

Demonstration of Fuel Economy Benefit of Friction Modifier Additives via Fuel-to-Lubricant Transfer in Euro-5 Gasoline Fleet

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ABSTRACT

Improved fuel economy is a key measure of performance in the automotive industry, driven both by market demand and increasingly stringent government emissions regulations. In this climate, targeting even small benefits to fuel consumption (FC) can have a large impact when considering fleet average CO₂ emissions. Lubricant properties over the course of an oil drain interval (ODI) directly influence long-term fuel consumption. Furthermore, viscosity control gasoline additives have been shown to provide FC benefit via fuel-to-lubricant transfer. This study investigated whether consistently fueling with gasoline containing friction modifier (FM) additives could provide a long-term fuel consumption benefit via a lubricant transfer mechanism.

A robust fleet trial method was employed to quantify fuel consumption benefits of two friction modifier additive packages relative to a baseline deposit control additive (DCA) package in a 95 RON, E5 fuel. FC was measured for 32 market relevant vehicles over the course of a European ODI. The test was performed with 12,000 mile on-road accumulation in a 60/40 urban/high speed driving route. Changes in FC were measured periodically on a chassis dynamometer (CD) using the industry standard New European Drive Cycle (NEDC) procedure. NEDC emissions results demonstrated statistically significant FC benefits for fuels containing FM additives relative to a DCA only reference fuel, with 0.60% and 0.71% benefit at the 95% confidence level. Lubricant analysis confirmed transfer of FM additives to the lubricant sump, providing support for a fuel-lubricant interaction mechanism. This study thus demonstrates that statistically significant long-term fuel consumption benefits can be obtained by consistent fueling with FM dosed gasoline.

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INTRODUCTION

Ambitious global targets for fleet average CO₂ emissions - for example, 130g/km (5.6L/100km) by 2015 and 95 g/km (4.1L/100km) by 2020 in Europe [1] - make fuel efficiency a key development area for the automotive industry. As a substantial proportion of energy from combustion is lost due to engine friction [2], lubricant or fuel formulations which can reduce friction provide effective means of reducing fuel consumption [3].

The mechanism of engine friction - and therefore the means of reducing it - is defined by the engine load, relative speed of engine surfaces and the viscosity of the lubricant film [4] and is often presented as a Stribeck Curve [5, 6]

(Figure 1). These properties are used to categorize engine friction into boundary, mixed or hydrodynamic regimes. Hydrodynamic friction is dominated by losses due to the viscosity of the thick lubricant film that separates the metal surfaces, and is primarily associated with the pump, crankshaft and other bearings. Conversely, boundary friction occurs as the lubricant film thins sufficiently to bring metal surfaces into direct contact [7], such as occurs in the valve train (10-15% of engine friction) [4]. In the mixed lubricant regime, a thin lubricant film begins to form and thus both mechanisms contribute. The piston and liner, which constitute between 40-70% of engine friction, operate in the boundary to hydrodynamic lubricant regimes [4].

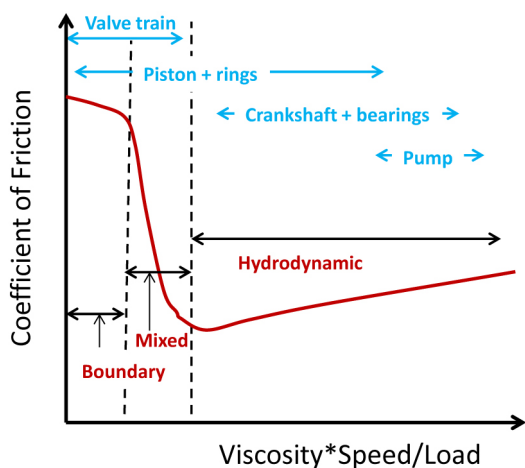


Figure 1. Schematic of Stribeck Curve. Friction regime is defined by lubricant dynamic viscosity, rotational speed of crankshaft, and load force per unit area.

Lubricant formulations must be carefully designed to reduce friction of the different engine components. While lowering viscosity reduces hydrodynamic friction [4], it necessitates the use of FM additives to reduce friction in boundary and mixed friction regimes - for example, in the piston and valve train [4, 8]. Organic FM additives consist of long straight chain hydrocarbons with polar head groups capable of adsorbing to the metal surface of the engine [2, 8, 9]. They form sacrificial monolayers which are easily sheared, preventing metal-to-metal contact yet maintaining a low coefficient of friction.

Split lubrication experiments [5, 10] have isolated the effects of the valve train from the rest of the engine to evaluate the effects of FM additives in the different friction regimes. FM benefits were shown to depend on engine operating condition [10], and though important for the piston liner, were found to be primarily associated with the cam-tappet interface of the direct acting valve train [5]. FM response was shown to have triple the effect in the integrated engine (with valve train) relative to the split configuration [5].

Lubricant properties can also be altered by the transfer of chemical additives from fuel to lubricant. This occurs via a well studied mechanism [11] whereby up to 25% [12] of the additive impinges on the thin lubricant layer of the cylinder wall and is transferred to the lubricant sump. Previous studies have shown that sufficient transfer of viscosity control fuel additives (VCA) can occur over the course of an ODI to provide a statistically significant long-term improvement in FC [13].

Demonstration of long-term¹, market-relevant changes in FC by fuel-borne additives necessitates a critical on-road fleet

test designed to minimize experimental noise and achieve high measurement precision. Shell has developed a test to discern FC benefits of fuel formulations for market relevant vehicles, measured via the industry standard NEDC emissions procedure following on-road mileage accumulation [14, 15, 16]. The updated protocol [16] recommends the use of quads of matched vehicles to achieve discrimination of FC differences below 1%. Furthermore, on-board diagnostics (OBD) have also been used to in an attempt discern cumulative, real world FC differences based upon data collected during on-road driving [17].

The aim of the current study is to evaluate the long-term FC benefit of fuel with two different FM additive packages relative to a DCA-only reference fuel. As such, this is a novel extension of previous studies [13, 14, 15, 16, 17]; to the best of our knowledge, it is the first attempt to show fleet average long-term FC benefits due to FM transfer from fuel to lubricant.

EXPERIMENTAL PROCEDURE

General Overview

The method for discriminating FC benefits associated with gasoline additive package composition is well established and has formed the basis for numerous previous studies [13, 14, 15, 16, 17]. It relies on evaluating performance in market-relevant test conditions, while identifying and minimizing variables within the test conditions to maximize the signal-to-noise ratio. The method implemented here is an extension of that described in detail in [16], with the addition of more stringent vehicle matching guidelines and OBD technology for an evaluation of on-road FC².

Market realistic conditions for the World Outside of North America (WONA) were achieved by careful selection of base fuel, lubricant, vehicle technology and on-road driving route. The length of the test was defined by a typical European ODI of 12,000 miles. FC was calculated by the carbon balance method from emissions data collected using the New European Drive Cycle (NEDC), an industry standard test designed to reflect typical vehicle use.

