The effect of engine and transmission oil viscometrics on vehicle fuel consumption

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Abstract

An extensive programme of work has been undertaken to assess the potential benefits of modulating the properties of both engine and transmission lubricating oils to achieve lower fuel consumption. The performance of the engine lubricants was evaluated on a production Diesel engine on a transient test bed. The main engine lubricating oil viscometric properties investigated were cold cranking shear (CCS), kinematic viscosity at 100°C (KV100) and high temperature high shear (HTHS). Up to 3.5% fuel economy improvement was observed over the New European Drive Cycle (NEDC), relative to current production lubricants. A model relating fuel consumption to oil properties was developed and verified using an experimental programme conducted on a chassis dynamometer.

In a related study, the effects of changes in transmission lubricant properties were evaluated using a standard five speed manual transmission fitted to a light goods vehicle and tested on a chassis dynamometer. The lubricant was heated using an external energy source to simulate the effect of a more rapid warm up, this reduced the viscosity of the lubricant and a fuel consumption improvement of 0.7% was demonstrated over the NEDC from a 25°C start. In addition, a lower viscosity lubricant blend was evaluated, which delivered a 1% improvement in fuel economy over the standard blend from a cold start, and a further 0.4% improvement if heated.

List of Symbols and Units

ACEA	Association of European car manufacturers
BSFC	Brake Specific Fuel Consumption (g/kWh)
CCS	Cold Cranking Simulator - a device used to measure the apparent viscosity of oils under cold (between -5 and -35°C) cranking conditions representative of those found within engines, the abbreviation CCS is commonly used to prefix the resulting viscosity value and often referred to as 'cold cranking shear' (Cp)
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DoE	Design of Experiments
DTI	Department of Trade and Industry
ECE	Also known as UDC – Urban Drive Cycle
ECU	Engine Control Unit
EU	European Union
EUDC	Extra Urban Drive Cycle
EURO3	European emissions limit January 2001
FC	Fuel Consumption
FE	Fuel Economy
HC	Hydrocarbons
HPCR	High Pressure Common Rail
HTHS	High Temperature High Shear, a measure of viscosity at high temperature (typically 150°C) under shearing conditions representative of those found within engines (Cp)
KV_{100}	Kinematic Viscosity measured at 100°C (cSt)
NEDC	New European Drive Cycle
NOx	Oxides of Nitrogen
PM	Particulate Matter
THC	Total Hydrocarbons

Introduction

The average CO_2 for new UK car registrations during 2009 was 158g/km [1], down from 190g/km in 1997. CO_2 reduction proposals and recommendations have changed frequently over the last few years ranging from a voluntary target of 120g/km by 2012 proposed by the association of European car manufacturers (ACEA) [2], to 100g/km by 2020 outlined in the King review in March 2008 [3]. However, with the adoption of the new car CO_2 regulation within the EU in December 2008, reducing the fleet average target to 130g/km by 2015, the automotive industry faces a stiff challenge in the coming years. Manufactures which fail to achieve the necessary CO_2 reductions will face substantial penalties of up to 95 euro per excess gram per vehicle produced [4]. An even more stringent target of 95g/km has been earmarked for 2020 dependant on the findings of an impact assessment [4].

In addition to proposed efficiency savings, an extra 10g/km reduction in CO_2 is required by 2015 through the use of 'complementary measures' [4] such as the use of biofuels and wider adoption of 'eco-driving' principles.

The average UK new car CO_2 emissions over the period 1997-2006 is shown in Figure 1 and these data are further expanded in Table 1.

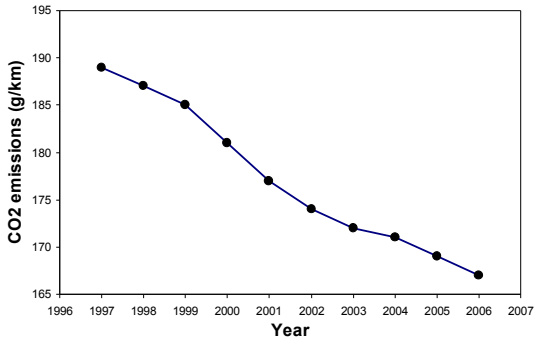

Figure 1 - Average UK new car CO_2 emissions 1997-2006 [1]

	1997	2006
Average new car CO_2 emissions	189.8 g/km	167.2 g/km (-11.9%)
New car sales	2,170,725	2,344,864 (+8.0%)
CO_2 emissions - all cars	72.2 Mt	68.7 Mt (-4.8%)
Total UK on-road cars	25.6 million	29.9 million (+16.8%)

Table 1 - UK car trends 1997-2006 [1]

Although the total vehicle parc has increased over the period 1997-2006 by 16.8%, a combination of CO_2 levels from new car registrations falling by 11.9%, the increasing proportion of diesel-powered vehicles on the road and the use of alternative fuels has resulted in an overall reduction in CO_2 emissions from all cars of 4.8% [1]. There is a direct correlation between CO_2 production and vehicle weight. Regulatory requirements relating to crashworthiness and pollution control, combined with a consumer appetite for larger, more powerful cars, have generally had an adverse effect on CO_2 emissions. Interestingly, a study conducted by Ricardo Consulting Engineers in 2005 concluded that UK CO_2 savings from cars have been countered by up to 50% as a result of vehicle weight increases [5].

Reducing the carbon footprint of automotive powertrains is a key R&D focus with many different avenues being explored to reduce fuel consumption (FC). One area that has received relatively little attention in open literature is the potential to re-formulate the lubricating oil and/or to improve thermal management of the lubricant to achieve low fuel consumption. The main opportunity here is for improvements concerning the engine lubricating oil. Shayler et al [6] show that engine oil viscometrics have a direct effect on engine friction but the impact on fuel usage is not presented. There are also potential savings from modifications to the transmission lubrication system. In a paper by Farrant et al [7], a thermal model was developed that could simulate the baseline powertrain and predict the potential improvements of alternative transmission thermal management strategies. The model, based on a naturally aspirated, 3.0L V6 engine with six-speed automatic transmission, indicated that a potential 3% improvement in fuel economy could be achieved over the NEDC for a constant transmission oil temperature of 94°C compared to a cold start from a 25°C ambient temperature. Matsuzaki et al [8] showed that reduced viscosity transmission oil can reduce friction by 10-20% in bench tests using a six-speed manual transmission operating at 2000rpm, but did not comment on the effect on whole vehicle performance. Kurashina et al [9] demonstrated that a 30% reduction in the kinematic viscosity of a manual transmission lubricant improved fuel consumption by around 1% over the NEDC, although no details were given as to the vehicle or transmission used.

This paper presents the results of a large experimental investigation to assess the potential benefits of modulating the properties of both diesel engine and transmission lubricating oil to achieve lower fuel consumption. The paper is divided into two parts. Part 1 considers the effect of lubricating oil viscometrics on the fuel consumption of a current Euro3 diesel engine while Part 2 investigates changes to the transmission oil properties, which were assessed on-vehicle.

Part 1 – Modulation of Lubricating Oil Properties

This part of the research programme was carried out in 2 phases. Phase 1 investigated the main viscometric properties that were considered to influence fuel consumption. Phase 2 was concerned with fuel consumption influences due to different additives with the same base oil. This 2nd activity will be reported in a later publication. The three main lubricating oil viscometric properties investigated were cold cranking shear (CCS), kinematic viscosity at 100°C (KV100) and high temperature high shear (HTHS). A brief description is given below.

Cold Cranking Shear (CCS)

CCS is measured using a Cold Cranking Simulator Test and provides a measure of the viscosity of the lubricating oil under conditions of low temperature and high shear rates. In general, a reduction in the CCS value of the lubrication oil lowers the viscosity under cold start conditions

and results in reduced engine friction and, in turn, lower fuel consumption.

