analysis of transient events but are typically specified as less accurate than their cumulative counterparts. The best combination of accuracy, reliability and analysis of transient events is achieved by combining a cumulative meter with a rate meter, using emissions analysis as a back up [8]. As this work is aimed at improving accuracy, detailed analysis of the volumetric devices and gravimetric rate device will not be presented, however some of the issues covered will be applicable to these approaches. Three measures of fuel consumption were considered:

- Gravimetric fuel balance

- Continuous carbon balance analysis of pre-catalyst exhaust emission

- ECU fuelling demand signal

2.2 Measurement offsets

Results from five experimental campaigns at the same facility using different engine setups form the basis for this work. For each setup, multiple tests were run over the New European Drive Cycle (NEDC) either from "cold start", following an overnight soak at 25°C, or "hot start", following a warm up procedure. Due to limitations of testing time for cold start testing, fewer of these tests were conducted, explaining lower confidence in these results compared to the hot start condition. It is important to note that regardless the measurement technique, the true fuel consumption is the same and the measured estimate will be the result of both random disturbances and bias in the methods. Random effects will be identified and minimised by multiple test runs, leaving the remaining measurement system bias.

For the five experimental setups, the offsets between the ECU demand and the other two measures was typically 100g (12%) and this offset is readily explained by a lack of calibration. On the other hand the offset between the carbon balance and gravimetric estimates is shown in figure 1: for cold start tests there is a difference of 8 to 15g, however this is lower for hot start tests. Unlike the ECU estimate, this offset is a result of bias within the measurement processes themselves and both methods require further investigation.

Figure 2 shows typical cumulative fuel consumption measurements over an NEDC for both a cold and hot start test. Considering first the results from the carbon balance measurement: initially cold start fuel consumption is higher, mainly as a result of lower oil temperatures which cause higher engine friction [4, 5, 13-15]. As the engine warms up, the instantaneous fuel consumption drops to the same level as in the hot start test and the difference in cumulative fuel consumption stabilises to 40g. Considering now the gravimetric method, over the first 600s the result follow a similar trend. However, over the second half of the drive cycle, the result suggests that fuel consumption is lower than in the cold start test. Nothing in engine operation is typical of this behaviour, suggesting a disturbance to the gravimetric measurement.

Each of these methods will now be considered separately and corrective actions will be proposed to reduce the discrepancies. These actions will aim to attenuate the effect of external disturbances either by corrective or preventative methods. Correction factors are proposed which include measurements of these disturbances to include them in the overall measurement process. Preventative methods will be discussed that inhibit the effect of these disturbances, reducing their influence on the measurement process.

3. DETAILED ANALYSIS OF FUEL CONSUMPTION MEASUREMENTS

3.1 Carbon Balance estimate

3.1.1 Overview

The carbon balance fuel consumption estimate is based on equating the measured carbon mass in the exhaust to the known concentration in the fuel. Overall fuel consumption is obtained using equation 1, where *0.428* and *0.273* represent the ratio of atomic weight of carbon to the molecular weight of carbon monoxide and carbon dioxide respectively.

$$FC_{CB} = \frac{1}{\frac{w_C}{100}} \left(\frac{w_C}{100} \times m_{THC} + 0.428 \times m_{CO} + 0.273 \times m_{CO_2} \right)$$

(1)

From the terms in equation 1 it is seen that the carbon balance estimate is dependent on knowledge of the fuel properties and the mass emissions of THC, CO and CO_2. This highlights the need to use reference fuels and accurate measurements of exhaust emissions by mass. Most older British Standards Institute (BSi) and American Society for Testing and Materials (ASTM) standards do not quote accuracies for carbon content of reference fuels [16-18], however a recent ASTM standard [19] describes the measurement of Carbon, Hydrogen and Nitrogen (CHN) concentrations. The specifications from this standard are summarised in table 1.

Species	Valid concentrations % by mass	Repeatability %	Reproducibility %
Carbon	75%-87%	+/-1%	+/-2.5%
Hydrogen	9%-16%	+/-1%	+/-2%
Nitrogen	0.2%-2%	+/-0.17%	+/-0.5%

Table 1: Repeatability and Reproducibility of CHN method for identifying fuel composition [19]

Emissions analysers measure the concentrations of their respective species by volume and post processing yields a mass estimate (equation 2). The exhaust mass flow rate must be estimated in addition to the ratio of densities of exhaust species to that of the total exhaust (see BSi standards [20]).

$$\dot{m}_X = \dot{m}_{ex} \times c_X \times \rho_{Ratio,X} = \dot{m}_{ex} \times \frac{v_X}{v_{ex}} \times \frac{\rho_X}{\rho_{ex}} \times K \qquad \textbf{(2)}$$

It is important to note the conditions of temperature and humidity where each of the terms in equation 2 are defined:

- **Exhaust mass flow**: commonly estimated as the sum of measured intake air flow and fuel flow, therefore includes all water vapour both from ambient air and combustion

- **Emissions concentrations**: emissions analysers measure under different conditions depending on emissions species. CO and CO_2 are measured by non dispersive infra red spectroscopy (NDIR) which analyses the light spectrum after certain frequencies have been absorbed by the gas. As the absorption spectrum of water vapour interferes with that of CO_2 and CO, the sample exhaust gases are cooled to remove the water vapour by condensation. In contrast, Hydrocarbon emissions are measured by flame ionisation (FID) [8] and are not affected by the presence of water and are measured under hot and humid conditions.

- **Relative density**: this term is defined under standard conditions from molecular mass and volume at $0^{\circ}C$ and 0% humidity [20].

Emissions analysers are capable of accurate measurements of CO_2, CO and THC concentrations but typically suffer from drift over a 24h period. Good practice specifies calibration before each experiment using calibration gases of known concentrations to ensure measurement accuracy is maintained. However, it is the different conditions within the measurement system that have a direct effect on accuracy. For example, as water vapour is removed from the sample gas before analysis for CO and CO_2, the concentration by volume will be higher in the gas analyser than in the wet

exhaust flow, which will be directly reflected in the fuel consumption estimate. For CO and CO_2, a correction factor K is required to compensate for different conditions: two correction factors will now be proposed.

3.1.2 BSi correction

BSi suggest adjusting the measured exhaust species concentration to account for the lack of water vapour [20]. This correction factor K reduces the measured volumetric concentration slightly to account for the volume of water vapour in the exhaust flow (equations 3 and 4)

$$K = \frac{c_{X,wet}}{c_{X,dry}} = \frac{\dot{v}_{ex,dry}}{\dot{v}_{ex,wet}} = 1 - \frac{\dot{v}_{H_2O,cond}}{\dot{v}_{ex,wet}} = 1.008 \times \left(1 - \frac{1.2442 \times H_a + 111.19 \times w_H \times \frac{\dot{m}_f}{\dot{m}_{air,dry}}}{773.4 + 1.2442 \times H_a + \frac{\dot{m}_f}{\dot{m}_{air,dry}} \times f_{fw} \times 1000} \right) \quad \textbf{(3)}$$

Where

$$f_{fw} = 0.055594 \times w_H + 0.0080021 \times w_N + 0.0070046 \times w_O \quad \textbf{(4)}$$

$v_{H2O,cond}$ *is the volume of water vapour that condenses in the analyser cooler.*

f_{fw} *is the volume change from combustion air to wet exhaust air per kg of fuel.*

The correction factor K is presented as the ratio of emissions species concentration in wet exhaust to the concentration in dry exhaust. This is equivalent to the ratio of dry exhaust to wet exhaust, on a volumetric basis. The volume of water condensing in the cooler is the sum of intake water vapour and combustion water vapour, less the water vapour remaining after the analyser cooler. The wet exhaust volume is the sum of volumes of intake water vapour, dry intake air and burnt fuel. Most values are basic measurable quantities in most experimental setups, however data relating to the water content downstream of the analyser cooler is not readily available. As a result, an unstated assumption has been made to account for this, which results in the final form in equation 3.