Previous studies have shown that FC benefits are best compared in distinct sets of 4 matched vehicles - a quad [16]. Based on results from previous studies, a minimum of 8 quads (32 vehicles) was estimated to be required to discriminate a statistically significant 1% FC benefit [13, 16].

In general, the method for each quad consisted of run-in of new vehicles, establishment of an OBD baseline and a start of test (SOT) emissions baseline with reference fuel. Following SOT, fueling for each vehicle was fixed: two vehicles were fueled with reference and two with different test fuel formulations throughout 12,000 mile on-road

¹Long term fuel consumption is defined over the course of an ODI.

²Telemetry data was collected to further explore the use of the method in on-road fleet trials, though the test was not specifically designed to statistically evaluate OBD data, and did not yield results with sufficient precision to enable FC comparisons.

accumulation, with mid (MID) and end-of-test (EOT) NEDC emissions measurements. FC benefits were calculated by comparing the change in FC for a vehicle with test fuel relative to the FC change for the reference vehicles. A graphical overview of the fleet trial procedure for a single quad of vehicles is shown in Figure 2 and described in detail in the following sections.

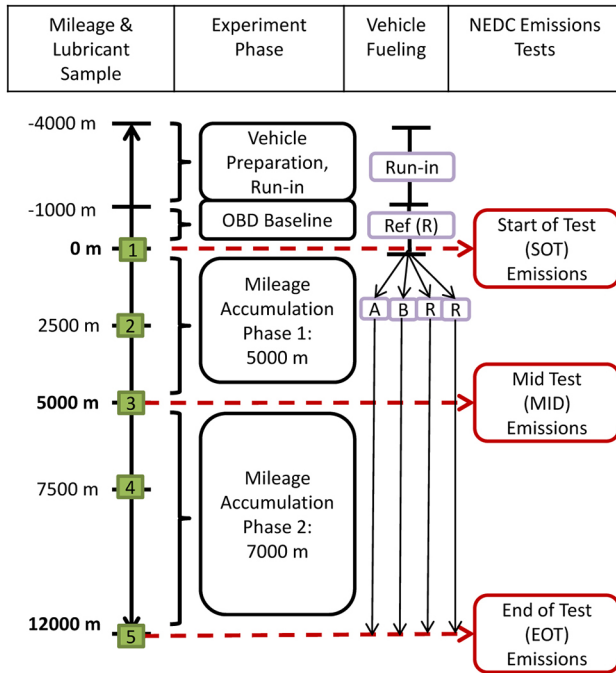


Figure 2. General overview of Fleet Trial Procedure. Vehicle fueling strategy indicated in purple.

Fuel Formulations

This experiment utilized four fuels:

1. Run-in fuel for vehicle conditioning (DCA)
2. Reference fuel (DCA)
3. Fuel A (FM-1 + DCA)
4. Fuel B (FM-2 + DCA)

All 4 fuels were chosen to be market representative, EN228 compliant, 95 RON and 5% volume ethanol, with equal levels of the same commercial DCA package. The same batch of base fuel was used for the reference fuel and test fuels, with properties as specified in Table 1. Test fuels A and B differed from reference only in the addition of equal amounts by mass of different FM additive packages.

Lubricant Formulations

Lubricant formulation and quality is a key factor in fuel consumption. Therefore, a single batch of a commercially available, FM-free, 5W-30 grade, ACEA A3/B4 lubricant

was used for the entire test fleet. The properties of this oil are shown in Table 2.

Table 1. Composition and Properties of Reference Gasoline

Composition (GC Analysis)		
Ethanol	4.98 v/v%	
Olefins	15.62 v/v%	
Aromatics	26.37 v/v%	
Paraffins	13.14 v/v%	
C/H/O Ratio	5.88 : 11.25 : 0.10	
Properties		
Density (at 15°C; ASTM D4052)	727.7 kg/m ³	
RON (ASTMD2699)	96.6	
MON (ASTM D2700)	85.2	
Distillation (IP 123)	IBP (°C)	24.9
	E70 (%v)	45.2
	E100 (%v)	65.2
	E120 (%v)	80.7
	E150 (%v)	94.6
FBP (°C)	185.0	
RVP (IP 394)	90.8 kPa	
Unwashed gum (IP 133)	25 / 25 mg/100ml	

Table 2. Composition and Properties of Fresh Lubricant

Parameter	Method	Units	Value
Kinematic viscosity at 100°C	Houillion Rapid Method	cSt	12.32
Kinematic viscosity at 40°C	Houillion Rapid Method	cSt	73.1
High temperature high shear (HTHS) dynamic viscosity	ASTM D4683	mPa.s	3.54
Calcium	ICP-AES	%m	0.264
Phosphorous	ICP-AES	%m	0.092
Zinc	ICP-AES	%m	0.106

Vehicle Acquisition and Preparation

Fleet details

Vehicles were chosen to be a cross section of popular makes and technologies for the 2010/2011 WONA market within the Euro-5 emissions class. Both port-fuel injection (PFI) and direct injection (DI) technologies were chosen as specified in Table 3; all vehicles were naturally aspirated technologies³. All vehicles came with manufacturer recommendations for 5W-30 grade lubricant with a 10,000 to 20,000 km ODI.

³Only one DI technology was included in the vehicle test fleet to reflect the lower penetration of this engine technology in mass market operations.

Table 3. Details of the Test Vehicle Fleet. Four vehicles were used for each model (quad). Each Euro-5 vehicle had a 2010-2011 registration and manual transmission.

Make / Model	Size (L)	Power (PS)	Engine Technology
Peugeot 207	1.4	75	PFI, inline-4, 8v SOHC
Nissan Qashqai +2	1.6	115	PFI, inline-4, 16v DOHC
Ford Focus	1.6	100	PFI, inline-4, 16v DOHC
Vauxhall Astra	1.6	115	PFI, inline-4, 16v DOHC
Ford Fiesta	1.25	82	PFI, inline-4, 16v DOHC
VW Polo	1.2	60	PFI, inline-3, 12v DOHC
Toyota Auris	1.6	132	PFI, inline-4, 16v DOHC VVT-i
BMW 320i	2	170	DI stratified charge, inline-4, 16v DOHC

Vehicle preparation and run-in

Rigorous standards were used to ensure that the vehicles in each quad were as closely matched as possible. Vehicles were purchased new, with matching make, model and emissions class. Matching tire type, tire size, net vehicle weight (± 50 kg of average), engine code, ECU software calibration, rated power, rated torque, gearbox and transmission specification were confirmed.

Factory fuel and lubricant were drained and flushed with run-in fuels and test lubricant. The vehicles were subjected to 3000 ± 250 miles of run-in by professional drivers to ensure stabilization and correct operation. The vehicles were run-in over the same on-road driving route as used in the mileage accumulation phases of the experiment (Figure 3).