High Temperature High Shear (HTHS)
HTHS is a measure of the lubricant's minimum dynamic viscosity when subjected to high temperature and shear conditions similar to those typically experienced during in-engine use. A higher HTHS value would suggest a higher dynamic viscosity within engine bearings resulting in increased fuel consumption but potentially reduced wear.

Kinematic Viscosity at 100°C (KV100)
KV_{100} gives the lubricating oil's resistance to shear or flow caused by intermolecular friction exerted when layers of molecules within the fluid attempt to slide over past each other, measured at 100°C. Specifically, the kinematic viscosity is the ratio of dynamic viscosity to density. The greater the KV_{100} value, the greater the fluid's resistance to flow resulting in increased engine friction and fuel consumption.

The experimental design is shown in Table 2. Initially, it was intended to only vary oil properties within generally accepted ranges seen in production oils but an additional oil was formulated with an exceptionally low CCS value in order to assess and quantify the impact this extreme would have on drive cycle fuel consumption.

Oil #	Oil Grade	CCS @ -25°C (cP)	KV_{100} (cSt)	HTHS @ 150°C (cP)
1	SAE 10W-40	6600	14.20	3.9
2	SAE 5W-40	4774	14.93	3.9
3	SAE 10W-20	6601	8.20	2.71
4	SAE 5W-20	4800	8.55	2.70
5	SAE 0W-30	196	9.57	2.69

Table 2 - Oil Properties – DoE design

Test procedure
The experimental study was performed on a modern 2.4l diesel engine mounted on a dynamic AC engine dynamometer. The New European Drive Cycle (NEDC) was the experimental datum with a thermally stable start condition of approximately 20°C. The experimental procedure was developed taking into account the influence of oil aging on fuel economy. Fuel consumption was measured via a carbon balance using an Horiba MEXA 7000 exhaust gas analyser.
Fuel consumption was evaluated with both fresh and aged engine oil to allow the effect of initial ageing mechanisms on vehicle fuel consumption to be considered.

Results
The fresh and aged oil properties are shown in Table 3. It should be noted that Table 2 outlines the DoE design values with fresh oil measurements carried out at BP's own labs for formulation purposes. Testing of used oil was outsourced with the fresh oil analysis repeated to ensure that fresh and aged viscometric values were comparable for modelling purposes. The discrepancies between values in Tables 2 and 3 are due to lab-to-lab variability.
Preliminary trials had confirmed that 30 hours of aging were required to stabilise the oils such that repeatable and consistent results were obtained. In general the oils held their grade quite well during testing. The notable exception to this is oil 5, which although blended aggressively to give superior fuel consumption, was unable to maintain this performance over the test programme. The CCS in particular rose by over 100% during the 30 hours of testing.

Oil #	Oil Condition	Oil Property		
		CCS @ -30°C (cP)	HTHS @ 150°C (cP)	KV_{100} @ 100°C (cSt)
1	Fresh	7180	4.01	14.53
	Aged	7100	3.71	13.61
	Change (%)	*-1.1*	*-7.5*	*-6.3*
2	Fresh	4720	4.07	15.33
	Aged	4280	3.72	14.32
	Change (%)	*-9.3*	*-8.6*	*-6.6*
3	Fresh	7340	2.89	8.12
	Aged	7040	2.73	8.28
	Change (%)	*-4.1*	*-5.5*	*2.0*
4	Fresh	4720	2.77	8.45
	Aged	4350	2.75	8.41
	Change (%)	*-7.8*	*-0.7*	*-0.5*
5	Fresh	657	2.69	9.57
	Aged	1330	3.43	12.18
	Change (%)	*102.4*	*27.5*	*27.3*

Table 3 - Oil Sample Analysis

Figure 2 shows the average BSFC for all 5 oil formulations over the whole NEDC drive cycle with error bars showing the 95% confidence interval of multiple repeat tests. Of the 4 oils falling within generally accepted viscometrics (oils 1-4), the oil with low values of CCS, KV_{100} and HTHS performed the best both when fresh and when aged. The high values of CCS, KV_{100} and HTHS seen in oil 1 resulted in approximately a 10g/kWh (3.2%) increase in BSFC compared with oil 4 regardless of oil age.

Oil 5 exhibited a much reduced BSFC when fresh compared with the other oils manifesting as a 3.2% reduction in BSFC over oil 4. However, oil 5 did not display the characteristic reduction in fuel consumption normally seen with increasing oil age, instead demonstrating a marked rise. The reason for this is evident in Table 3. CCS, HTHS and KV_{100} values for oil 5 significantly increased with age by 102.4, 27.5 and 27.3%, respectively, in agreement with the observed increase in BSFC, thus adding confidence in this trend as a real result. This trend of increasing CCS, HTHS and KV_{100} values with age was likely to be caused by lighter, more volatile organic compounds within the oil evaporating off over time and causing the oil to thicken. Oil 5 would be particularly susceptible to this effect due to it containing a higher than normal proportion of these volatile fractions in order to achieve the much-reduced CCS value.

Oil 2 provides an interesting comparison to oil 5 as it too displayed an increase in fuel consumption with time, however fully aged data for oil 2 were subject to a larger-than-normal degree of experimental scatter resulting in reduced confidence in the sample mean representing a true population mean. Looking again at Table 3, it can be seen that CCS, HTHS and KV_{100} all decrease (9.3%, 8.6% and 6.4%, respectively) as oil 2 is aged, which would be expected to cause a reduction in fuel consumption, thus implying that the slight increase in observed BSFC can be attributed to experimental error.

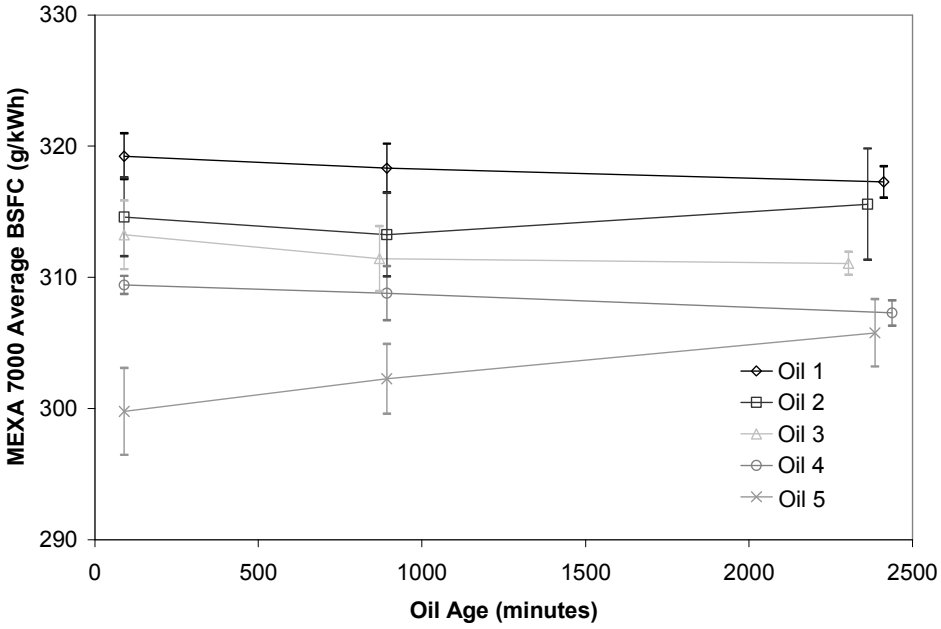

Figure 2 - NEDC Oil Performance (BSFC)