3.1.3 Dry Exhaust Correction

An alternative approach to the BSi correction would be to correct the exhaust mass flow rate to a cold and dry condition The exhaust mass flow rate under analyser conditions can be calculated using equations 5 to 7 and then using equation 2 for emissions species measured under cold dry conditions. Firstly the mass of water due to combustion is calculated in equation 5 assuming complete combustion. It is worth noting at this stage that the estimate of carbon balance is dependant on knowledge of the mass flow of fuel, which is the ultimate sought value. However, the sensitivity of carbon balance to the gravimetric measurement is extremely low, with a 1% error causing only a 0.035% error in carbon balance estimate. If gravimetric measure is not available, the ECU demand is an acceptable alternative. The total mass of water in the exhaust flow is then calculated using equation 6 by adding ambient moisture from engine intake. Finally this is used to calculate corrected exhaust mass flow rate under analyser conditions. The residual water vapour in the analyser is assumed to be equivalent to 100% relative humidity at 6°C, ambient pressure.

$$\dot{m}_{comb,H_2O} = \dot{m}_f \times w_H \times \frac{M_{H_2O}}{2 \times M_H} \tag{5}$$

$$\dot{m}_{ex,H_2O} = \dot{m}_{comb,H_2O} + \dot{m}_{air,H_2O} \tag{6}$$

$$\dot{m}_{ex,analyser} = \dot{m}_{ex} - \dot{m}_{ex,H_2O} + \left(H_{a,analyser} \times \dot{m}_{air,dry} \right) \tag{7}$$

As a result of adjusting the exhaust mass flow rate, the density ratio quoted in British standards is not longer valid because this represents the ratio of emission spices density to wet exhaust density. This was corrected using estimates for dry and wet exhaust densities detailed in the standard (equation 8).

$$\rho_{Ratio,2} = \rho_{Ratio} \times \frac{\rho_{ex,wet}}{\rho_{ex,dry}} \tag{8}$$

3.2 Gravimetric measurement

3.2.1 Overview

In contrast to the carbon balance, this fuel consumption estimate is based on a single measurement. The fuel consumption between any two instances is the change of fuel weight in the beaker over that time period (see equation 9). As with the emissions analysers, the gravimetric fuel balance has a high accuracy (±0.05% or ±0.03g) and a built in calibration procedure using calibrated weight to ensure the device performs well over time. However, it is necessary to consider the fuel system as a whole.

$$FC_{grav} = m_{f,b,mes,start} - m_{f,b,mes,end} \tag{9}$$

Figure 3 shows the fuel supply circuit with the measurement balance: fuel is supplied from the fuel balance to the engine using a gravity feed. At this stage, it should be noted that the installation of the measurement instrument within the system means that the measurement is the fuel flow to the engine, not the fuel flowing into the cylinder. After filtration, the High pressure (HP) fuel pump supplies pressurises the common rail which subsequently supplies the injectors. Such is the design of the electro-hydraulic injectors (see Guerrassi and Dupraz [21]) and leakage from the pump and rail, a significant amount of fuel is returned via a low pressure route downstream of the fuel balance as suggested by Stone [12]. The fuel flow in the spill circuit was estimated by thermal balance of the mixing of spill and supply fuel (equation 10). For the engine used in this study, these flows were 10-50% that of fuel consumption and can represent over 7L/hr (see figure 4). By the same process the fuel acts as a cooling medium for the injection system and a fuel cooler is required to avoid excessively high fuel temperatures. It should be acknowledged as this stage that the fuel cooling system in this setup was very basic and more sophisticated systems are commercially available such as that detailed by Kock and Wiesinger [11]. However, no system is able to completely suppress fuel temperature rises downstream of the conditioning unit.

$$\dot{v}_{f,spill} = \dot{v}_{f,sply} \times \frac{T_{f,Coolspill} - T_{f,prefilt}}{T_{f,prefilt} - T_{f,sply}} \tag{10}$$

Differences in fuel consumption estimates were observed between hot and cold start tests and a detailed analysis of fuel temperatures is presented in figure 5. Significant temperature gradients exist during the cold start test with temperatures in the spill circuit before and after the cooler rising by approximately 35°C and 25°C respectively. This rise in temperatures will reduce the density, and hence the mass of the fuel in the circuit. If the mass of fuel downstream of the fuel beaker changes then the fuel consumption measured by the fuel balance will be wrong. It must be emphasised that the flow meter measures fuel flow into the fuelling circuit, not necessarily fuel consumed by the engine.

To illustrate this effect, consider the situation where fuel is not flowing: an increase in temperature would cause fuel expansion, pushing fuel back into the beaker. The fuel beaker would then suggest negative fuel consumption, despite no real fuel use. In the case of flowing fuel this does not result in a negative reading, but an underestimate of true fuel consumption. On the other hand, thermal expansion will also increase pipe volumes which will have the opposite effect on fuel mass in the circuit. Finally significant pressure drops may cause air release, resulting in further fuel expansion. A corrective procedure will now be derived to account for changes in fuel mass in the fuelling circuit.

3.2.2 Fuel Temperature Correction

Thermal expansion may be corrected in post processing by calculating the change in fuel mass downstream of the beaker. The fuel circuit was split into known volumes and a representative temperature was measured for each (figure 5). A volume-weighted mean fuel temperature was then calculated and used to estimate mean fuel density. It is often difficult obtaining detailed volumes of bespoke components like the fuel pump or engine filter, however error analysis has shown that a

25% error in volume estimates for these two components yields only a 2.5% or 8.5% error in fuel circuit mass estimate respectively: the knock-on effect on fuel consumption would be insignificant.

The temperature-density characteristic of diesel fuel has been measured in considerable detail by Dzida and Prusakiewicz [22]. Rodriguez-Anton et al. [23] also studied this behaviour for a variety of diesel fuels and found that whilst absolute values of density varied +/-20kg/m^3, the variation with temperature was consistent in all but one case. Consequently, the temperature-density characteristic for the fuel in this study has been derived from the detailed data [22], normalised to a known density at 15$^{\mathrm{o}}$C (see figure 6).

The mass of fuel in the circuit can be calculated using mean fuel density and total circuit volume (equation 11). Any change in mass should be accounted for by establishing a corrected beaker mass (equations 12-13) to be used in the fuel consumption estimate (equation 9).

$$m_{f,c} = v_c \times \rho_f \tag{11}$$

$$\Delta m_{f,c} = m_{f,c,t=0} - m_{f,c,t=t} \tag{12}$$

$$m_{f,b,corr} = m_{f,b,mes} - \Delta m_{f,c} \tag{13}$$

3.2.3 Fuel Pressure Correction

Modern fuel injection systems operate at pressures exceeding 2000bar under high load conditions. Figure 7 shows fuel density as a function of pressure and temperature based on published values from Dzida and Prusakiewicz [22]. As before, the density has been adjusted to suit the particular fuel in this study. The fuel is expected to operate at pressures of up to 1600bar and temperatures up to 90$^{\mathrm{o}}$C: over this range, the effect of pressure is of the same order of magnitude as that of temperature, with higher pressures increasing the fuel density.