Build or mechanical differences within the quad were assessed by measuring (1) steady-state power at the road wheels at speeds between 40-120km/h in 4th gear and (2) coast down time from 125-35 km/h in 10 km/h speed gates. A quad was considered matched if steady-state power for each speed fell within $\pm 5\%$ of the quad average. Coast down profiles were used to identify potential mechanical faults (e.g. sticking brakes) which could influence FC. Vehicle matching checks were performed both at start and end of test. All quads were found to be matched at start and end of test, with no evidence of mechanical faults during coast-down.

Telemetry (OBD) baseline

Telemetry units were installed for each vehicle to record engine and dynamical data during the road phases of the trial. Engine data enabled calculation of FC from the mass air flow rate (MAF) as described in [17]; as well as identification of engine faults during the course of the trial.

Following run-in, fuel tanks were flushed to reference fuel; lubricant was drained and flushed to fresh test lubricant. A telemetry baseline was established for 1000 on-road miles

with the reference fuel. OBD data was recorded for all subsequent on-road testing.

Road Test Procedure

The fleet trial was conducted such that changes in FC could be measured during the course of 12,000 mile on-road accumulation. FC was measured both via a temperature and humidity controlled chassis dynamometer (CD) NEDC emissions test, and via collection of OBD data during the on-road portion of the experiment. It should be noted that while the former is the most precise and industry standard measure, it affords an instantaneous measurement of FC following an accumulated benefit. By contrast, the OBD data affords an understanding of changes to the cumulative, real-world FC.

SOT (baseline) NEDC emissions were measured for each vehicle with reference fuel and fresh lubricant. Lubricant was not changed following this measurement; samples were subsequently taken to monitor degradation and FM content during the experiment as outlined in Figure 2⁴.

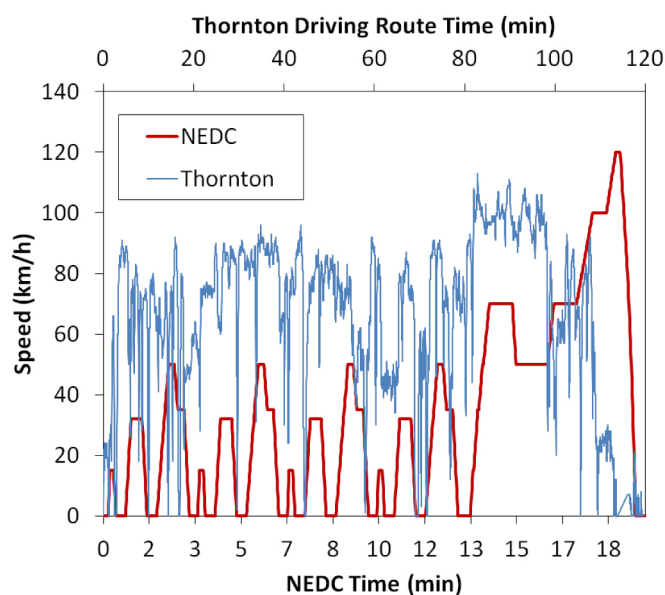


Figure 3. NEDC cycle and Thornton Road Route.

Following SOT, the vehicles were flushed to reference fuel (2 per quad), Fuel A (1 per quad), or Fuel B (1 per quad) (Figure 2), after which the fuel assignment for a given vehicle remained constant. Phase 1 consisted of 5000 miles of on-road accumulation with a 60/40 urban simulation / high speed road test route, hereafter referred to as the Thornton route. Vehicles were driven over this ~ 87 mile circuit 3 times per day. To minimize differences in road or weather conditions, the vehicles in each quad were driven in staggered convoys. Clear guidelines were given to drivers on control settings that

⁴Oil levels were monitored throughout the trial, and in general, no top-ups were performed, with the exception of the Ford Focus (573 g each), the BMW 320i (400g each), and the VW Polo fueled with test fuel B (188g).

Table 4. Experimental Variables & Mitigating Actions

Variable	Mitigating Action
Vehicle matching	Matched new vehicles, power and coast down checks at start and end of test
Driver behavior: speed, braking, gears	Same route, driven at same time, professional drivers, driver rotation
Road conditions: inclines, temperature, wind	Quads driven in convoy to experience same route, driven at same time
Electrical controls	Strict instructions to drivers on use of lights (on), air conditioning (on to set level), windows and sunroofs (closed).
Tires	Matched type, pressure checked weekly Reference wheels used for CD tests
Lubricant	Same formulation used, sample throughout to monitor changes
Fuel	Same base fuel used for test and reference fuels, sampled throughout to monitor changes. Same level of DCA package to minimize any difference in deposit formation. Vehicles in quad fueled to matched level.

can impact FC: i.e. air conditioning, use of lights, and windows / sunroofs (Table 4).

NEDC emissions were measured mid-test at 5000 accumulated miles (MID), in order to observe directional changes in FC. On-road mileage accumulation continued until a total of 12,000 cumulative miles from SOT was reached, where EOT NEDC emissions were measured.

A typical Thornton driving route - as measured with OBD on one Vauxhall Astra - is compared to the NEDC cycle in Figure 3. The NEDC drive cycle is comprised of four urban drive cycles (ECE-15), and followed by one extra-urban drive cycle (EUDC). The Thornton driving route is a longer, higher speed, and more transient route than the NEDC.

NEDC emissions method

The NEDC emissions test is the primary, most precise measure of FC used in the current study. The carbon balance method was used to determine FC from the CO₂, CO and HC emissions. Drummed test or reference fuels were used. For each test, road wheels were replaced with reference CD wheels to prevent any influence of wear on final FC values. A 250 mile, 1 day preconditioning procedure was implemented for MID and EOT emissions measurements, with an extra day for lubricant degreening before SOT measurements.

Duplicate emissions measurements were performed for each quad on two successive days, with a reversal of in-quad test order on the second day. The same sequence was used for each quad for logistical simplicity. Variations in the NEDC emissions results test were checked against standard criteria [13] and variation in previous experiments; a 3rd test was

carried out in the instance that a vehicle failed the variability criteria for FC or CO₂ emissions⁵.

Data Analysis

Minimizing data variability in test design

This test has been designed to maximize the signal-to-noise ratio and thereby isolate the long term FC effects of the fuel FM additive. Therefore, care has been taken to identify and mitigate the effects of variables that impact FC, as described in previous sections. For clarity, these variables are also summarized in Table 4.

Statistical analysis

Invalid data

High fluctuations in trip-to-trip OBD data prompted investigation of engine error codes, enabling verification of a combustion fault in the BMW 320i vehicle fueled with Fuel B. This engine malfunction during stratified charge operation was verified by an independent 3rd party (Halliwell Jones BMW dealer, Chester⁶). Thus, the BMW320i data set for Fuel B was rejected from subsequent analysis and no FC data is presented for FM-2 on the BMW 320i series.

