

Development of a Novel Vehicle-Based Method to Assess the Impact of Lubricant Quality on Passenger Car Energy Efficiency

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ABSTRACT

The traditional vehicle-based approach to measuring the effect of oil-related fuel economy has relied on separate oil-aging and measurement processes where oil-aging takes place using an established driving protocol like the EPA Approved Mileage Accumulation (AMA) Driving Schedule for vehicle aging, then at set mileage intervals fuel economy is assessed using procedures such as the EPA FTP75 and Highway Fuel Economy emission test protocols described in 40 CFR, Parts 86 and 600. These test methods are useful for producing discrete snapshots of fuel economy at set mileage intervals but are unable to provide continuous information about oil-related changes in fuel economy. During the tests, the vehicle's fuel economy is indirectly calculated using a carbon-balance method of the bagged sample of dilute tailpipe emissions that effectively integrates the fuel economy of the vehicle during the sample interval which varies between eight and fifteen minutes. While being well-established and scientifically accepted the emission sampling method provides no information on the continuous process of oil-related fuel economy change with time and limits the ability to investigate transient driving effects on fuel consumption. In this paper the authors address a novel method to simultaneously age engine oils for gasoline-fueled vehicles, and directly assess vehicle fuel consumption using real-world transient driving conditions with high-speed data acquisition. Due to the use of high-speed data acquisition, the resulting large data files yield continuous information about oil durability, engine operation, and oil-related vehicle fuel economy effects. Comprehensive maps of fuel consumption can be derived based on the matrix of operating conditions (acceleration, deceleration, and steady-state cruising) facilitating the development of optimized engine oil formulations. The method yields vehicle make and model-specific information about engine oil effects under all driving scenarios and correlation to EPA window-sticker fuel economy is established.

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INTRODUCTION

Background Information

Traditional methods for measuring the effect of engine oils on fuel economy fall into two categories: vehicle test methods and industry-standard laboratory engine tests. Both methods have their advantages and limitations when it comes to measuring real-world fuel economy. The authors of this paper sought to find a method that was related to real-world driving, and with continuous measurement of fuel economy throughout the aging of the engine oil. They were unsuccessful in this search and set out to develop a test to meet their needs. The following discussion describes why the conventional methods were found to be lacking and a new method was developed.

Note to reader: the primary units of measurement for fuel economy in this paper will be miles per US gallon (mpg). In several figures vehicle speed will be expressed in miles per hour (mph) and distance in miles as these are the primary units of the test procedures. All of the cited EPA documents, both historical and current use these units of measure and they are the primary unit of commerce for the test vehicles when it comes to window sticker fuel economy. Where ever practical the remaining items will be expressed in dual SI/English units, but the English unit will be shown first followed by the SI unit in parentheses.

Historical Vehicle Testing

Vehicle-based fuel economy tests usually rely on a vehicle aging sequence followed by fuel economy measurement. Vehicle aging (and therefore oil aging) is



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accomplished using an accelerated aging protocol like the Approved Mileage Accumulation (AMA) driving schedule shown in [Figure 1](#). This driving schedule was developed by the US EPA for automakers to use when demonstrating vehicle emission system compliance with EPA in-use standards. In a typical test the vehicles are computer-operated on an outdoor mileage accumulation dynamometer for a set interval then brought indoors into a well-controlled emission testing laboratory to be operated according to EPA emission testing procedures to measure city and highway fuel economy as shown in [Figures 2](#) and [3](#). City fuel economy is measured using the EPA FTP75 (FTP) procedure while highway fuel economy is measured using the EPA Highway Fuel Economy Test procedure (HFET). Both of these methods are described in 40 CFR, Part 86 and 600. Fuel economy is calculated through a complex analysis of bagged gaseous samples of dilute tailpipe emissions collected using a constant volume sampling system that effectively integrates the exhaust emissions emitted over a specific driving interval [1].¹

Past efforts to use vehicle aging followed by emission testing for engine oil-related fuel economy have experienced mixed results when it comes to showing discrimination of oil-related effects [2]. The consortium of companies that ultimately developed the Sequence VID Sequence Test (for which the authors' company was a member) reviewed automaker-submitted data from more than 600 FTP/ HFET tests and concluded the following in their report to the ASTM Passenger Car Engine Oil Classification Panel [3]:

- There was no statistical evidence that the development oils differed from a preselected baseline oil.
- There was no statistical evidence that development oils discriminated from one another.
- There was no statistical evidence that lighter viscosity grade oils offered fuel economy improvement among the development oils.
- There was no statistical evidence that oils with lower boundary friction improved fuel economy.
- There was directional evidence that friction modified oils showed some benefit over non-friction modified oils.
- There was not enough statistical evidence to support a decline in fuel economy performance of the test oils as they age from 2000 miles (3226 km) to 6500 miles (10484 km).