Data in figure 7 over the region of 1000bar to 1600bar and 45°C to 105°C has been obtained through extrapolation. Whilst this may cause inaccuracies, the data relating to NEDC operating points (small black points in figure 7) demonstrates the limited use of extrapolated data over the NEDC test: the majority of operating points lie within the published data. The fuel circuit was again split into sections of known volume and assigned both a representative temperature measurement and pressure estimate (either low "supply" or high "rail"). Details of the circuit breakdown are presented in table 2

#	Description	Volume (cm^3)	% total volume	Temperature	Pressure
1	Filter and piping	375	53	Pre-filter	Supply
2	HP Pump and piping	25	3.5	HP Pump-in	Supply
3	Rail, Injectors and HP piping	25	3.5	Hot Spill	Rail
4	Spill Piping	160	23	Hot Spill	Supply
5	Fuel Cooler and piping	125	17	Cool Spill	Supply
	Total Circuit Volume	**710**			

Table 2 Sections of fuel circuit with measured volume and assigned temperature and pressure

The mass of fuel in the circuit was determined by summing up the mass of fuel in each of the five sections (equations 14 and 15). Corrected fuel consumption was then calculated as previously described in equations 12 and 13 and finally equation 9.

$$m_{f,c} = \sum_{i=1}^{5} \rho_i \times v_i \qquad (14)$$

Where

$$\rho_i = f(T_i, P_i) \qquad (15)$$

3.2.4 Pipe Expansion

The temperature rise causing expansion and reduced fuel density would also cause expansion of the components, connectors and hoses in the fuelling circuit, increasing the total volume. A complete investigation into the thermal expansion of components in the fuelling circuit is beyond the scope of

this work, however a brief analysis of hose expansion will be presented. The circuit comprised both PVC hoses and copper pipes and the approximate cumulative lengths and mean diameters are detailed in table 3. Using thermal expansion coefficients both longitudinal and circumferential expansion have been considered (equations 16 and 17).

$$\Delta L = \alpha \times L \times \Delta T_f \qquad\qquad (16)$$

$$\Delta C = \alpha \times C \times \Delta T_f \qquad\qquad (17)$$

3.2.5 Air Release

Entrained air dissolved into the fuel may be released when the fuel undergoes large drops in pressure when leaking from the HP pump, spilling through the rail pressure relief valve or flowing through the various orifices in the electro-hydraulic injectors. The release of this air would cause an overall reduction of density within the constrained system volume as highlighted by Plint and Martyr [8]. The effect of any subsequent temperature gradients would then also be amplified by air expansion. To observe and quantify this phenomenon, an air trap was installed in the proximity of the fuel filter as shown in figure 8. This was considered the most likely location for air accumulation as it represents both a local high point in the circuit and low flow velocities due to large pipe diameters.

3.2.6 Cooldown Analysis

As the error in fuel consumption measurement is due to a change in thermal conditions, the experimental procedure can be modified to include a cooling period to return the fuel to its initial thermal state.

4. RESULTS

4.1 Carbon Balance Method

Figure 9 shows the standard BSi fuel consumption estimate along with a raw estimate (omitting the correction factor K) and the dry exhaust estimate. This clearly highlights the need for the correction factor as it's omission causes an overestimate of 55-75g (7-8%). The correction factor also seems to improve the test to test repeatability as confidence bands are slightly tighter in the corrected results: this is thought to be the result of including ambient conditions in the measurement process, notably ambient humidity. The dry exhaust method consistently estimates fuel consumption 10g lower than the BSi method.

4.2 Gravimetric Method

For a particular set of cold and hot NEDC tests, the effects of fuel temperature and pressure correction are presented in figure 10. The shape of the curve representing the difference between hot and cold start tests is now consistent with the carbon balance (see figure 2). The temperature correction increased the fuel consumption measurement of the cold test by around 15g, however, the effect of pressure was negligible. In both cases the hot start test was not affected by the correction factors as no significant net change in temperature occurs over the cycle.

Analysis of the thermal expansion of pipe work is presented in table 3. The effect of a $30^{o}C$ increase in temperature would expand the total volume by $1.7mm^{3}$. For the PVC hoses this represents approximately 9% of the effect due to thermal expansion of the fuel: in the example test (figure 10) the gravimetric fuel consumption correction would be 13.5g rather than 15g. The effect of thermal expansion of the copper pipes is less than 1%.

Material	Thermal expansion coefficient ($^{o}C^{-1}$)	Total section length (mm)	D (mm)	Thermal expansion (mm)		Volume increase (mm^3)	Circuit mass increase (g)	% relative to fuel expansion effect *
				Length	Diameter			
PVC	58.3×10^{-6} (†)	2570	12	4.50	0.02	1.5	1.3	8.6%
Copper	19×10^{-6} (#)	910	10	0.50	0.00	0.2	0.1	0.7%
Total						1.7	1.4	9.3%

* This percentage represents how much the increase in volume due to pipe expansion offsets the decrease in fuel circuit mass due to the reduction in fuel density. For example, the mass of fuel in the circuit reduced by approx 15g due to fuel expansion in a cold start test, so this analysis suggests that due to pipe expansion the actual value would be 8.6% (1.3g) lower.

data from ESDU metallic materials data book [24]

† data from The Engineering Toolbox for PVC pipes [25]

Table 3 Fuel pipe expansion analysis for PVC and copper pipes

The air trap was closely observed during hot and cold start NEDC runs. No measurable air release was observed, suggesting that this does not contribute significantly to errors in the fuel consumption measurement. It is possible that air accumulated in a different part of the circuit and extensively modifying the fuel circuit may provide an insight to this. It is also possible that air released from the fuel re-dissolves at other parts of the circuit.

Temperatures and fuel consumption measurements during a cold start NEDC and subsequent 4 hour cooling period are presented in figure 11. The detailed view of the NEDC shows the rises in fuel temperatures throughout the circuit as previously seen in figure 5. The detailed view of the cooldown period shows selected fuel temperatures and the apparent fuel consumption. Following engine shutdown at the end of the NEDC, the apparent fuel consumption continues to rise as the fuel temperatures drop. After 4 hours the apparent fuel consumption was 30g higher than at the end of the test. The low frequency fluctuations in fuel temperature over the cool down period were

caused by the experimental facility ambient temperature control system. It is interesting to note that these fluctuations are also observed in the fuel consumption measurement, clearly highlighting the thermal link with the measurement process.

4.3 Overall Results

Figure 12 shows the fuel consumption estimates for each of the methods described above for a particular cold start NEDC; the detailed view clearly shows the offsets between methods. The largest difference (80g, 10%) is observed between the raw carbon balance and uncorrected gravimetric measures. Each of the alternative methods improved agreement between the two base methods and the spread of corrected results is less than 25g (3%).

With the exception of the post test cooldown, the various methods have been applied to the five previous experimental setups and these are presented in figure 13. The BSi result have already been presented in figure 9 and the gravimetric correction increases the raw measure by 10-15g for cold tests, but does not significantly change the hot start tests. For the experimental setups considered here, best agreement appears to be between the BSi corrected carbon balance and the corrected gravimetric methods. The difference between these two methods is less than 10g (1%) and in most cases there is no statistically significant difference between the two.