NEDC FC benefit

The fuel consumption benefit is essentially a measure of how FC changes for a given vehicle on test fuel over the course of mileage accumulation, in comparison to how the average FC of the two vehicles fueled with reference fuel changes. Hence, it is the relative change of test fuel to

⁵Three tests were performed for the Toyota Auris with Fuel A. The first test showed an extreme result and was discarded from further analysis.

⁶The following error codes were found for one BMW 320i: (a) 3101 DME: "Rough running, stratified-charge mode" (b) 2C32 DME: "Oxygen sensor before catalytic converter 2, trim control". These codes indicated problems with mixture preparation, particularly in stratified mode.

reference that determines the benefit, as demonstrated in Figure 4.

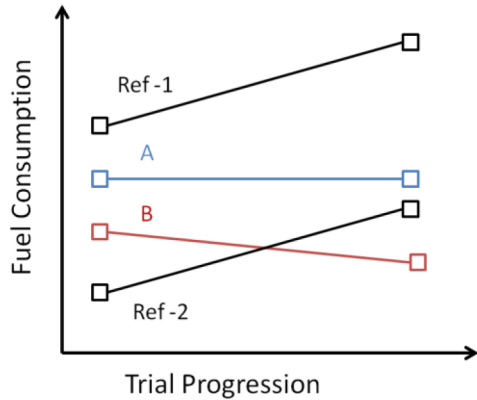


Figure 4. Hypothetical schematic of FC comparison: Test Fuels A and B show FC benefit relative to reference.

Repeat NEDC FC results were averaged to give a single FC measure per vehicle per fuel per experimental stage. For each vehicle, the percent change in FC from SOT to MID or EOT was computed as follows:

$$\Delta FC(I) = \left[\left(1 - \frac{\overline{FC}_{T,I}}{\overline{FC}_{SOT,I}} \right) - \frac{\left(1 - \frac{\overline{FC}_{T,R1}}{\overline{FC}_{SOT,R1}} \right) + \left(1 - \frac{\overline{FC}_{T,R2}}{\overline{FC}_{SOT,R2}} \right)}{2} \right] \times 100\% \tag{2}$$

where I refers to Fuel A or Fuel B, R1 and R2 are the vehicles fueled on reference, and \overline{FC}_T and \overline{FC}_{SOT} refer to the average FC at either T=MID or EOT and at SOT, respectively. Note that in comparing FC at MID or EOT to SOT, this test design does not rule out potential effects due to an instantaneous FM mechanism.

The fleet average FC benefit was then computed as follows:

$$\Delta FC(\text{Fleet}, I) = \frac{\sum_1^n \Delta FC(I)}{n} \tag{3}$$

where *n* refers to the number of quads for which FC benefits were computed.

NEDC statistical analysis

Analysis of Variance (ANOVA) techniques were used to compute the significance of the fleet average FC benefit for Fuels A and B. The ANOVA table and degrees of freedom (DOF) in the system are described in Table 5.

Table 5. Degrees of Freedom for ANOVA Analysis.

Term	DOF	Description
Model	7	The difference between the 8 vehicle models.
Fuel	2	The difference between the 3 fuel formulations.
Model × Fuel	14	Interaction term. How the effect of fuel varies across the 8 vehicle models.
Residual	8	Residual error – car to car variation within each model quad.
Total	31	Sum of the above; total DOF.

The significance of the interaction term was assessed via the full model. In the instance of a small interaction term relative to in-quad variation, the interaction term was pooled into residual error. Results were adjusted for the presence of two comparisons.

RESULTS AND DISCUSSION

Friction Modifier Additives

FM-1 and FM-2 are composed of different friction modifier chemistries. Prior to the start of the road test method, laboratory tests independently⁷ confirmed the additives as friction reducing agents in reference base oil. When dosed in FM-free, high viscosity base oil, FM-1 and FM-2 showed lower coefficients of friction (μ) than reference oils in Mini Traction Machine (MTM) tests - where mixed rolling and sliding friction of a steel disc and ball were evaluated at conditions representative of engine boundary friction (Figure 5).

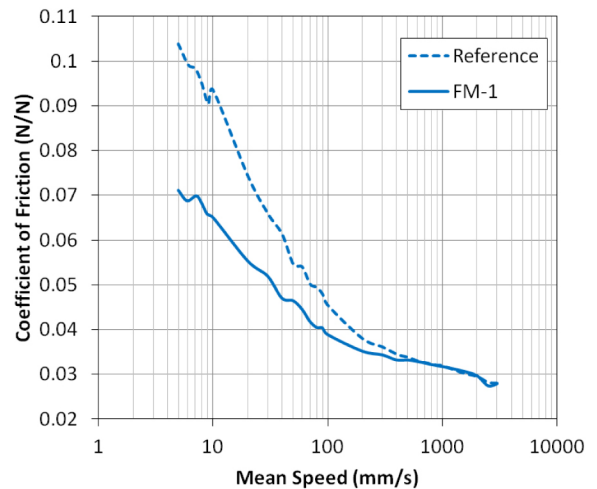


Figure 5. MTM Curves for FM-free base oil with 5% FM-1 or FM-2 relative to reference at 45°C, 20N load, 0.82 GPa pressure, and slide-to-roll ratio of 100%.

⁷The results shown in Figure 5 are from two independent experiments and therefore no direct comparison can be made between FM-1 and FM-2.

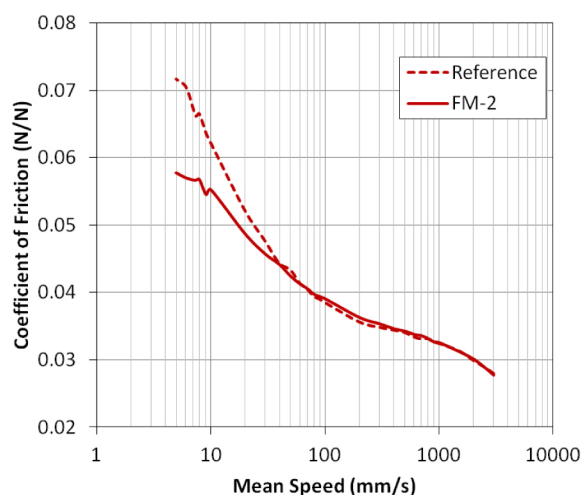


Figure 5 (cont.). MTM Curves for FM-free base oil with 5% FM-1 or FM-2 relative to reference at 45°C, 20N load, 0.82 GPa pressure, and slide-to-roll ratio of 100%.