Based on these conclusions it can be inferred that engine oil impact on vehicle fuel economy can be quite subtle and the vehicle aging/emission test method does not offer sufficient accuracy to reliably discriminate these differences. The VID consortium eventually developed the Sequence VID engine test [4] which does discriminate engine oil effects and is currently used in North American specifications like those listed by ILSAC [5] and API [6].

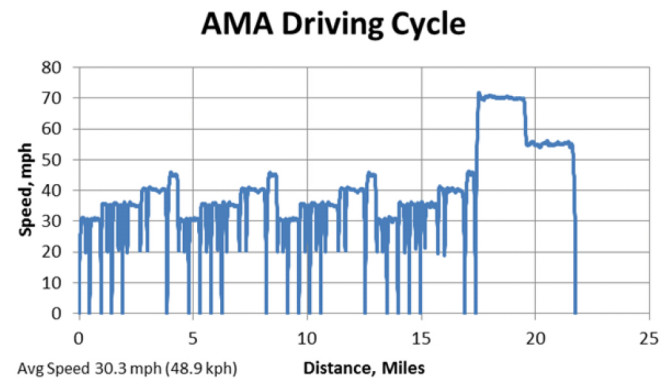


Figure 1. EPA AMA Vehicle Aging Driving Schedule

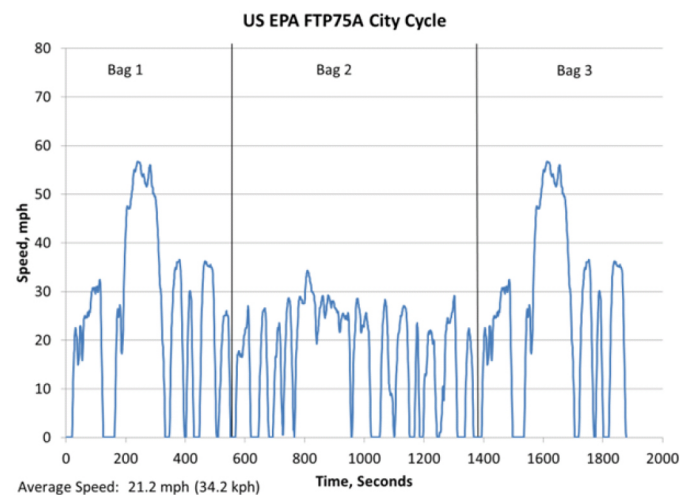


Figure 2. US EPA FTP 75A City Driving Emission Cycle

¹The city cycle averages 21.2 mph (34.2 kph) and is divided into three phases, or bags (the term "bag" is in reference to the bagged emissions). The highway cycle's emissions are collected in a single bag. Bag 1 is 505 seconds in length and includes a "cold" start. Prior to the test the vehicle has been stored for a period of time at 75°F (24°C) before being started. Bag 2 is 871 seconds in length and follows immediately after Bag 1. Bag 3 is a hot-start repeat of Bag 1 after a relatively short 10-minute period with the key off. The highway test is 765 seconds in length with an average speed of 48 mph (77.4 kph). The city and highway cycles are used by automakers along with three other tests (the US06, SC03 and a 20°F (-7 °C) FTP test) to derive the fuel economy numbers used on new vehicle window stickers (window-sticker fuel economy) as reported in the EPA Window Sticker Support Document, EPA420-R-06-017, December 2006.