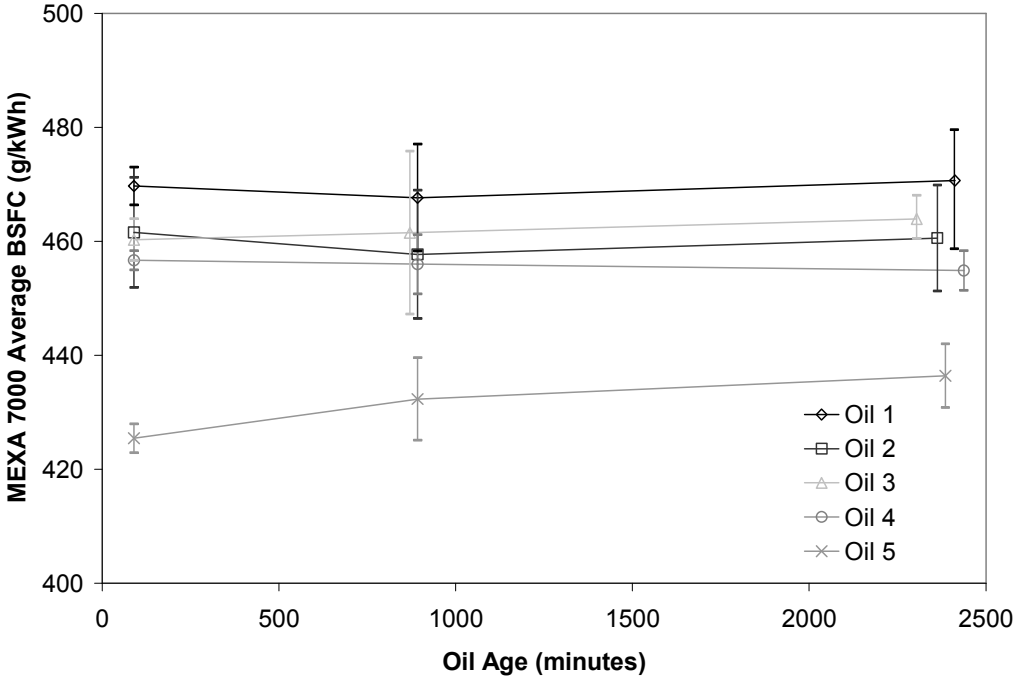

Figure 3 - ECE Oil Performance (BSFC)

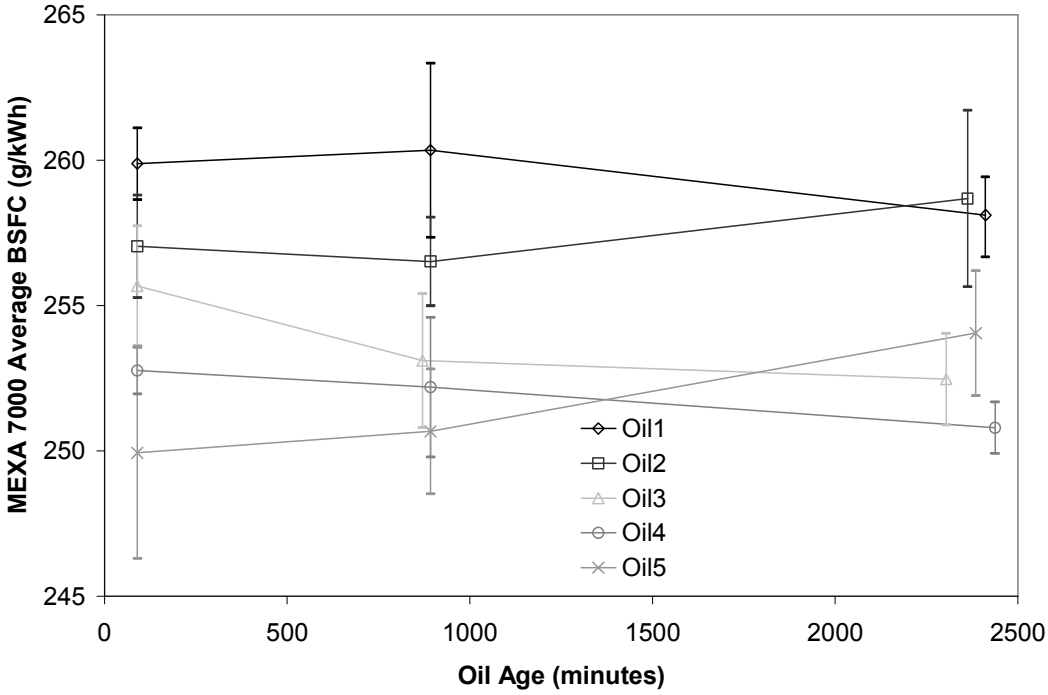

Figure 4 - EUDC Oil Performance (BSFC)

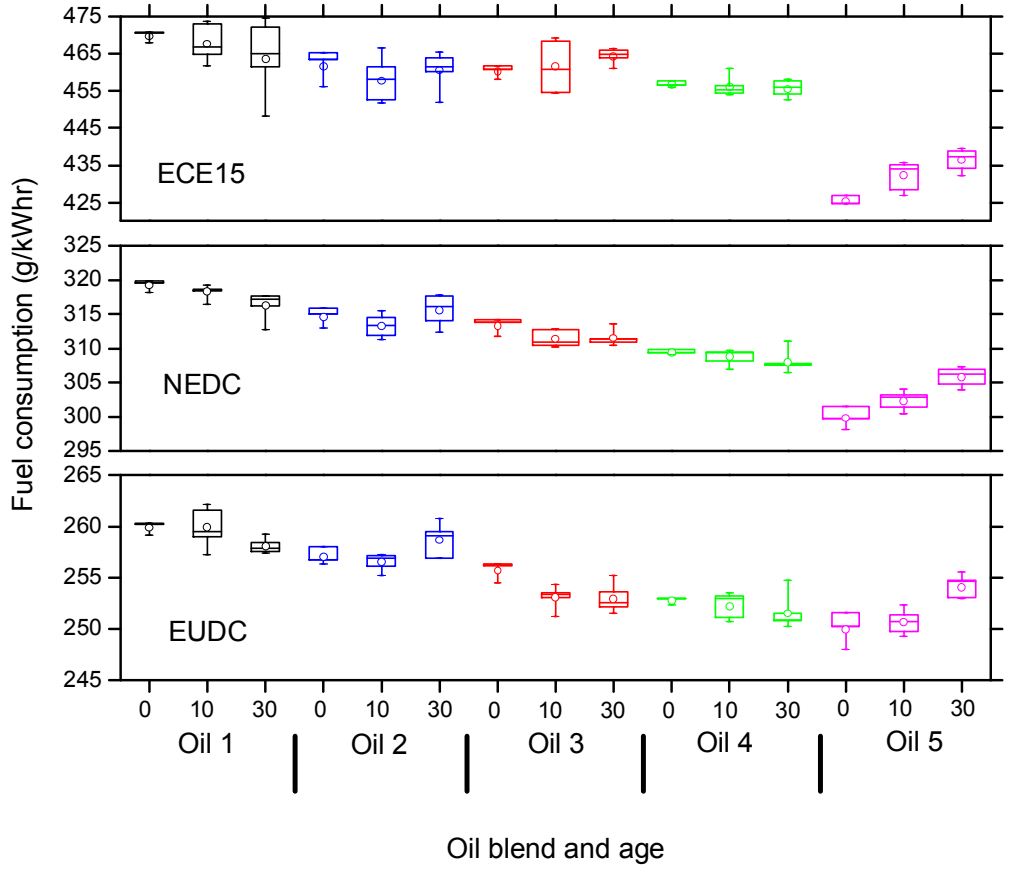

Figure 5 - Oil Performance (BSFC) Comparison

The effect of the differing oil formulations on BSFC during the initial ECE portion of the NEDC can be seen in Figure 3. As would be expected from the oil CCS values, oil 4 exhibits a 3.4% reduction in BSFC compared with oil 1 when aged, while oil 5 reduces the BSFC by an additional 4.1%.