Fuel Analysis

As fuel quality has an impact of FC, fuels were monitored on a fortnightly basis during the experiment. Test and reference fuels for use in NEDC emissions tests were stored in sealed drums, while fuels for mileage accumulation were stored in underground forecourt tanks. No evidence of abnormal fuel quality degradation or contamination was observed during the course of the trial - all fuels appeared bright and clear. Density increased slightly from fresh blend until start of trial, after which it remained unaltered. No loss of stability was indicated by induction period tests. Ethanol and water content were unaltered, indicating minimal phase separation. Additives did not fall out of solution as measured by unwashed gum tests; washed gum results reflected a clean and stable base fuel throughout the course of the experiment. There was no evidence of metal pick-up from forecourt tanks. The test procedures used for this analysis are given in the [Appendix](#).

Lubricant Analysis

Lubricant samples were taken throughout the trial as described in [Figure 1](#) to assess quality changes and FM additive accumulation. No evidence of abnormal lubricant degradation was observed during the course of the trial. Changes in lubricant qualities were observed between models but no fuel related in-quad variation was discerned. Kinematic and dynamic viscosity increased slightly as expected due to increased oxidation with aging. Acid content increased slightly and alkalinity decreased slightly. Approximately constant concentrations of detergent and anti-wear metal additives and wear metals were observed. Fuel

dilution increased initially before reaching equilibrium, with a slight decrease towards end of test, indicating that evaporative losses occurred at a faster rate than fuel accumulation. Kinematic and dynamic viscosities, as well as fuel dilution data, are presented in more detail in the [Appendix](#).

A key result is the demonstration of fuel additive accumulation in the lubricant over the course of the trial. Levels of fuel additive carrier fluid were monitored at MID and EOT via Nuclear Magnetic Resonance (NMR), and are shown in [Figure 6](#) normalized to the concentration of calcium (Ca) in the lubricant⁸. Additive carrier fluid concentration increased over the course of the trial, and was found to be lower in the DI technology (BMW 320i).

The levels of FM-1 and FM-2 in the lubricant samples were also monitored via reverse phase liquid chromatography separation and mass spectrometry detection (LC/MS). MS response of a target molecular ion for each species was monitored relative to a fresh oil calibration curve to derive approximate FM concentration. FM-1 and FM-2 were confirmed to be present in the used oil at both MID and EOT for vehicles fueled with test fuel A and B, respectively, confirming the mechanism of transfer⁹.

The results of FM lubricant analysis were normalized to the oil sample Ca content and are shown in [Figure 6](#). The concentration of FM-1 appears to be higher than FM-2. Furthermore, the concentrations of FM-1 and FM-2 appear to decrease over the course of the trial, in contrast to the carrier fluid which exhibits a monotonic increase. The former observation is likely attributed to the fact that a single molecular ion is monitored in the detection method - which may not have a 1:1 ratio with respect to the active ingredient in the engine environment. The decrease in apparent FM concentration with trial progression is not well understood, but could be attributed to a variety of factors: (1) ionization efficiency of the target molecular ion could be affected by the presence of additional components in the sample at EOT compared to MID, (2) the higher acid content of the aged oil could contribute to decreased stability of the target species in the engine or sample prior to analysis, or (3) the target molecular ion could correspond to a chemical intermediate in the reaction to form boundary layers on the engine surfaces. Regardless, the matched viscosity properties of test and reference lubricant samples throughout the test, the monotonic increase in concentration of the carrier fluid, and the presence of the FM species at both MID and EOT provide compelling evidence for a fuel-to-lubricant FM transfer mechanism.

Finally, lubricity laboratory tests (HFRR) did not show significant changes for used oil samples in comparison to fresh. Frictional properties as monitored by MTM tests also showed limited differences in comparison to fresh lubricant.

⁸Ca is a reasonable normalization parameter as it was present only in the lubricant and the concentration was not expected to increase over the course of the trial.

⁹Lubricants for vehicles with reference fuel did not contain FM-1 and FM-2, providing further support of the lubricant transfer mechanism.

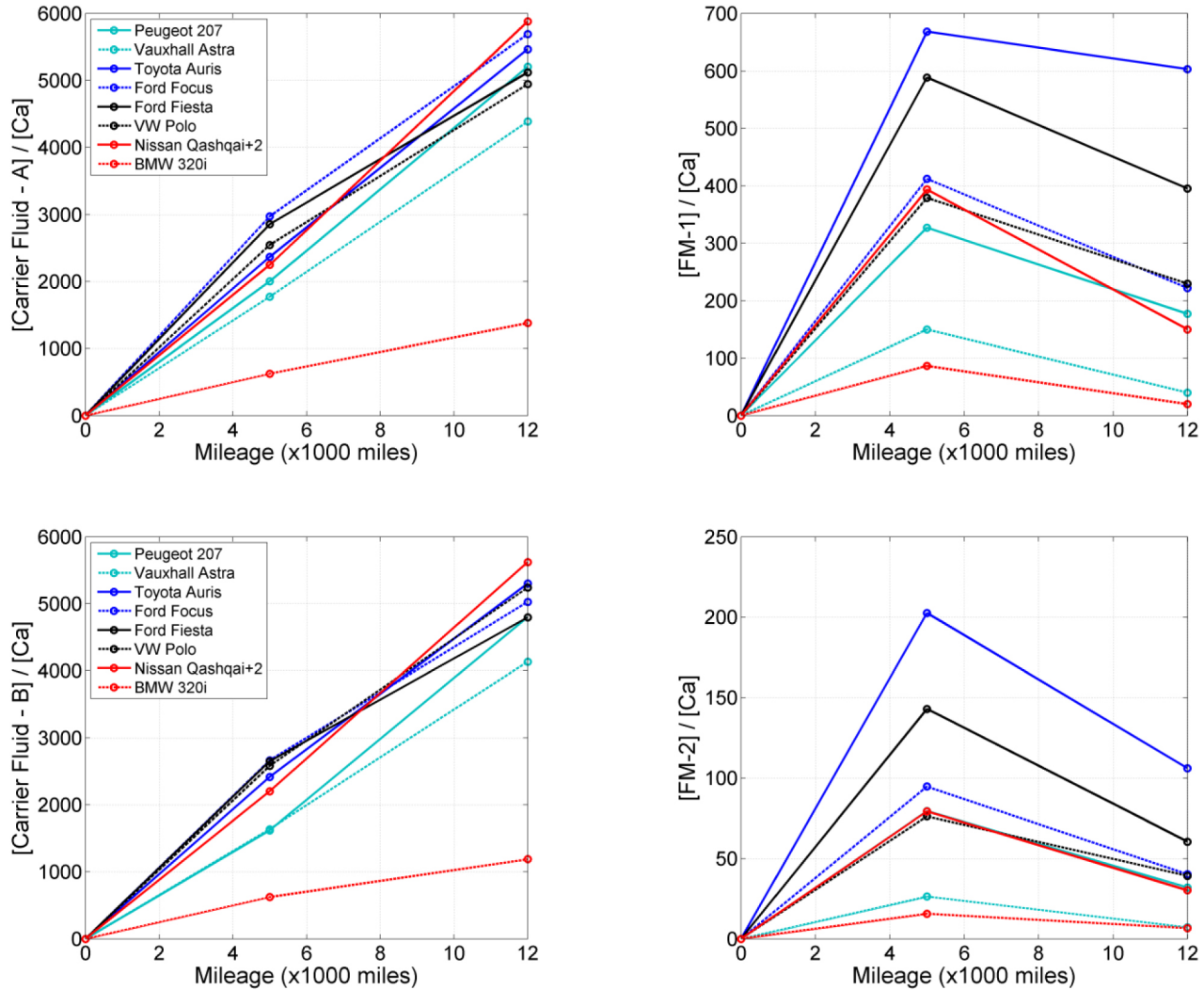


Figure 6. Accumulation of additive carrier fluid and FM additive in lubricant with on-road mileage accumulation for vehicles fueled with Test Fuels A and B.