5. DISCUSSION

The correction factors discussed for the carbon balance method were all concerned with compensating for the different conditions of exhaust gas in the gas analysers and exhaust pipe. Humidity was identified as a key issue in this relationship. The method proposed by British standards was seen to give similar results to a proposed alternative method of calculating a dry exhaust flow. The omission of a correction factor was seen to have an adverse effect both on accuracy (offsetting the result by 7-8%) and repeatability. The BSi method was seen to perform best

as this ultimately gave better agreement with the corrected gravimetric method, however this method is more complex in derivation than the dry exhaust method. The accuracy of fuel carbon content is a clear shortfall for this method and directly compromises the accuracy of the fuel consumption measurement. This highlights that the use of consistent reference fuels is essential for continued repeatability and correlation of results.

The gravimetric corrections were required to increase the accuracy by accounting for significant temperature gradients, notably after a cold start. This highlighted the need for good fuel temperature management either through preventive, corrective or procedural methods. In addition, hardware changes could be introduced to limit the temperature change throughout the test. This may simply be an adequately large fuel cooling unit, limiting the spill circuit volume or introducing a more advanced cooling system such as concentric hose with water cooling. Instrument manufacturers and Plint and Martyr [8] recommend returning spilt fuel to the fuel beaker, however not all facilities lend themselves easily to this setup and this could increase the volume of fuel downstream of the beaker. Implementation of the proposed correction procedure requires fuel temperature measurements, however this may represent significantly lower investment than the other suggested methods. The cooldown method does not require any additional hardware, however it is unlikely that this will be acceptable for busy industrial testing facilities. Finally, it is important to rigorously isolate any small leaks in the fuel circuit that may not have significant effects over the 20 minute NEDC cycle, but will be critical over the lengthily cooldown.

It was surprising that the effect of pressure was insignificant compared to that of temperature in the gravimetric correction. On closer inspection, the proportion of the fuel circuit under high pressure represents only 5% of the total volume and the average rail pressure during the NEDC is 550bar. Whilst insignificant under these conditions, on a different engine, working at higher pressures with

a larger high pressure fuel volume and operating nearer to full load for extended periods, this effect may need to be considered.

The offset between the cooldown estimate and the correction algorithm (highlighted in figure 12) remains unexplained. This could be a result from a small leak in the fuel circuit although none were observed. It could also be the result of inaccurate estimates of the fuel circuit volumes that would affect the correction algorithm. A third explanation could be air pockets developing within the system that slowly fill with fuel after the engine has shut down.

In this work, the correction has been applied to the gravimetric fuel balance because this has previously shown the best performance in terms of accuracy; however the issue of fuel thermal expansion would equally affect cumulative volumetric devices as well as gravimetric and volumetric rate measures. The example application of the correction methods has been applied to a common rail Diesel engine operating over the NEDC drive cycle, however for both the gravimetric and carbon balance this may be extended to other engine types:

- Emissions analysers do not differ depending on engine type and CO and CO_2 measurements are commonly taken under dry cold conditions, meaning the discrepancies between emissions concentrations, exhaust mass flow and relative densities will still be significant. As a result, there will always be a requirement for this correction factor regardless of engine type and duty cycle.

- Whilst the spill flows from the common rail system amplify the increases in fuel temperature, any engine operating from cold start will inevitably experience temperature rises. This will always affect the fuel balance as it is integrated into the system as a measure of the net mass of fuel flowing through it, not the mass of fuel burnt. The impact on fuel consumption accuracy increases for larger changes in temperature and is therefore minimal when fuel temperatures remain constant. As a result, the gravimetric correction factor will

be redundant for steady state fuel temperatures. The impact of duty cycle depends on the impact of engine speed and load on fuel temperature and the duration of operation at extreme conditions. In the case exposed here this is quite small as bulk fuel temperature does not vary significantly during a hot start NEDC, but for other engine operating under different duty cycles this may be significant.

The raw measures of carbon balance and gravimetric fuel consumption showed an offset of 50-80g (7-10%) for a NEDC test, however the application of various correction factors, derived from first principles, has given various estimates that agree to within 25g (3%). The best agreement was observed between BSi corrected carbon balance and corrected gravimetric (approximately 1% or 10g). This offers a significant improvement and changes the interpretation of the measurement results. With large discrepancies the test operator is faced with deciding which method is most trusted. In contrast, with significantly better agreement between methods, and no statistical difference between the two, confidence is increased in both methods and the final result. Finally, with better agreement, these offer a good platform to calibrate ECU fuel consumption estimate for accurate detailed transient analysis.

6. CONCLUSIONS

A study of the accuracy of on-engine fuel consumption measurement has been conducted to improve the performance of testing installations to aid in demonstrating future engine developments. Although the work presented here was applied exclusively to a common rail Diesel engine operating over and NEDC cycle, the methods could be applied to different engines running different duty cycles. Both the carbon balance and gravimetric methods have been analysed and corrective and preventive procedures have been suggested to avoid measurement inaccuracies. Correction factors allow identified disturbances to be accounted for in the fuel consumption estimate.

Two correction factors have been compared for carbon balance fuel consumption to compensate for different conditions of humidity in exhaust flows and emissions analysers. Without these factors, fuel consumption can be overestimated by approximately 7%. Thermal expansion of the fuel affected the gravimetric measurement through changes in fuel temperature; this was especially noticeable during cold start tests. An inexpensive method based on fuel temperature measurements was presented to account for this phenomenon. Alternatively, preventive and procedural methods were also suggested to avoid the requirement of post processing. Agreement between the two methods was improved and the offset between measurements reduced to below 1%, increasing significantly the confidence in the results. In some cases repeatability and test scatter was also improved.

The improved accuracy should allow easier demonstration of small differences in engine development, giving better judgement of novel engine technologies. This will be achieved through better control and understanding of interactions between experimental facilities and different engine setups. The work should also improve correlation of experimental results from different facilities and contribute to ongoing analysis of uncertainty of experimental procedures.

7. REFERENCES

1 **European Commission,** COMMISSION REGULATION (EC) No 692/2008 implementing and amending Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, 2008

2 **ImechE**. Low Carbon Vehicles, Driving The UK's Transport Revolution, 2009.

3 **Owen, N. and Jackson, N.** A new look at the low carbon Roadmap. *Low-Carbon Vehicles 2009* (Chandos Publishing Ltd., London (UK), 2009).

4   **Burke, R.D., Brace, C.J., Hawley, G. and Pegg, I.** Systems analysis of the interactions of thermal, lubricant and combustion processes of Diesel engines. *Proceedings of the Institution of Mechanical Engineers Part D-Journal of Automobile Engineering*, 2010, **224**(5), 681-704.

5   **Kunze, K., Wolff, S., Lade, I. and Tonhauser, J.** A systematic analysis of CO2 reduction by an optimized heat supply during vehicle warm up, SAE Paper Number 2006-01-1450, 2006.

6   **Martyr, A.** The Challenge of Global Correlation of Automotive Test Results. In Ebrahimi, K., ed. *Meeting the Chellenges in Powertrain Testing* (IMechE, Solihull, 2009).

7   **Brace, C.J., Burke, R.D. and Moffa, J.** Increasing accuracy and repeatability of fuel consumption measurement in chassis dynamometer testing. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 2009, **223**(9), 1163-1177.

8   **Plint, M. and Martyr, A.** *Engine Testing Theory and Practice*, (SAE International, Warrendale, 1999).

9   **Bannister, C.D.** Vehicle Emissions Measurement. *Department of Mechanical Engineering* (University of Bath, Bath, 2007).