Results for the EUDC given in Figure 4 correlate exceptionally well with the high temperature oil viscometrics, HTHS and KV_{100} values, with the measured rank order of oils 1 and 2 having the highest fuel consumption with oils 3, 4 and 5 performing better. Once the oils are fully aged, the increase in HTHS and KV_{100} for oil 5 (due to evaporation of volatile fractions) causes a rise in BSFC to a level greater than oils 3 and 4 but still less than that of oil 1 and 2. This trend is as expected based on aged oil sample property analysis.

EUDC data suggests a maximum BSFC improvement of 3.1% (between oils 2 and 4) can be obtained for aged oil by varying the high temperature viscometric properties.

Figure 5 shows the impact of oil viscometrics on fuel consumption for each section of the NEDC cycle in boxplot form[1]. It should be noted that the

[1] In descriptive statistics, a boxplot (also known as a box-and-whisker diagram or plot) is a convenient way of graphically depicting groups of numerical data through their five-number summaries (the smallest observation, lower quartile (Q1), median (Q2), upper quartile (Q3), and largest observation). A boxplot may also indicate which observations, if any, might be considered outliers. The boxplot was invented in 1977 by the American statistician John Tukey.

axis scales for the NEDC, ECE and EUDC differ from each other.

Response model to predict the effect of viscometrics on fuel economy

The effect of CCS, HTHS and KV_{100} on BSFC for aged oil during the ECE, EUDC and NEDC as a whole was modelled using the Matlab model based calibration toolbox [10] and the results are shown in Figures 6, 7 and 8, respectively.

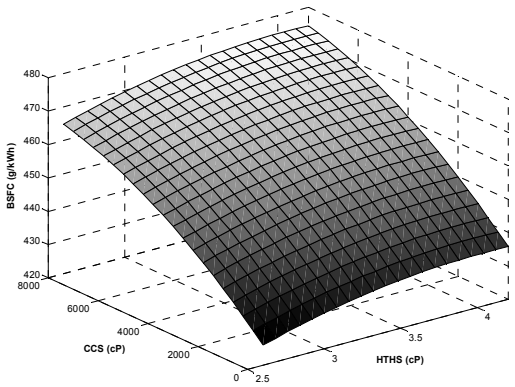

Figure 6 - Phase 2: ECE FE prediction from oil viscometrics

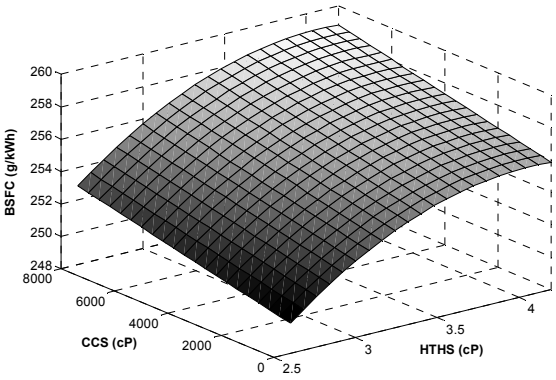

Figure 7 - Phase 2: EUDC FE prediction from oil viscometrics

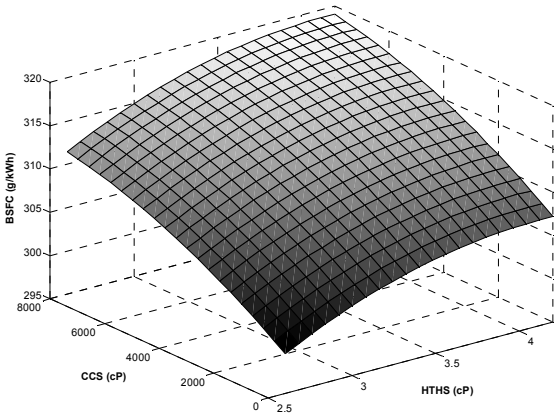

Figure 8 - Phase 2: NEDC FE prediction from oil viscometrics

It is evident that CCS is by far the most significant factor during the cold ECE section of the cycle while HTHS and KV_{100} become dominant during the EUDC. All three factors have a significant effect on total-cycle (NEDC) fuel consumption.

The model presented above is empirical and has no predictive ability. If lubricants are used in other engines or the engine is tested over different cycles it should not be expected that the model is able to predict accurately the result. Nevertheless, the overall trends may be indicative of performance in other situations. For example, a programme of work was undertaken on a chassis dynamometer using an engine of the same general type but of 2l displacement rather than 2.4 used on the engine test stand. The engine was installed in a light goods vehicle. The test procedure was identical to that employed on the dynamic test cell. While the performance characteristics of the engine were similar it would be expected that the performance over the drive cycle would be measurably different due to the reduced displacement. The effect of engine friction will be a smaller proportion of overall work performed by a smaller engine subject to similar loads, reducing the effect of oil improvements. It was, however, considered that the same general trends in response to engine oil viscometrics would be evident. Two lubricant blends were tested, a

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Boxplots can be useful to display differences between populations without making any assumptions of the underlying statistical distribution. The spacings between the different parts of the box help indicate the degree of dispersion (spread) and skewness in the data, and identify outliers.

current production blend and a revised blend designed to improve fuel consumption based on the results of the engine tests.

The fresh and aged viscometric data are presented in Table 4. The candidate oil is less viscous throughout the operating range, both fresh and aged. The fresh viscosity profiles are presented in Figure 9 as a function of oil temperature. The response model predicted that the candidate oil would be 2% better in fuel economy (FE) terms than the production oil when fresh.
The experimental validation results are presented in Figure 10 in boxplot form. The data for fresh oil demonstrated a 1.7% improvement, which, when compared with the 2% improvement predicted, suggests good model accuracy. In addition, it is evident from Table 4 that the production oil HTHS value reduced by approximately 5% during the test while remaining almost constant for the candidate blend. The decrease in HTHS for the production blend with age lead to a reduction in the predicted specific FE saving between the two aged oils.

In terms of drive cycle BSFC reported in Table 4, the model predicted a 2.3% reduction between the aged candidate and production blends compared to a measured reduction of 1.5%.

It should be noted that the stated accuracy of CCS and HTHS measurements is approximately ±1% of full scale, which equates to 50cP for CCS and 0.03cP for HTHS. These inaccuracies will introduce additional errors into the model predictions.

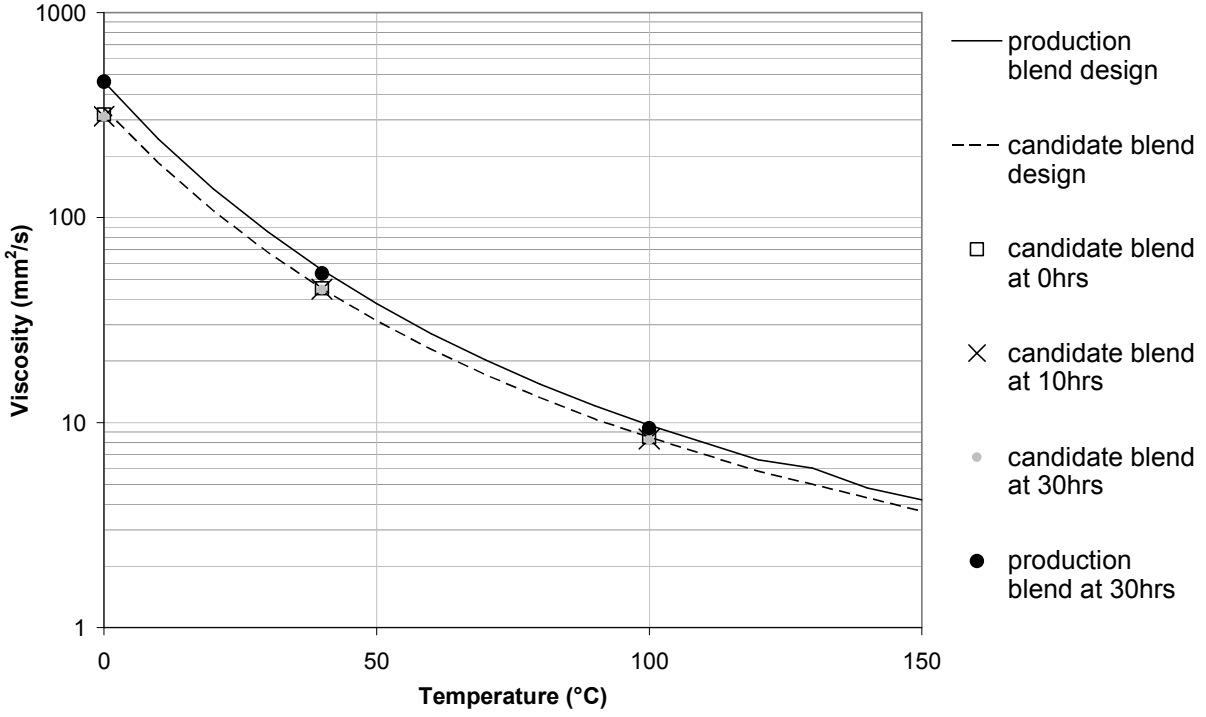

Figure 9 – viscosity of production and candidate oils across working temperature range