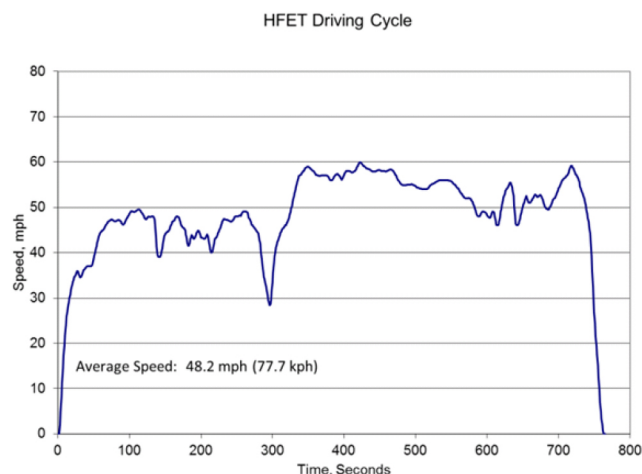


Figure 3. US EPA Highway Fuel Economy Driving Cycle

Laboratory Engine Testing - The Sequence VID Test

Sequence tests like the VID are accelerated-aging tests maintained by ASTM as consensus, standardized methods. A complete listing of all Sequence tests can be found in Standard D4485 Standard Specification for Performance of Active API Service Category Engine Oils maintained by the ASTM Passenger Car Engine Oil Classification Panel, a panel under ASTM D02 Subcommittee B. In most cases these tests have been developed and their results directly correlated with field experience using reference oils. As accelerated aging tests, Sequence tests are meant to compress the time necessary to stress engine oils in intentional ways to exacerbate problem areas sometimes found at the extremes of consumer service, like sludge, piston deposits, oil oxidation and engine wear. As with any accelerated aging procedure, test developers must be vigilant for the introduction of artifacts not seen in consumer service and assure that the interpretation of results is viewed in light of these artifacts. Examples of these artifacts include specially-formulated test fuels for sludge generation, intentionally large ring gaps to promote blowby, or over-fueling to promote fuel dilution.

Results from the Sequence VID are expressed as Percent Fuel Economy Improvement (FEI, %) and are assessed after 16 hours of oil aging (the equivalent of about 2000 miles of vehicle service) and 100 hours (the equivalent of about 6500 miles of vehicle service). FEI is determined using six discrete sets of test conditions where speed, load, and operating temperatures are held constant at specified conditions as shown in [Table 1](#). Fuel consumption results are weighted as shown in the table.

Table 1. Summary of Sequence VID Measurement Stages

Stage #	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
Speed, rpm	2000	2000	1500	695	695	695
Power, kw	22	22	16.5	1.5	1.5	2.9
Oil Temp, C	115	65	115	115	35	115
Coolant In Temp, C	109	65	109	109	35	109
Stage Weight	0.300	0.032	0.310	0.174	0.011	0.172

To calculate Percent Fuel Economy Improvement (FEI, %) the results from the candidate test oil are compared to an identical set of measurements using baseline oil in separate tests that proceed and follow the test oil. The baseline oil is not aged and has an SAE 20W-30 viscosity grade classification. Similar to the test stages, oil aging in the Sequence VID is a steady-state process where speed, load and temperatures are held constant for the 100-hour duration (16 hours before FEI 1 and 84 hours after FEI 1, before FEI 2) as shown in [Table 2](#). The aging conditions in [Table 2](#) were determined by the Sequence VID Consortium and designed to yield used oil oxidation in alignment with oils aged in the vehicles driven according to the AMA driving cycle.

Table 2. Summary of Sequence VID Aging Conditions

Speed, rpm	Load, Nm	Oil Temp., C	Length, hours
2250	110	120	100

For research purposes, interpretation of results from the Sequence VID can be problematic. First, the test is time-consuming taking over six days to complete. This places a practical limitation on the size of experimental designs. Second, for research purposes the Sequence VID has variability that can mask the subtle effects under investigation. [Figure 4](#) shows an analysis of accepted reference tests on one of the Sequence VID reference oils, No. 542. The whiskers above and below the bars show upper and lower range of results, and illustrate the variability which can occur among different laboratories and stands that have tested the oil. Variability complicates the interpretation of single-run test matrices and can lead to erroneous conclusions. Third, the steady-state aging conditions nearly always yield results showing declining fuel economy as shown by the FEI 2 average relative to FEI 1 in [Figure 4](#). This is an acceptable artifact for an accelerated aging test used to qualify oils against a high performance standard, but the authors desired a test that yields results more in-line with vehicle-produced results like those that preceded development of the Sequence VID test.