10 **Bannister, C.D., Hawley, J.G., Brace, C.J., Cox, A., Ketcher, D. and Stark, R.** Further Investigations on Time Alignment, SAE Paper Number 2004-01-1441, 2004.

11 **K. Kock and M. Wiesinger,** Requirements for Fuel Consumption Measurement for Emissions Regulations US07/10 and for Euro 4/5Design Criteria and Layout of the Fuel Measurement Systems, SAE Paper 2007-01-0059, 2007.

12 **R. Stone**, Introduction to Internal Combustion Engines, 3rd ed. Basingstoke: Macmillan Press LTD, 1999.

13 **Shayler, P.J., Allen, A.J., Leong, D.K.W., Pegg, I., Brown, A.J. and Dumenil, J.-C.** Characterising Lubricant Oil Viscosity to Describe Effects on Engine Friction, SAE Paper Number 2007-01-1984, 2007.

14 **Wakuri, Y., Soejima, M., Ejima, Y., Hamatake, T. and Kitahara, T.** Studies on Friction Characteristics of reciprocating Engines, SAE Paper Number 952471, 1995.

15 **Daniels, C.C. and Braun, M.** The friction behaviour of individual components of a spark-ignition engine during warm-up. *Tribology and Lubrication Technology*, 2006, **62**(11), 62-69.

16 **BSI**. BS ISO 8178-5:2008: Reciprocating internal combustion engines. Exhaust emission measurement, Test fuels, 2009.

17 **ASTM**. ASTM D3343-90 Standard Test Method for Estimation of Hydrogen Content of aviation fuels, 1990.

18 **ASTM**. ASTM D1018-91 Standard Test method for hydrogen in petroleum fractions, 1991.

19 **ASTM**. ASTM D5291-02 Standard Test Methods for Instrumental Determination of Carbon, Hydrogen and Nitrogen in Petroleum Products and Lubricants, 2007.

20 **BSI**. BS ISO 8178-1:2006, Reciprocating internal combustion engines. Exhaust emission measurement. Test-bed measurement of gaseous and particulate exhaust emissions. (BSI, 2009).

21 **Guerrassi, N. and Dupraz, P.** A common rail injection system for high-speed, direct-injection diesel engines. *SAE International Congress and Exposition* (SAE International Warrendale Pennsylvania USA, Detroit, Michigan, 1998).

22 **Dzida, M. and Prusakiewicz, P.** The effect of temperature and pressure on the physicochemical properties of petroleum diesel oil and biodiesel fuel. *Fuel*, 2008, **87**(10-11), 1941-1948.

23 **Rodriguez-Anton, L.M., Casanova-Kindelan, J. and Tardajos, G.** High Pressure Physical Properties of Fluids used in Diesel Injection Systems, SAE paper number 2000-01-2046. *International Spring Fuels and Lubricants meeting and exposition* (SAE International Warrendale Pennsylvania USA, Paris, 2000).

24 **Anon**. Metallic Materials Data Handbook - Specification B27. (IHS ESDU, 2005).

25 **TheEngineeringToolbox.com**. Thermal Expansion of PVC, CPVC, Carbon Steel, Stainless Steel and Fiberglass Pipes. (The Engineering Toolbox, 2005), Available from:

http://www.engineeringtoolbox.com/thermal-expansion-pvc-d_782.html [Accessed: 11/01/2010]

8. APPENDIX

Abbreviations

CO2   Carbon Dioxide

CO   Carbon Monoxide

THC   Total Hydrocarbons

ECU   Engine Control Unit

NEDC New European Drive Cycle

BSi   British Standards Institute

ASTM American Society for Testing and Materials

FID   Flame Ionization Detector

NDIR Non Dispersive Infra Red

HP   High Pressure

PVC   Polyvinyl Chloride

Notation and Units

Latin letters

C   Pipe circumference [m]

FC   Fuel Consumption [g or g/s]

H_a Absolute humidity [g/kg dry air]

K   Emissions correction factor

L   Pipe length [m]

M   Atomic/Molecular weight [g/mol]

P   Pressure [bar]

T   Temperature [$^{\circ}$C]

c Emissions concentration [% or ppm]

ffw Fuel specific factor for wet exhaust calculations

m Mass [g or kg]

$\dot{m}$ Mass flow rate [g/s]

v Volume [m^3]

$\dot{v}$ Volume flow rate [m^3/s]

w Fuel composition by weight [%]

Greek letters

α   Coefficient of thermal expansion [$m/m^{\circ}C^{-1}$]

Δm Mass correction [g]

ρ Density [kg/m^3]