A potential explanation for this could be that FM additives were not present in sufficient quantities to affect lubricity in these laboratory tests, given that in the engine these compounds exist in equilibrium between bulk oil and surface adsorbed layers.

Fuel Consumption Measurements

NEDC emissions

NEDC FC benefits of Fuel A and B relative to reference for MID (5,000 miles) and EOT (12,000 miles) are shown for each vehicle in Table 6. EOT results are shown in Figure 7. While some variability exists in vehicle response at MID and EOT, a directional, statistically insignificant benefit, was observed after 5000 accumulated on-road miles. Following 12,000 accumulated miles (Figure 7), most vehicles exhibited FC benefits for both FM-1 and FM-2, with fleet average benefits of 0.60% and 0.71% significant at the 95% confidence level (CL).

Table 6. Percent NEDC Fuel Consumption Benefits Relative to SOT at 5000 m (MID) and 12,000 m (EOT) by vehicle quad.

Vehicle Quad	Test Fuel A		Test Fuel B	
	MID	EOT	MID	EOT
Nissan Qashqai	1.33	1.33	1.97	1.44
Vauxhall Astra	0.67	1.11	-0.14	0.68
BMW 320i	-0.59	0.76		
Peugeot 207	-0.80	0.55	-0.72	0.16
Ford Focus	-0.40	0.54	-0.62	0.81
Toyota Auris	-0.01	0.46	1.11	0.75
VW Polo	0.39	0.14	0.21	0.42
Ford Fiesta	0.00	-0.11	0.74	0.68
Fleet	0.07	0.60	0.36	0.71
95% CL	0.56	0.56	0.60	0.69

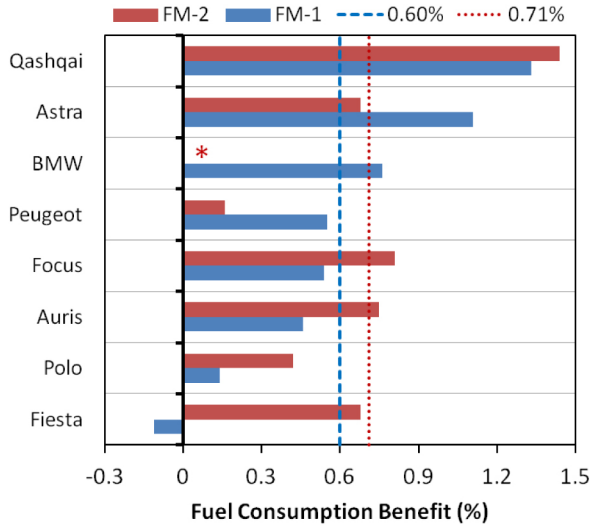


Figure 7. NEDC Fuel Consumption Benefits for Test fuels A and B at 12,000 accumulated on-road miles by vehicle model. Fleet average benefits shown as dashed lines. BMW data not shown for FM-2, discarded due to combustion fault.

The fleet average FC benefit was also computed for the ECE and EUDC portions of the total NEDC cycle (Table 7, Figure 8). For both FM-1 and FM-2, statistically significant fleet average benefits were found for the ECE cycles after 5,000 cumulative on-road miles; this trend was directionally confirmed at EOT but the results were not significant at the 95% CL. The EUDC cycle did not yield statistically significant results at either mileage point. Finally, the total NEDC cycle benefits are shown in Figure 8. While directional benefits are indicated at MID; at EOT, these benefits are significant at the 95% CL.

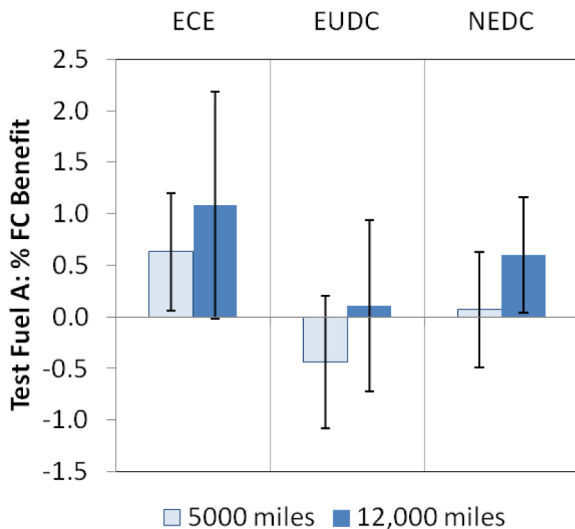


Figure 8.

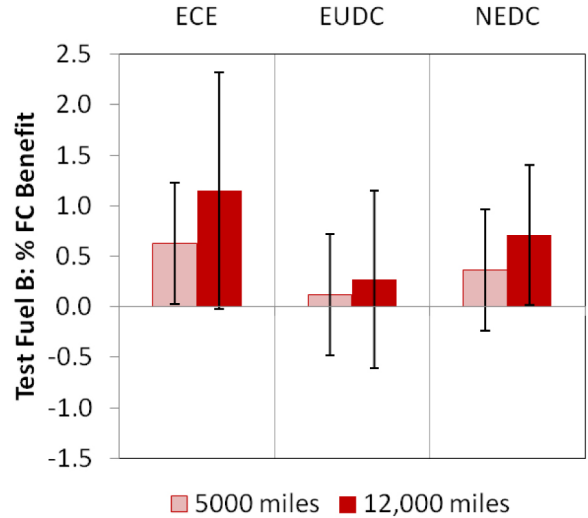


Figure 8 (cont.). Fleet average ECE, EUDC and NEDC Fuel Consumption Benefits for Fuel A and Fuel B relative to reference at 5,000 and 12,000 accumulated on-road miles.

Table 7. Fleet average ECE, EUDC and NEDC Percent Fuel Consumption Benefits Relative to SOT.