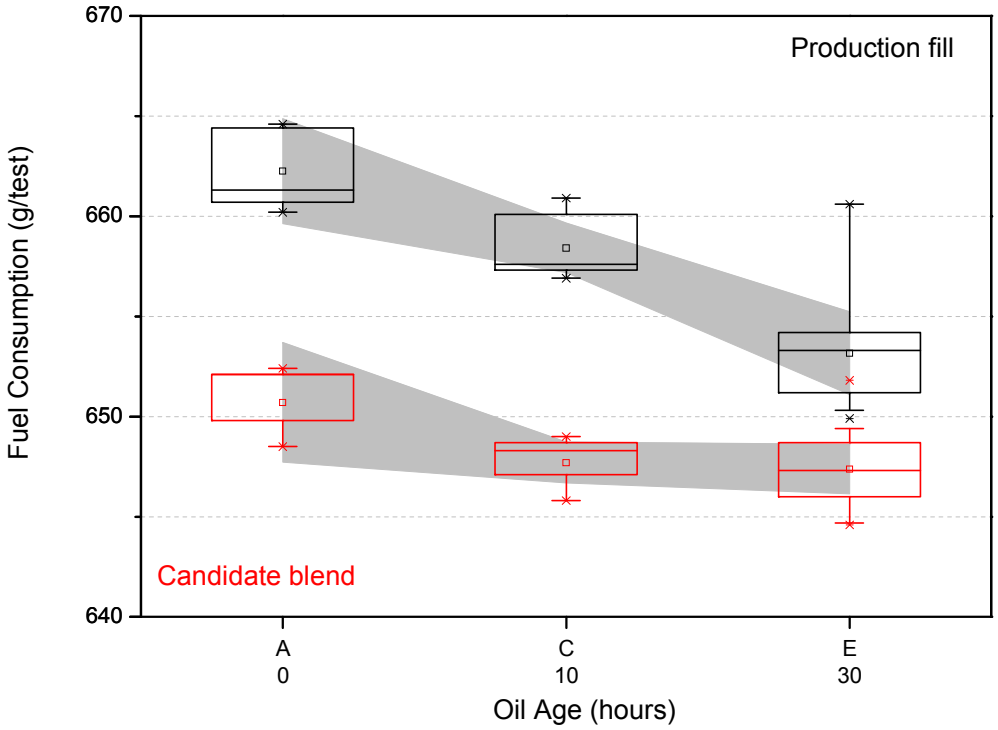

Figure 10 – Chassis dynamometer tests to validate viscometric response model.

	Production Blend		Candidate Blend		
	Fresh	Aged 30hrs	Fresh	Aged 10hrs	Aged 30hrs
CCS @ -30°C (cP)	3740	3800	1910	1950	1970
HTHS @ 150°C (cP)	3.07	2.92	2.59	2.57	2.6
KV_{100} @ 100°C (cSt)	8.452	9.353	8.476	8.301	8.227
Predicted NEDC fuel usage (g/kWh)	310.1	308.8	301.4	301.2	301.6
Measured NEDC fuel usage (g/kWh)	320.9	318.5	314.6	315.4	313.7

Table 4 – Oil properties during chassis dynamometer testing

Part 2 – Modulation of transmission oil properties

The aim of this aspect of the study was to investigate the effects on fuel economy of using waste heat from the engine to reduce the transmission oil viscosity from a cold start. In order to evaluate the maximum potential gain, an electrical heating system was developed to emulate the effect of such a waste heat recovery system. This had the dual benefits of being more controllable and flexible whilst allowing the effect of transmission heating to be isolated from any detrimental effect on the engine performance that may result from sharing the available thermal energy.

In addition to the heating study, the effect of a reduced-viscosity transmission oil was investigated. This measure could be implemented either in isolation or in combination with the heating in a production solution. The investigations were conducted on a light goods vehicle equipped with a 2 litre High Pressure Common Rail (HPCR) diesel engine and manual transmission.

Vehicle and transmission modifications. The 5-speed manual transmission was modified to incorporate bulkhead fittings to accept five cylindrical induction heaters. Figure 11 shows the location of these heaters, indicated here by wooden dowels. The fittings were located such that the heaters are adjacent to the gear cluster with maximum heated length immersed in the oil. The heated length and thus the wattage of each heater varies according to the penetration into the oil. The power density of the heaters was limited to eliminate the possibility of localised overheating of the oil. The total power output from the 5 heaters was initially 495W, which was subsequently uprated to 1080 W to achieve a higher oil operating temperature. Each heater was fitted with an internal thermocouple mid-way along its heated length. The electrical power to run the heaters was drawn from the mains to avoid affecting the fuel consumption by increasing the load on the alternator. This allows the effect of the heating to be viewed in isolation.

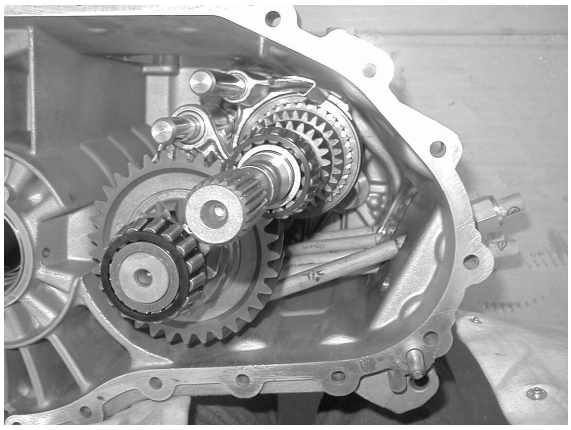

Figure 11 – Location of heating elements in transmission

Experimental approach.
The NEDC was used as the benchmark evaluation of the results. The standard bag approach was used to determine the fuel consumption with sufficient repeat tests performed to achieve an acceptable repeatability (+/-1%) at the 95% (4 standard deviations) confidence limit. The vehicle remained undisturbed on the chassis dynamometer for the entire experimental programme.

The testing was split into five phases. For each phase a baseline test sequence was performed together with a modified configuration as described below. All tests were performed at a standard ambient temperature of 25^{o}C except for phase 2, which was conducted at an ambient temperature of -7°C. Each configuration was tested at least five times from a fully conditioned state to allow statistical evaluation of the results. Phases 1 to 4 were conducted with the production blend of transmission oil. Phase 5 investigated the effect of a reduced viscosity formulation.

Details of the experimental phases are given below:

Phase 1 – Effect of heaters. A set of conditioned cycles were performed in a baseline configuration. A series of tests were then conducted with a heat input of 495W delivered from engine start onwards.

Phase 2 – Investigation of the effect of -7^{o}C ambient temperature. The baseline test sequence was repeated without heat input to the oil followed by a set of tests conducted with 495W of heat input delivered from engine start onwards.