Subscripts

C   Carbon

CB   Carbon balance

CO   Carbon monoxide

CO_2 Carbon dioxide

H   Hydrogen

H_2O Water

N   Nitrogen

O   Oxygen

Ratio   Ratio to exhaust gas

| THC | Total Hydrocarbons |
| X | Emissions species |

air	Intake air
analyser	Analyser conditions
b	Gravimetric fuel beaker
c	circuit
comb	Combustion
cond	Condensing in Analyser cooler
coolspill	Cooled spill fuel
corr	Corrected value
dry	Dry (excluding water vapour)
end	End of test
ex	Exhaust
f	Fuel
grav	Gravimetric
i	Portion of fuel circuit (1 to 5)
mes	Raw measured value
prefilt	Pre-fuel filter
start	Start of test
spill	Fuel Spill circuit
sply	Fuel Supply
t	time
wet	Wet (including water vapour)
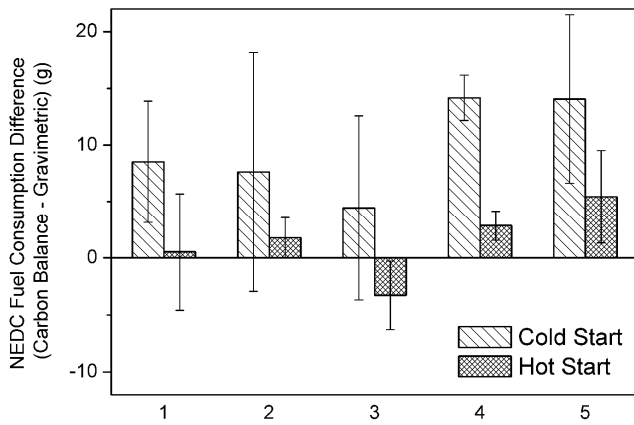
Figure 1 Difference between raw carbon balance and gravimetric estimates for hot and cold start tests, for 5 testing series
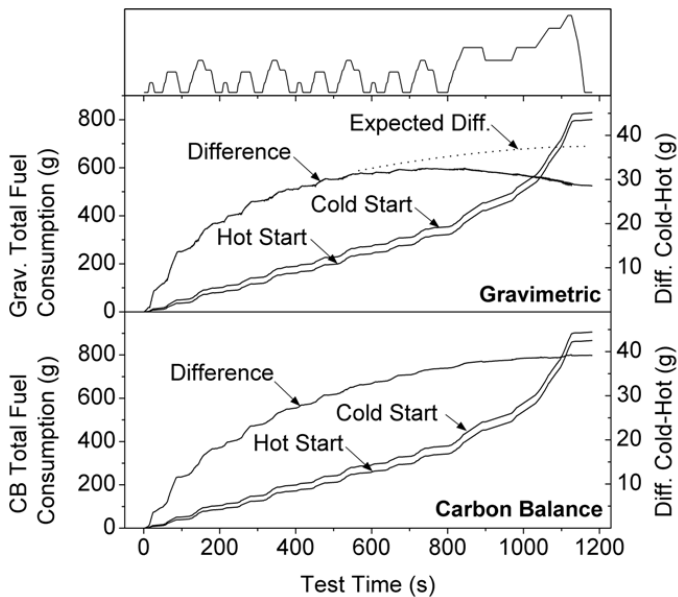
Figure 2 Gravimetric and carbon balance fuel consumption over an NEDC for a hot and cold start drive cycle, including difference between cold and hot start tests
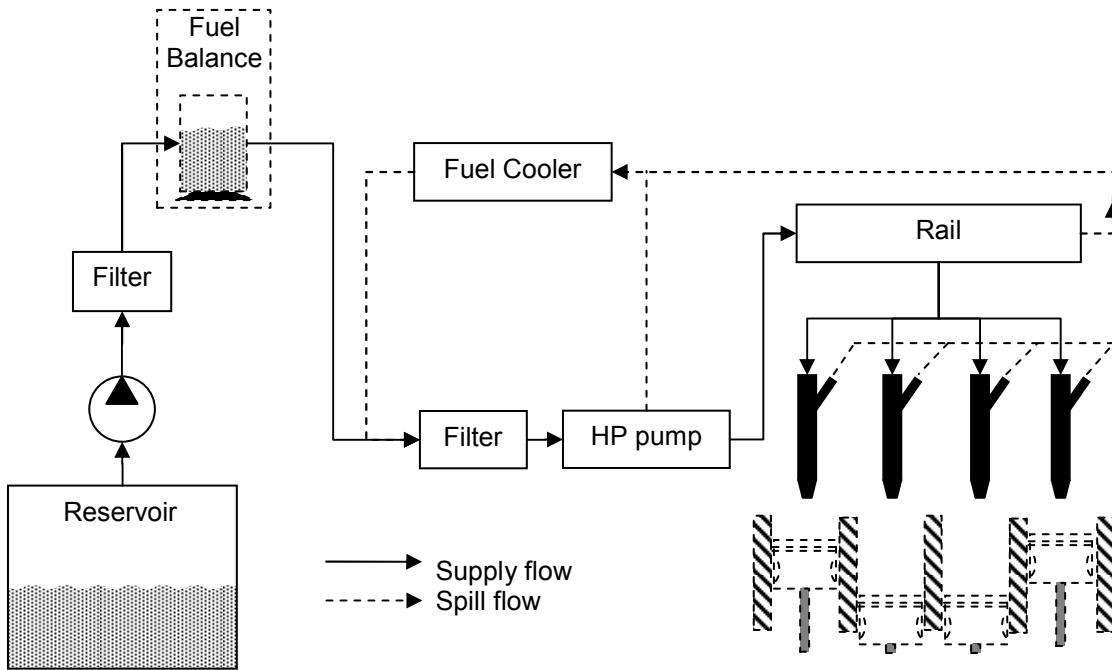
Figure 3 Diagram of fuel supply circuit with gravimetric fuel balance
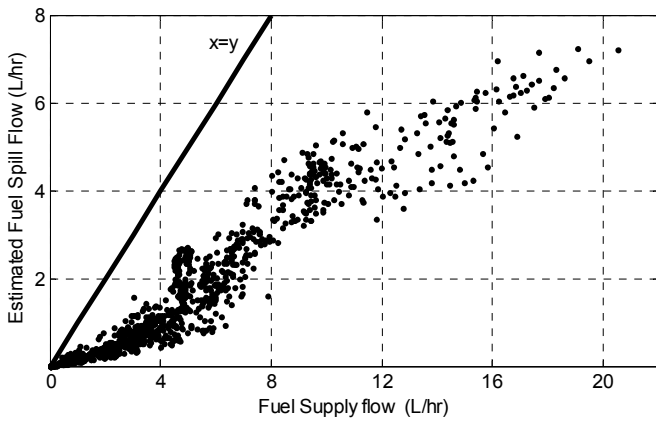
Figure 4 Fuel flows in supply and spill circuits
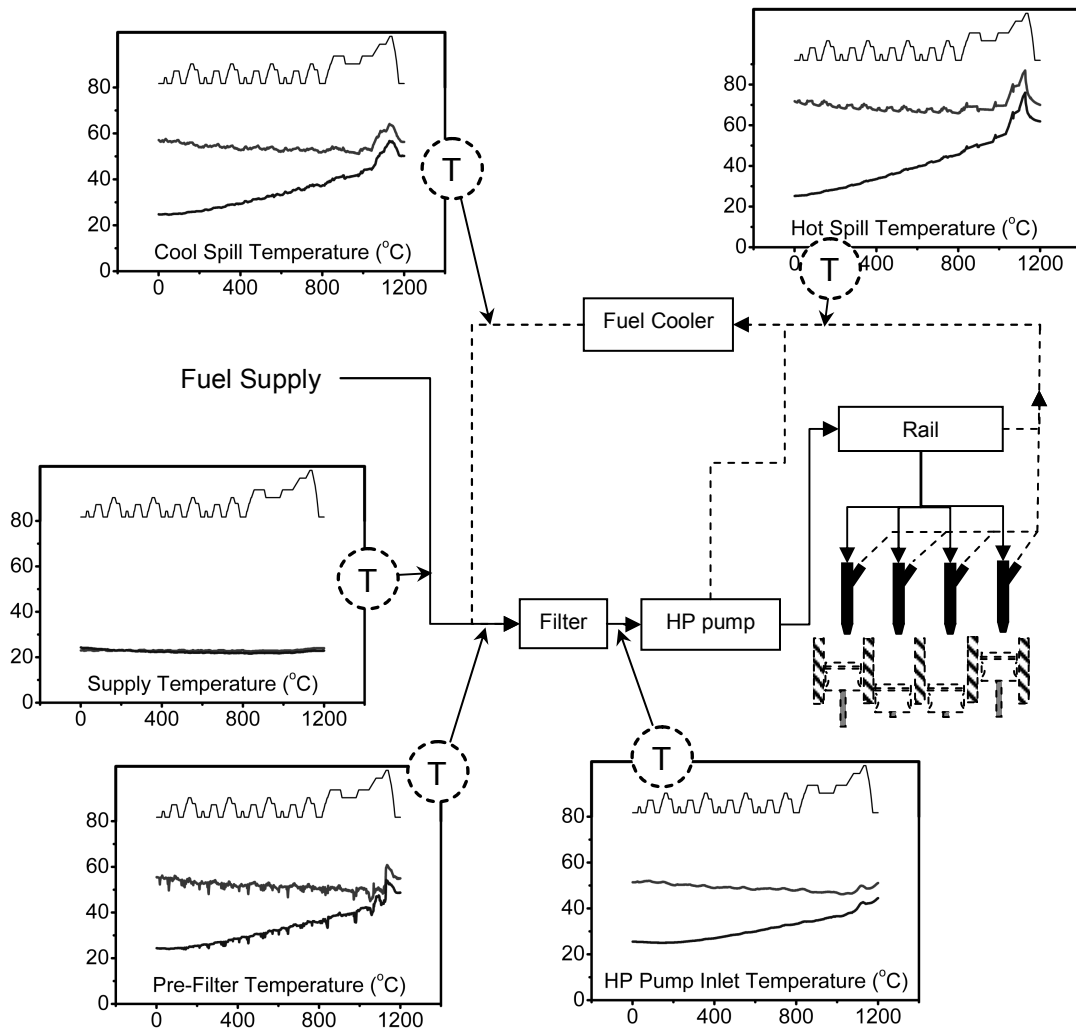