Fuel	Quad	Miles	% Benefit	95% CL
A	ECE	5000	0.63	0.57
		12000	1.08	1.10
	EUDC	5000	-0.44	0.64
		12000	0.11	0.83
	NEDC	5000	0.07	0.56
		12000	0.60	0.56
B	ECE	5000	0.63	0.60
		12000	1.15	1.17
	EUDC	5000	0.12	0.60
		12000	0.27	0.88
	NEDC	5000	0.36	0.60
		12000	0.71	0.69

OBD / telemetry

Collection of telemetry data for this experiment proved useful in diagnosing combustion faults for one of the vehicles. However, due to telemetry faults leading to incomplete data recording in the Nissan Qashqai+2 quad, the data set was reduced sufficiently such that no statistically significant results could be obtained from the on-road mileage accumulation phase of the trial.

SUMMARY/CONCLUSIONS

A robust fleet trial method was used to discern the FC benefit of consistently fueling with two gasoline formulations containing different friction modifiers over the course of 12,000 on-road miles. The effect of market doses of the FM

additives in an E5, 95 RON base fuel in 32 market-relevant vehicles (8 matched quads) was measured relative to a DCA only reference fuel. Care was taken in test design to minimize the impact of all variables except the influence of the FM fuel additives in test fuels relative to reference. In particular, fuel and lubricant samples were monitored over the course of the trial; no evidence of lubricant or fuel degradation that could have impacted the FC results was found.

Laboratory experiments with fresh lubricant confirmed the frictional properties of the additives. Furthermore, oil sample analysis confirmed FM additive transfer to the lubricant sump over the course of the trial, providing evidence for a fuel-lubricant interaction mechanism. The FC benefit is hypothesized to be due in-part to the action of the FM additives in the lubricant - FM additives are known to form sacrificial monolayers on engine surfaces susceptible to boundary friction, such as in the cam-tappet interface of the valve train.

This study showed that consistently fueling with gasoline containing the FM additives resulted in statistically significant FC benefits as measured by the industry standard NEDC drive cycle method. Statistically significant FC benefits with the ECE drive cycle were observed at mid-mileage. Following 12,000 cumulative test miles, FM-1 and FM-2 showed 0.60% and 0.71% long term FC benefit at the 95% CL over the NEDC cycle, respectively.

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DEFINITIONS/ABBREVIATIONS

A/C - Air Conditioning

AFR - Air Fuel Ratio

ANOVA - Analysis of Variance

CD - Chassis Dynamometer

CL - Confidence Level

DCA - Deposit Control Additive

DOHC - Double Over Head Camshaft

DOF - Degrees of Freedom

DI - Direct Injection

E5 - Gasoline with 5% volume ethanol

E0 - Gasoline with 0% volume ethanol

ECE - Urban drive cycle

ECU - Engine Control Unit

EOT - End Of Test

EU - European Union

EUDC - Extra Urban Drive Cycle

FC - Fuel Consumption

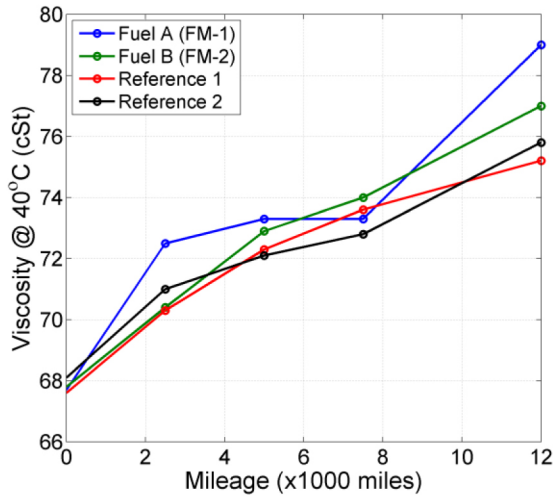
FM - Friction Modifier

FTIR - Fourier Transform Infra Red
HFRR - High Frequency Reciprocating Rig
HTHS - High Temperature High Shear (Dynamic Viscosity)
ICP-AES - Inductively Coupled Plasma Atomic Emission Spectroscopy
LC-MS - Liquid Chromatography Mass Spectrometry
MAF - Mass Air Flow
MID - Mid Test
MON - Motor Octane Number
MTM - Mini Traction Machine
NEDC - New European Drive Cycle
NMR - Nuclear Magnetic Resonance
OBD - On Board Diagnostics
ODI - Oil Drain Interval
PFI - Port Fuel Injection
RON - Research Octane Number
RVP - Reid Vapor Pressure
SOHC - Single Over Head Camshaft
SOT - Start Of Test
TAN - Total Acid Number
TBN - Total Base Number
VCA - Viscosity Control Additive
WONA - World outside North America