Phase 3 – Investigation of the effect of increased heater power. The baseline test sequence was repeated without heat input to the oil followed by a set of tests conducted with 1080W of heat input delivered from engine start onwards.

Phase 4 – Investigation of the effect of pre-heating. The baseline testing sequence was followed by an evaluation of the effect of pre-heating the oil (via the cartridge heaters) to a temperature of 70^{o}C, switching off the heaters before engine start.

Phase 5 – Evaluation of a reduced viscosity transmission oil. Following a repeat of the baseline tests, a flushing cycle was performed before filling the transmission with the reduced viscosity blend. The effect of this oil with no heating was investigated, followed by an evaluation of the effect of the higher heat input (1080W) from engine start onwards.

Results and Discussion

Table 5 summarises the results of the test programme. Figure 12 shows these results graphically, together with an indication of the 95% confidence interval associated with each result. Figure 13 shows typical temperature profiles of the transmission oil during the drive cycles in the various configurations.

Phase	Test Condition	Average NEDC Fuel Consumption	
		(g/test)	(Reduction %)
1	Baseline	654.9	-
	Heated 495W	651.6	0.5
2	Cold Baseline (-7°C)	752.9	-
	Cold (-7°C), Heated 495W	748.4	0.6
3	Baseline	655.2	-
	Heated 1080W	650.6	0.7
4	Baseline	655.4	-
	Pre heated to 70°C	646	1.4
5	Baseline	655.4	-
	Reduced Viscosity	648.2	1.1
	Reduced Viscosity, Heated 1080W	645.8	1.5

Table 5 – Effect of transmission oil heating on fuel consumption.

Phase 1 - At an ambient temperature of 25°C it can be seen from Figure 13 that the transmission oil temperature naturally rises by about 20°C (from +24°C to 44°C) over the 20 minute NEDC, primarily due to the churning of the oil in the transmission. The addition of 495W of electrical heating from engine start causes the transmission oil to rise by an extra 12°C over the NEDC, (i.e. from +24°C at start to +56°C at end of NEDC). As expected, this results in a 0.5% reduction in fuel consumption attributable to the electrical heating.

Phase 2 – Figure 13 shows that at an ambient temperature of -7°C the transmission oil temperature naturally rises by 31°C (from -7°C, to 24°C) over the NEDC without any additional heating. The increased warming over that seen at the 25°C tests is most likely attributable to the increased work done to shear the highly viscous oil at the very low temperatures. This increased work is a significant proportion of the extra parasitic load that, when combined with thermodynamic effects on engine combustion, and temperature-dependant fuelling maps, give a fuel consumption increase of 15% when compared with the results at 25°C. Another significant factor in this increased parasitic load is the increased rolling resistance of the cold tyres at -7°C.

Interestingly, the impact of the additional heating at -7°C is very similar to that observed at 25°C in terms of temperature rise and fuel consumption reduction, with a 0.6% saving observed over the cycle.

A major aspect not considered in detail is the additional electrical loading which would be required to power the heaters if an electrical solution was to be considered. By way of comparison, the heaters consumed approximately the same power as the heated front screen which, on the test vehicle, was always active under cold-start conditions. However, due to the fuel consumption penalty which would be incurred if the transmission oil were to be electrically heated at start-up, it is envisaged that that additional heating would be provided from exhaust gas waste heat while ensuring no impact on catalyst light-off time.

Phase 3 – As expected, doubling the electrical heating to 1080W approximately doubles the temperature rise of the transmission oil with the oil temperature increasing by an extra 30°C over the NEDC, (i.e. from +24°C at start to 74°C at end of NEDC). This increase in temperature results in a 0.7% reduction in FC.

Phase 4 – Pre-heating the transmission oil to 70°C immediately prior to the test yielded a 1.4% reduction in FC compared with the baseline. Examining Figures 14 & 15, it can be seen that, as expected, pre-heating significantly reduced the predicted transmission oil viscosity during the cycle, in particular through the ECE. It is highly probable that the reduction in FC is due to the reduced viscosity of the oil at the elevated temperature leading to reduced churning losses in the transmission. Preheating the oil should have no impact on any other engine-related systems which would affect fuel consumption.

The preheated tests show a temperature overshoot at the start of the cycle (Figure 13) where locally hot oil is mixed with the bulk oil as the gearbox components begin to rotate.

The intended outcome of preheating was to identify the ultimate potential benefit available via thermal management of the existing transmission oil. As previously stated, electrically preheating the oil is not considered a production-viable solution but does demonstrate the potential benefits of reducing the oil's viscosity. For this reason, a reduced viscosity oil was evaluated to demonstrate the FC benefits without the need for heating.

Phase 5 – Use of a lower viscosity oil gave a 1.1% reduction in FC when compared with the 'production' transmission oil if neither are heated over the NEDC. As with the preheated oil investigated during Phase 4 testing, FC benefits are attributed entirely to the lower oil viscosity and reduced churning losses in the transmission.

Heating the lower viscosity oil during the cycle resulted in a further 0.4 % reduction in FC over the NEDC, giving a total improvement of 1.5% in FC compared to the un-heated 'production' oil. Figure 14 shows the predicted effect of temperature on oil viscosity over the cycle, showing that the reduced viscosity oil with 1080W of heating (dotted line) achieves a lower viscosity by the end of the cycle than all other combinations examined.

Figure 15 presents cumulative or integrated kinematic viscosity plot. While having no "physical" meaning, this measure represents a combination of the effects of base oil viscosity and heater performance over the test and is analogous to the mean oil viscosity over the cycle. This metric is useful to allow direct comparison between the effect of less viscous oils and transmission thermal management measures.

Figure 16 plots fuel consumed over the test cycle against the integrated viscosity metric. The linear correlation between the viscosity and FC is clearly evident for tests at 25°C. Tests performed at -7°C are expected to show a similar correlation but would not be expected to lie on the same line as the warmer data due to other effects on fuel consumption, such as changes in rolling resistance of the colder tyres, increased engine friction and changes to the fuelling rates controlled by temperature-dependant warm-up strategies

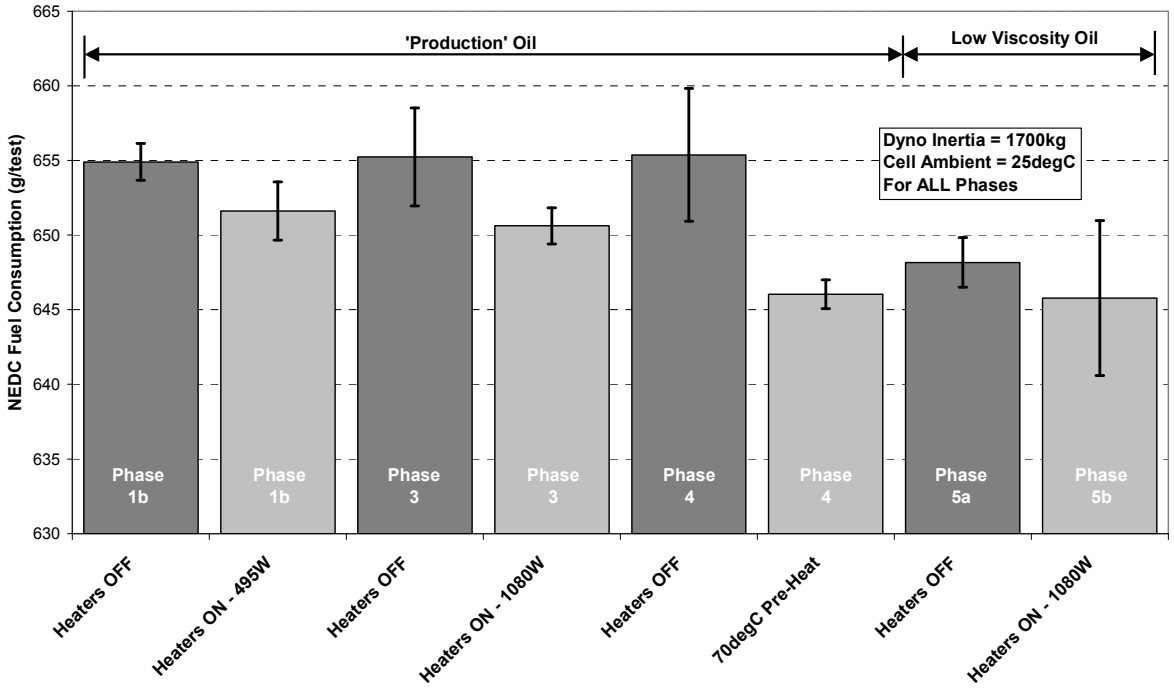

Figure 12 – Effect of transmission oil heating and reduced viscosity on fuel consumption