Figure 5 Evolution of fuel temperatures throughout the fuel supply circuit for hot and cold start tests (hot start tests represent the higher, constant temperatures)
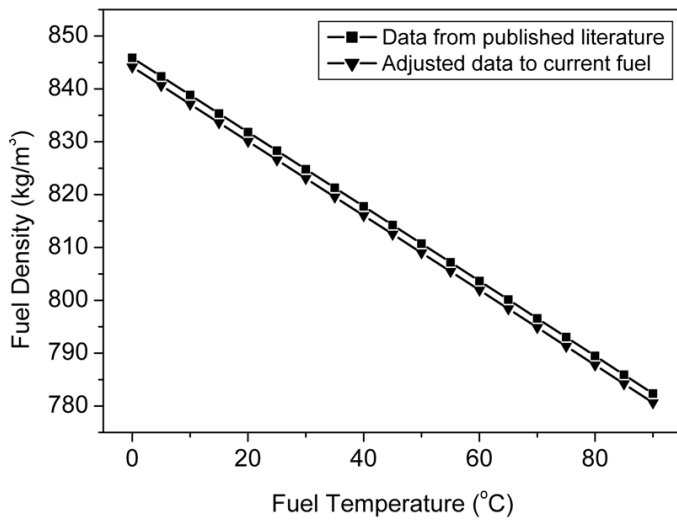
Figure 6 Fuel density as a function of temperature from published literature [22] and normalised to actual fuel
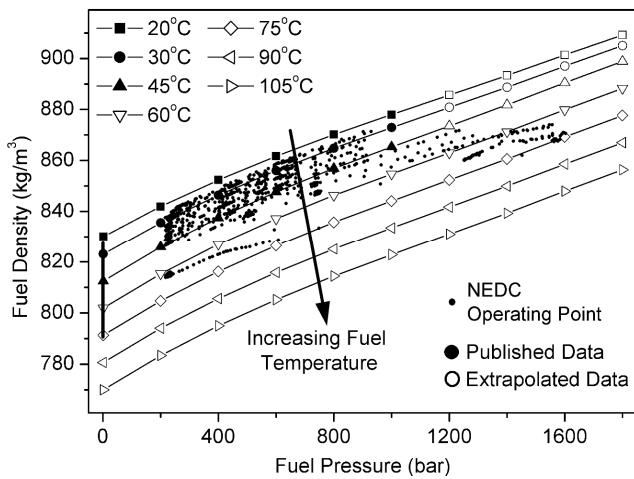
Figure 7 Fuel density with respect to pressure and temperature, showing regions from published data [22] and extrapolated region including all calculated operating points during NEDC
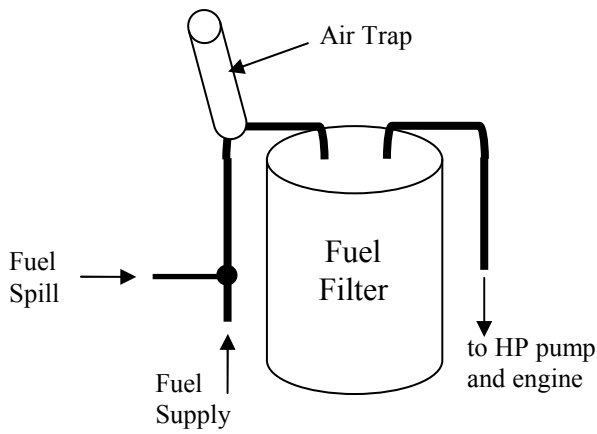
Figure 8 Air trap and filter layout
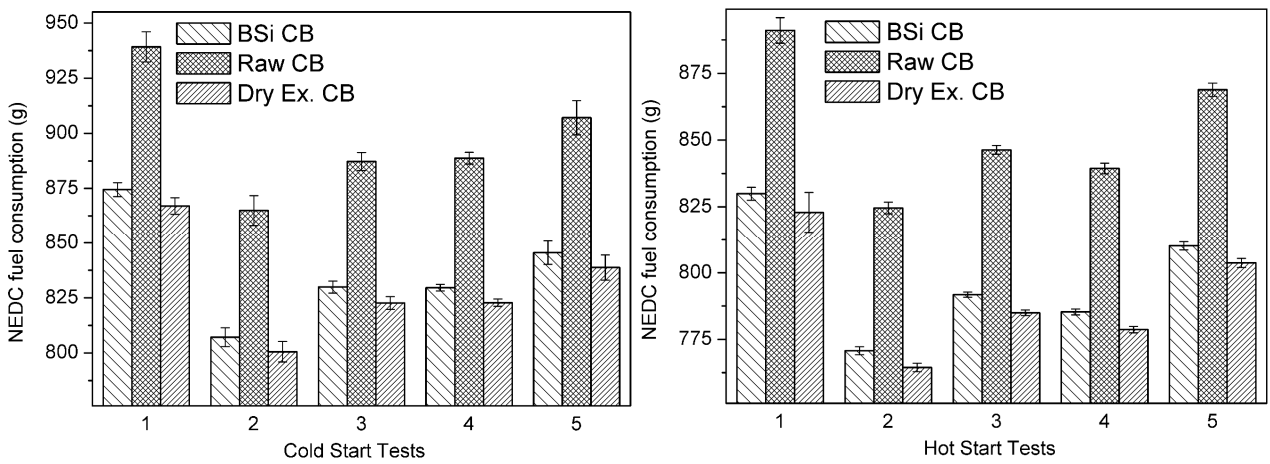
Figure 9 Carbon balance fuel consumption using British Standards correction factor (CB BSi), omitting correction factor (Raw CB) and using dry exhaust correction factor (Dry Ex. CB) for five experimental setups and for hot and cold starts.
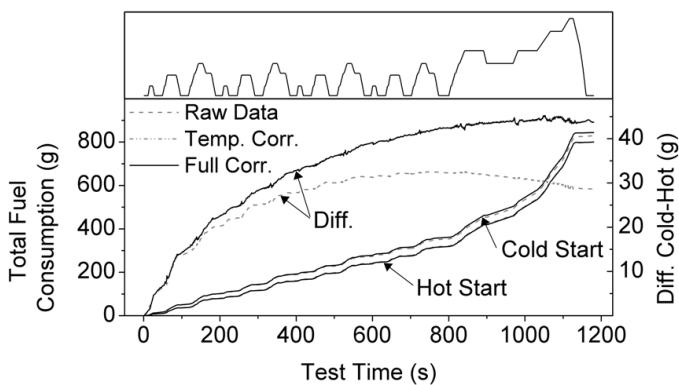
Figure 10 Raw, temperature corrected and fully (temperature and pressure) corrected fuel consumption for hot and cold start NEDC
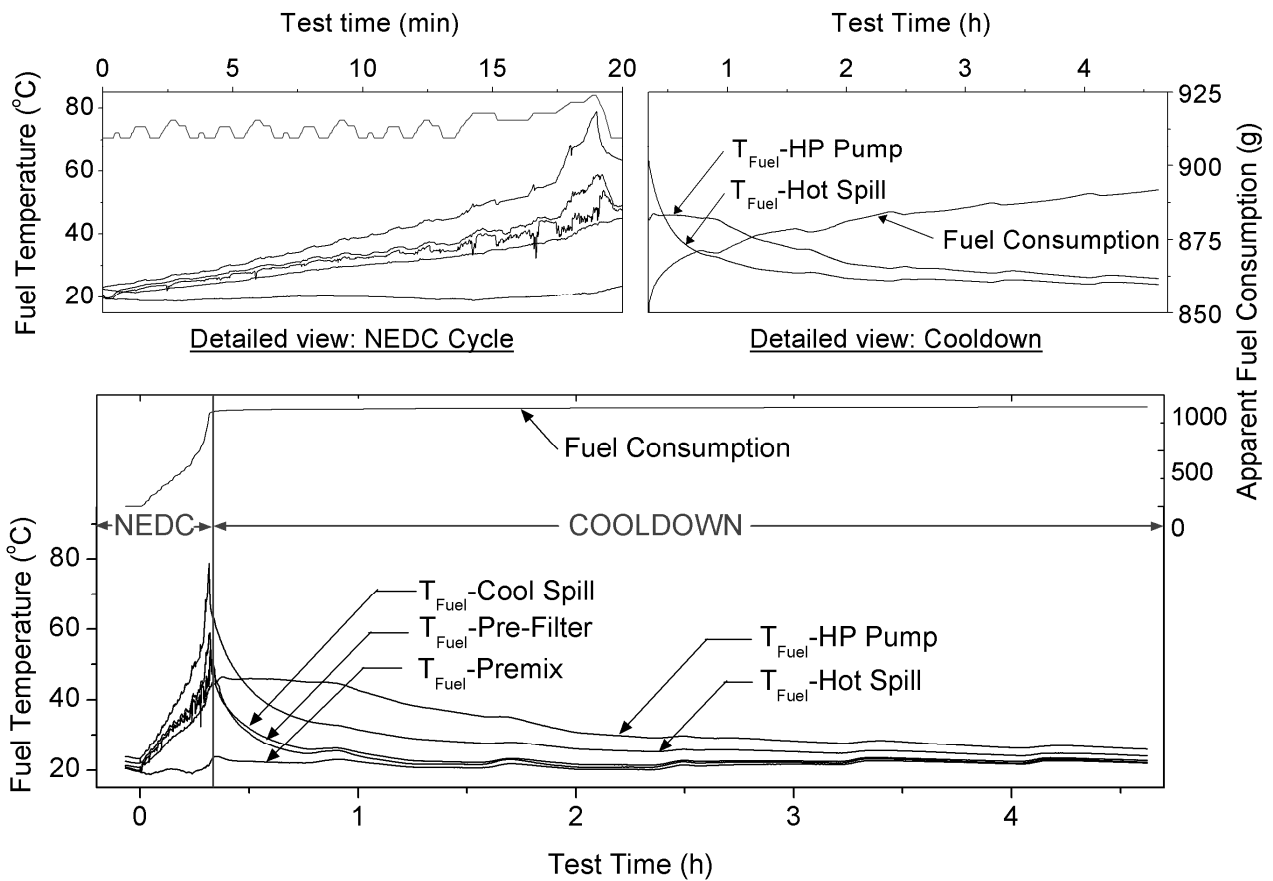
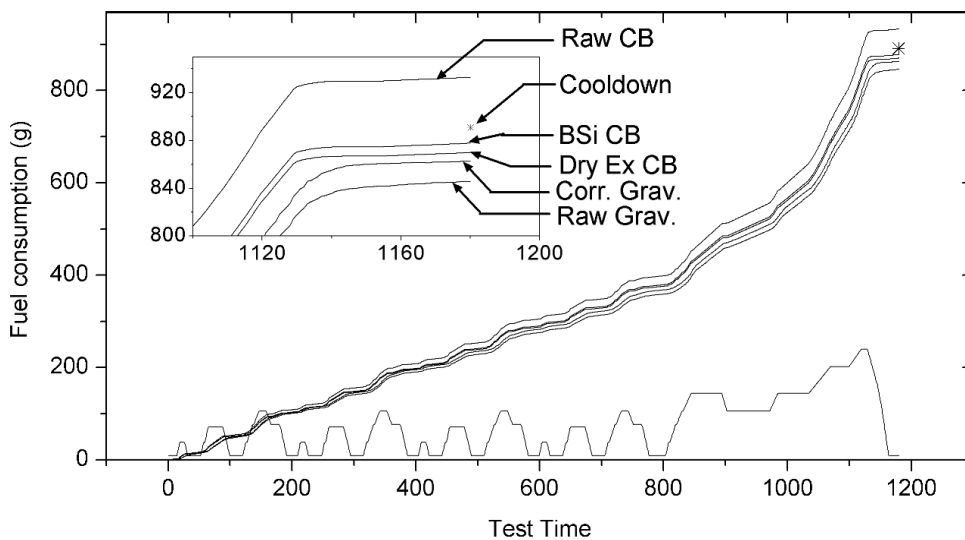**Figure 11** Fuel temperatures and apparent fuel consumption over cold start NEDC and cooldown

