

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].

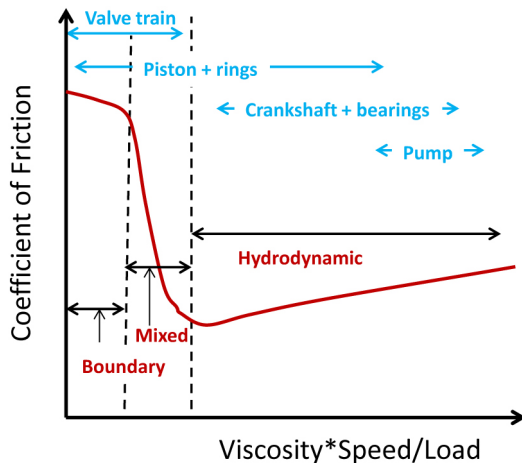


Figure 1. Schematic of Stribeck Curve. Friction regime is defined by lubricant dynamic viscosity, rotational speed of crankshaft, and load force per unit area.

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.

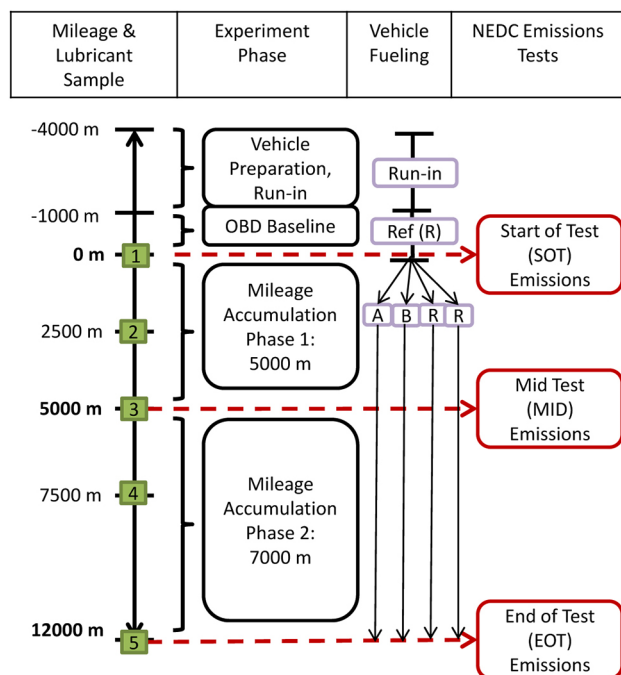


Figure 2. General overview of Fleet Trial Procedure.
Vehicle fueling strategy indicated in purple.

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 sheer (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.

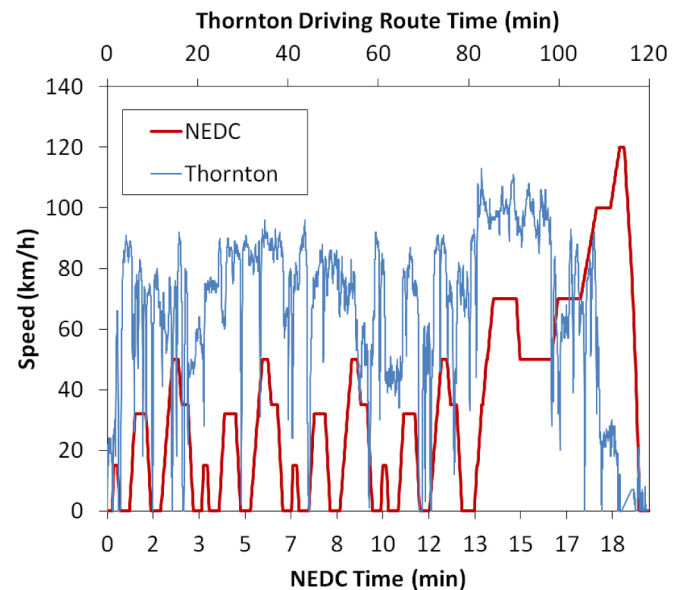


Figure 3. NEDC cycle and Thornton Road Route.

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.