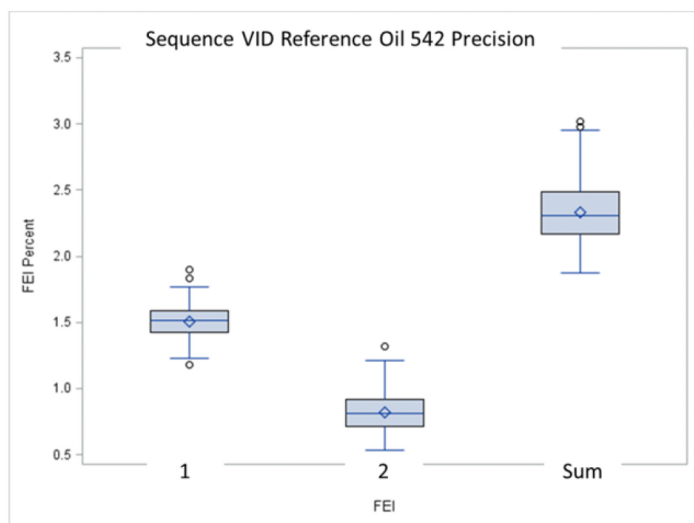


Figure 4. Example of Reference Oil Precision

OEM Trends in Fuel Economy Assessment

There is a recent trend among some OEMs to move away from standardized engine fuel economy tests in favor of proprietary tests that more closely relate to their technology and CO₂ reduction strategies. At the 16th ICIS World Base Oils & Lubricants Conference held in February 2012 a presentation was given detailing a new engine lubricant development for modern gasoline engines. The presenter described a method using the Ford 1.0L “Ecoboost” engine using a semi-transient laboratory method correlated with the NEDC for measuring fuel economy of new oils. According to the presenter this method is being incorporated into the Ford WSS M2C948 B specification and was developed because it was assumed that there would be limited correlation between industry standard fuel economy tests like the ACEA test based around the M111 or the ASTM Sequence VID Fuel Economy Test.

There is also a new engine oil requirement for Daimler vehicles that requires new (un-aged) oils to be evaluated in a vehicle-based fuel economy test method. In a presentation given at the UNITI Mineral Oil Technology Congress 2012 in Stuttgart, Germany a presenter described a “New Engine Oil Requirements for MB Engines” This specification requires four Mercedes Benz vehicles to be tested according to the NEDC using baseline oil and test oil. The results are interpreted after repeated NEDC emission tests on the baseline oil followed by the test oil.

It is obvious from the efforts of Ford and Daimler that there is an increasing emphasis of fuel economy testing that more closely relates to their specific vehicle engineering and certification needs. In both cases there is a reliance on the NEDC emissions cycle over standardized engine tests.

EXPERIMENTAL

Design of a New Test

With a desire to simultaneously age oils and continuously measure fuel economy under real-world driving conditions the authors set out to develop a new method to test engine oils. The design requirements were as follows:

1. Use modern vehicles with state-of-the-art engines.
2. Age oils in a way that is more representative of real-world driving than EPA in-use verification cycles.
3. Assess vehicle and engine age impact on fuel economy discrimination.
4. Assess driving patterns and their impact on fuel economy.
5. Develop a flexible testing platform to allow the screening of as many different vehicle makes and models as possible.
6. Develop a test with global applicability.

Driving Cycle Selection

In order to measure the impact of engine oil formulations on real-world engine operation the authors sought to find a driving schedule that would meet two fundamental criteria: (1) it would have to simulate real-world transient driving, and (2) it would have a high enough average speed to keep the aging process to a manageable time period (about 800 miles (1290 km)/day). Two vehicle aging cycles have been documented by the US EPA in the 40 CFR Part 86: the Approved Mileage Accumulation Driving Schedule (AMA) as shown in Figure 1 and the Standard Road Cycle [7] which replaced the AMA cycle in 2006 as shown in Figure 5. These cycles were developed by the EPA for use by automakers in predicting the emissions of new model year vehicles at the end of their useful life. While these cycles may be useful for their intended purpose - vehicle and emission component aging - it is obvious from their regular, repeating appearance they do not represent any form of real-world driving and therefore fail to meet the first driving cycle selection criterion.