Figure 12 Fuel consumption estimates over a cold start NEDC for raw carbon balance (Raw CB),

BSi corrected carbon balance (BSi CB), Dry exhaust corrected carbon balance (Dry ex. CB), raw

gravimetric (Raw Grav.), corrected gravimetric (Corr. Grav.) and post cooldown measure
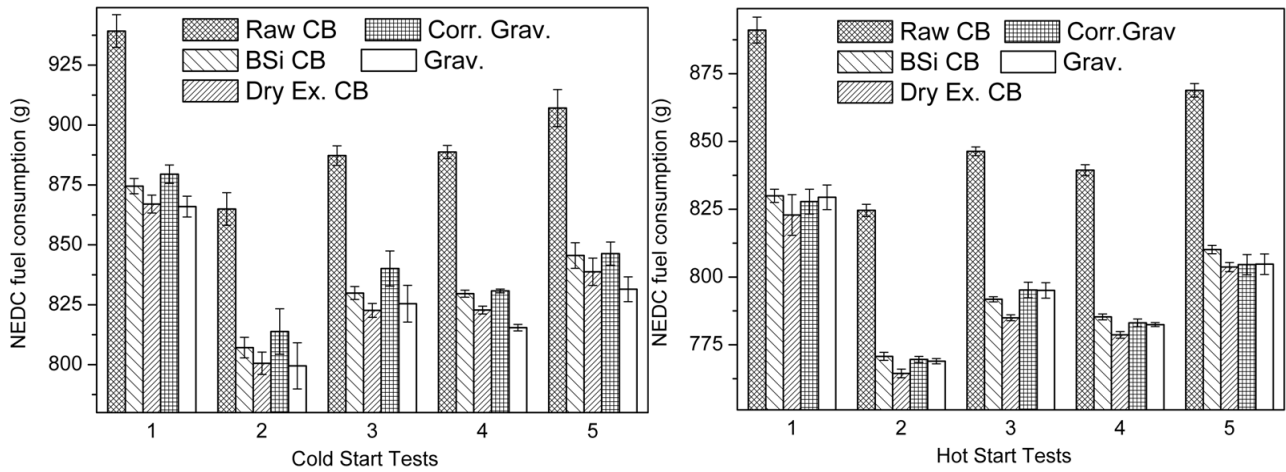
(Cooldown)

Figure 13 Fuel consumption estimates for five experimental setups and for cold and hot start tests for raw carbon balance (Raw CB), British Standard corrected carbon balance (BSi CB), dry exhaust corrected carbon balance (Dry Ex. CB), Temperature and pressure corrected gravimetric (Corr. Grav.) and raw gravimetric (Raw Grav.)