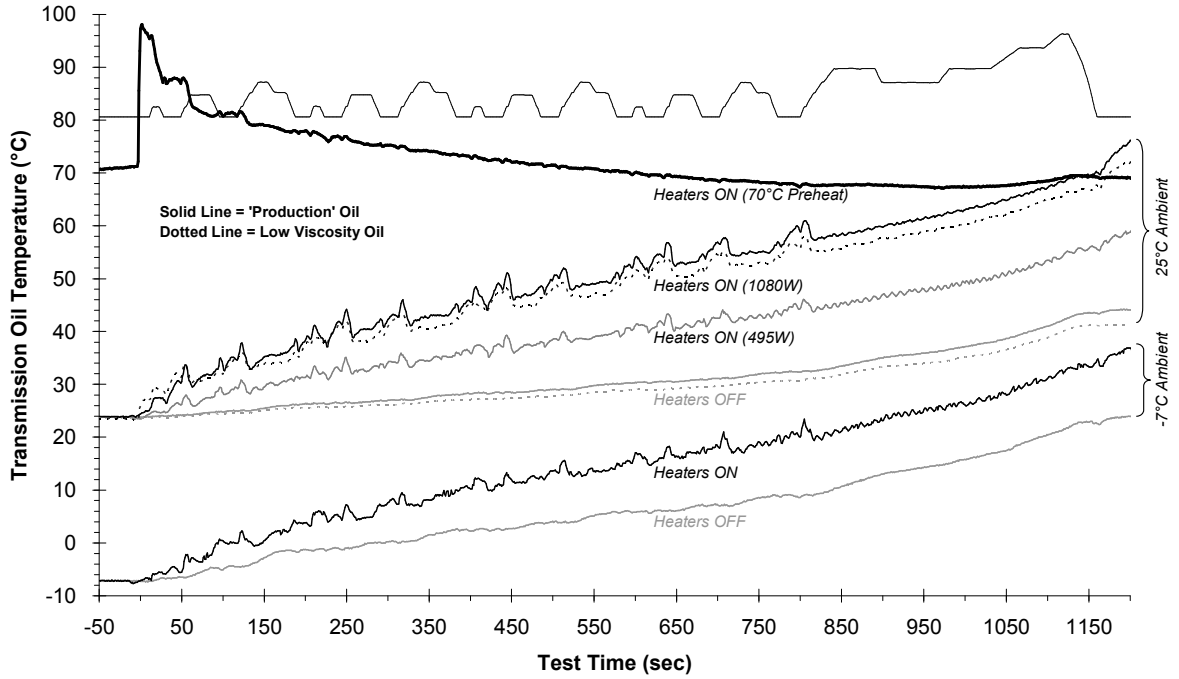

Figure 13 – Temperature rise over NEDC with heaters on and heaters off at -7°C and +25°C, also showing effect of preheat to 70°C

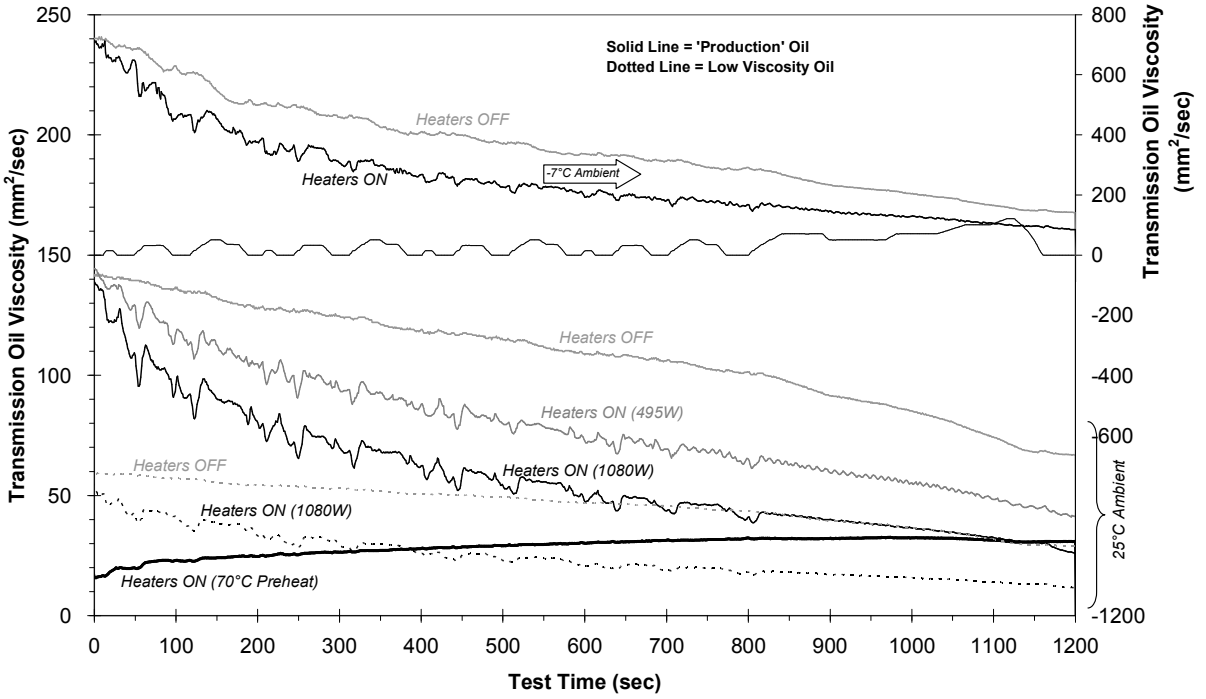

Figure 14 – Predicted transmission oil viscosity based on bulk oil temperatures during the NEDC