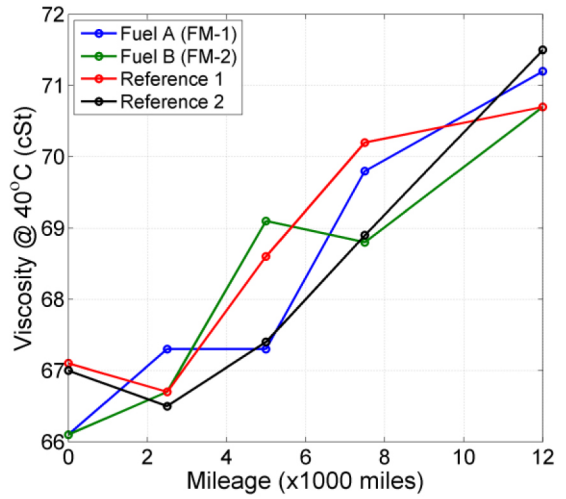
APPENDIX

Fuel and Lubricant Analysis Test Procedures and Summarized Results

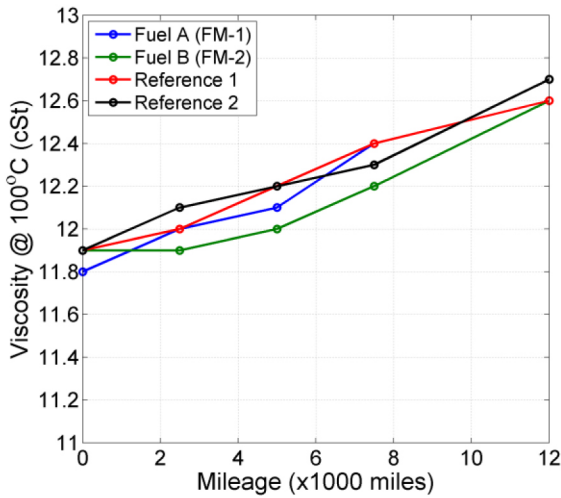
Fuel Test Procedures		
Measurement	Test Procedure	Result
Appearance	ASTM D4176	All fuels remained clear and bright.
Density at 15°C	IP 365	Unaltered after SOT.
Induction period	IP40	Unaltered throughout trial; no indication of stability difference between test fuels and reference.
Ethanol content	LTP/26	Unaltered throughout trial for all fuels.
Unwashed gum	IP131	Constant throughout trial, no depletion in additive content.
Washed gum	IP131	Indicated clean and stable base fuel throughout entire experiment.
Water levels	UK 3367	Constant with no significant differences between fuels.
Metal Pick-Up	ICP-AES	No indication of metal pick-up or fuel related differences.
Lubricant Test Procedures		
Measurement	Test Procedure	Result
Kinematic viscosity at 40°C, 100°C	Houillion Rapid Method	Slight increase as expected, no in-quad difference between vehicles fueled on test and reference fuels. Model to model differences observed.
Acid content (TAN)	ASTM D664	Increased slightly. No evidence of fuel related effects.
Alkalinity reserve (TBN)	ASTM D2896	Decreased due to acid neutralization. No evidence of fuel related effects.
Oxidation	FTIR	Increased. No fuel related effects in quad, variation larger model to model.
Metal content	ICP-AES	Additive metals: Levels essentially unaltered with no in-quad differences. Wear metals: no evidence of significant wear or metal pick up; no fuel related differences.
Dynamic viscosity	ASTMD4683 (fresh) Tannas kit (used)	Slight increase from SOT, as expected. Model to model variation; little variation within quad.
Fuel dilution	ASTM D3535	Values similar within quad, variations model to model.
Fuel additive carrier fluid concentration	Nuclear Magnetic Resonance (NMR)	Large model to model variation (BMW lower), little difference within quad. Increased over the course of trial with additive transfer.
FM Content	LC/MS	Large model to model variation. Present at MID and EOT. FM content found only in test fuel cars, confirming mechanism of transfer.
Lubricity; High Frequency Reciprocating Rig	HFRR	No significant change in wear scar measurements for used versus fresh lubricant.
Lubricity (MTM)	Mini traction machine	Limited signs of reduced friction due to lubricant source.



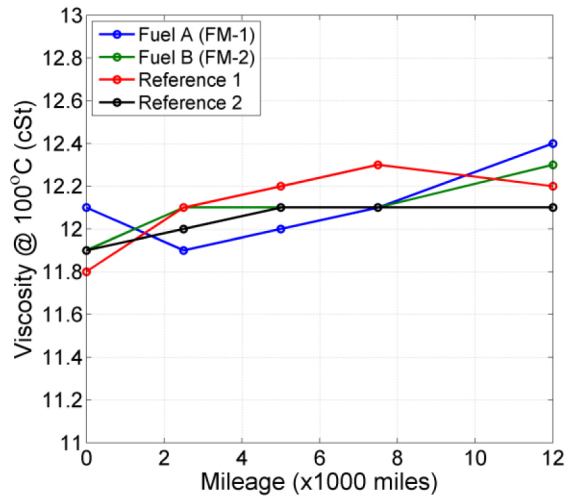
(a) Vauxhall Astra: Viscosity at 40°C



(b) Nissan Qashqai+2: Viscosity at 40°C



(c) Ford Fiesta: Viscosity at 100°C

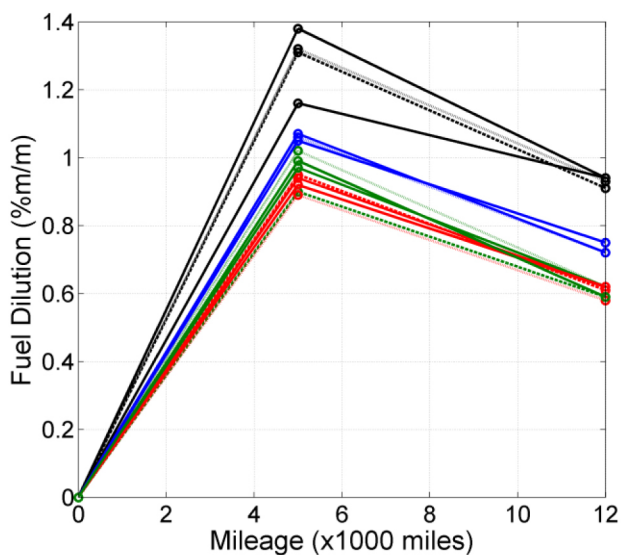


(d) VW Polo: Viscosity at 100°C

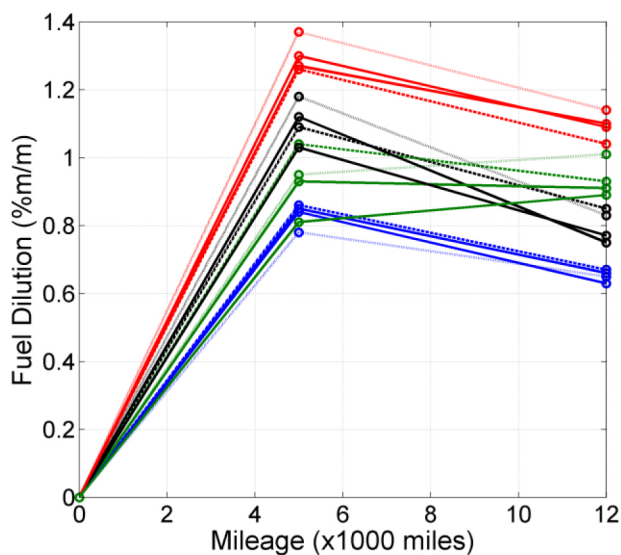
Figure A.1. Kinematic Viscosity at 40 and 100°C for Select Quads

Table A.1. Absolute viscosity of used oil samples at EOT (12,000 miles; Tannas Kit). [Fresh oil absolute viscosity measured via HTHS at 3.54 mPas.]

Vehicle	Test Fuel A (mPas)	Test Fuel B (mPas)	Reference 1 (mPas)	Reference 2 (mPas)
Peugot 207	3.859	3.807	3.800	3.777
Vauxhall Astra	3.747	3.728	3.681	3.669
Toyota Auris	3.67	3.64	3.641	3.636
Ford Focus	3.816	3.734	3.771	3.757
Ford Fiesta	3.747	3.715	3.739	3.727
VW Polo	3.714	3.715	3.672	3.678
Nissan Qashqai+2	3.605	3.567	3.541	3.528
BMW 320i	3.602	3.639	3.605	3.600



(a) Black: Peugeot 207; Blue: Vauxhall Astra; Red: Toyota Auris; Green: Ford Focus. Solid: Reference, Dashed: Fuel A (FM-1), Dotted: Fuel B (FM-2)



(b) Black: Ford Fiesta; Blue: VW Polo; Red: Nissan Qashqai+2; Green: BMW320i. Solid: Reference, Dashed: Fuel A (FM-1), Dotted: Fuel B (FM-2)

Figure A.2. Fuel Dilution over the course of mileage accumulation