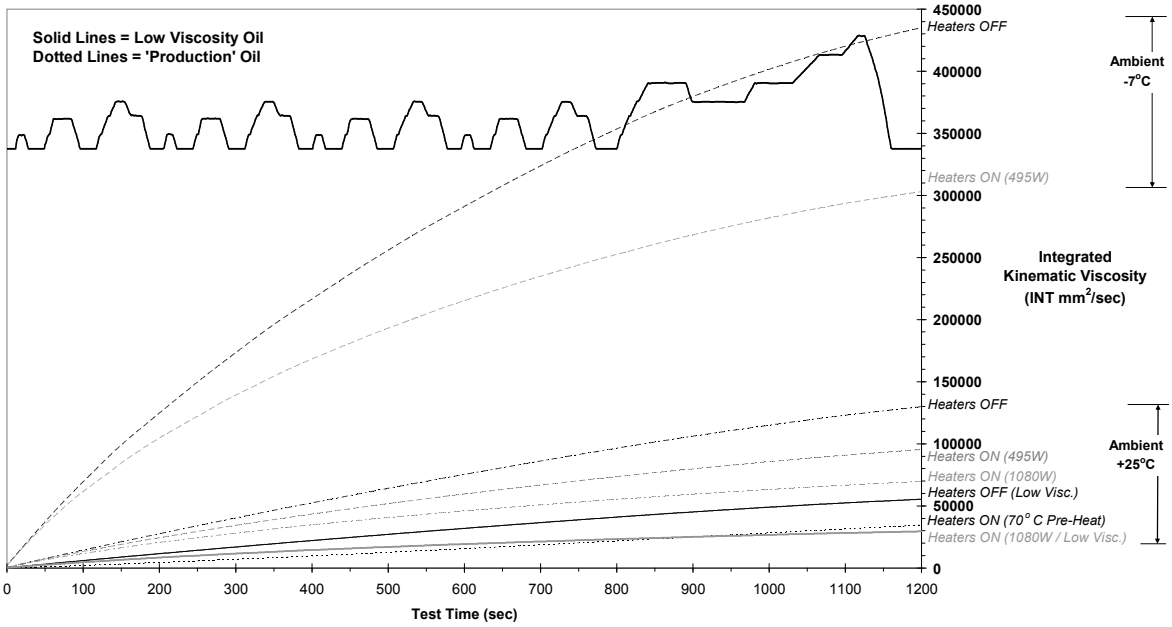

Figure 15 – Integrated kinematic viscosity over NEDC showing cumulative effect of oil type and heater performance

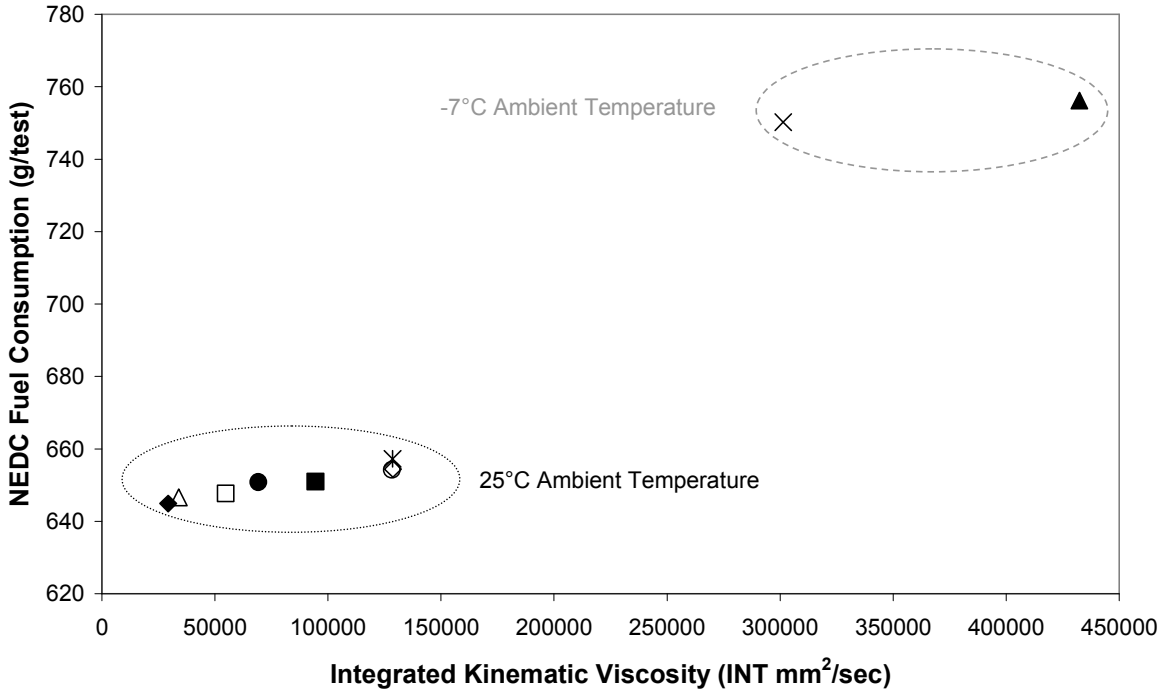

Figure 16 – Correlation between integrated kinematic viscosity and fuel consumption during the NEDC

Conclusions

Due to the distinct nature of the two parts of this study, the conclusions for each will be discussed separately:

Engine oil viscometrics – An experimental programme has been conducted to evaluate the effect of engine oil viscometrics on the fuel consumption of a EURO3 common rail diesel engine-powered vehicle.

It was found that the CCS is the dominant factor on fuel consumption during the early stages (ECE) of the NEDC drive cycle when the engine oil temperature is still low.
A reduction in CCS of approximately 30% resulted in a fuel economy improvement of 5.5% over the cycle. However, this benefit is not observed during the later, hot portions of the cycle (EUDC). As the majority of fuel is consumed during the 'hot', high speed portion of the cycle, the benefit observed for the NEDC as a whole is slight at 1.5%.

While having little impact early in the drive cycle, HTHS and KV_{100} become more dominant with increasing oil temperature during the EUDC portion of the NEDC cycle. Reducing the values of HTHS and KV_{100} were found to improve fuel consumption by 3.1% over the 'hot' EUDC for fully aged oil.

A combination of low CCS, HTHS and KV_{100} values reduced total cycle BSFC, for fully aged oil, by a maximum of 3.2% compared with the baseline. However, oil formulated with exceptionally low CCS values performed well when fresh but suffered from an increase in viscosity (and hence BSFC) with age as volatile compounds were lost via evaporation, negating potential in-service benefits.
DoE analysis confirmed the expected trends in fuel consumption based on oil viscometric properties and quantified the magnitude of their impact. The derived DoE model showed good agreement with experimental validation data and could be used to predict changes in fuel

consumption over the new European drive cycle for given oil viscometric properties.

Transmission oil viscometrics – The use of electric heating cartridges within the transmission oil allowed a useful fuel saving to be realised.

It was found that 495W of heating applied from the start of the drive cycle resulted in a 0.5% reduction in fuel consumption, while 1080W of heating yielded a 0.7% reduction. In order to demonstrate the maximum achievable benefit of heating the current production transmission oil, the oil was preheated to 70°C prior to the start of the cycle resulting in a 1.4% reduction in fuel consumption.

This electrical configuration demonstrated the potential benefits of transferring waste heat from the engine to the transmission oil, however, the additional complexity of engine modifications required to transfer heat from the engine to the transmission using engine coolant or exhaust as the heat transfer medium would be significant, costly and therefore unlikely to be production feasible.

The fuel saving achieved by using an un-heated, reduced viscosity, transmission oil was found to be 1.1% compared with the baseline, which is greater than was achieved when applying 1080W of heating to the current production oil. Providing the reduced viscosity oil can satisfy durability and other production criteria, its use would be a less complex solution to reducing transmission churning losses and drive cycle fuel consumption than heating the current production oil.

Heating the lower viscosity oil during the cycle yielded a further 0.4 % reduction in fuel consumption over the NEDC, giving a total improvement of 1.5% compared with the un-heated 'production' oil. Despite the additional benefit of heating the lower viscosity oil, it is unlikely that the small fuel consumption reduction would justify the additional complexity of providing heating.

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Acknowledgements

This work has been conducted under the dti "Succeeding through innovation" programme (project number TP/2/5/10036) and the funding and support for the project is acknowledged. Also, the funding from the collaborating partners, the Ford Motor Company and BP and the support received is also acknowledged as well as the permission to publish this paper. The work has been conducted at the Powertrain and Vehicle Research Centre in the Department of Mechanical Engineering at the University of Bath with the grateful assistance of the support and research staff.

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Appendix

European emissions limits for diesel-powered light commercial vehicles.
(1760kg < Curb weight < 3500kg) :

Tier	Date	CO g/km	NOx g/km	HC+NOx g/km	Particulate Matter g/km
EURO1	October 1994	6.90	-	1.70	0.25
EURO2	January 1998	1.50	-	1.20	0.17
EURO3	January 2001	0.95	0.78	0.86	0.10
EURO4	January 2006	0.74	0.39	0.46	0.06