The use of transient emission cycles was considered as another option. FTP and the HFET cycles shown in Figures 2 and 3 were examined for applicability and given a high degree of consideration because of their use in determining the window sticker fuel economy values of new cars. The average speeds of the FTP and HFET driving schedules are 21.2 mph (34.2 kph) and 48.0 mph (77.4 kph), respectively, and if combined the overall average speed would be 29.8 mph (48.1 kph). While this satisfies the second criterion for average speed, it fails the first criterion for not being realistic. In the EPA document “Final Technical Support Document, Fuel Economy Labeling of Motor Vehicle Revisions to Improve Calculation of Fuel Economy” [1] they state “a

fundamental issue with today's fuel economy estimates is that the underlying test procedures do not fully represent real-world driving conditions². They describe these issues as follows: they were developed in the 1970's, they have relatively mild acceleration rates, and they have a limited top speed of 60 mph (96.8 kph). To compensate for these deficiencies, in 2005 the EPA put several additional procedures in place to adjust the window sticker fuel economy values which include: the US06, the SC03, and the Cold FTP². The US06 and SC03 driving cycles are shown in [Figures 6 and 7](#). While it would be technically feasible to put together some combination of the FTP, HFET, US06, and SC03 cycles, the composite cycle would be arbitrary and still not entirely meet the first criterion of being real-world.

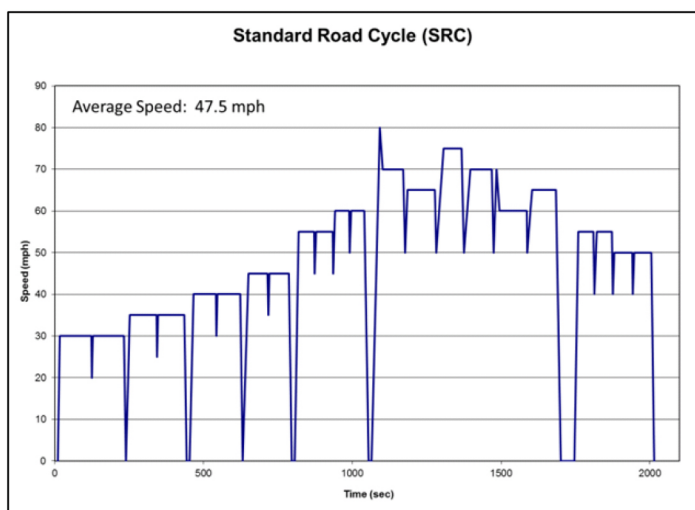


Figure 5. US EPA Standard Road Cycle for Vehicle Aging

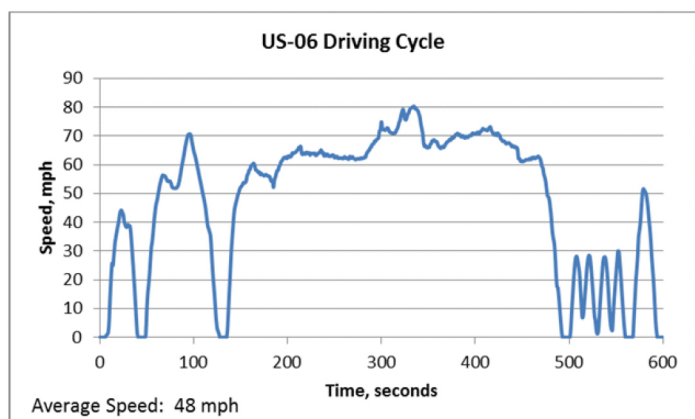


Figure 6. US EPA US-06 Aggressive Driving Schedule

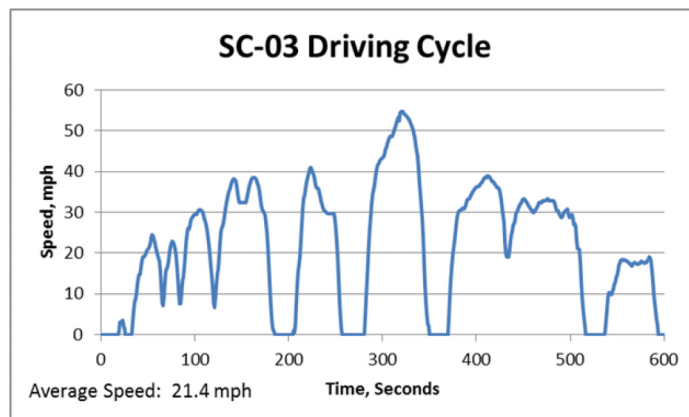


Figure 7. US EPA SC03 Air Conditioner Test Driving Cycle

Other Emissions-Based Vehicle Drive Cycles

The New European Drive Cycle (NEDC) was briefly considered because of its relevance to European emission and fuel economy determination. It is depicted in [Figure 8](#). As with the SRC, its regular, repeating appearance does not represent any form of real-world driving and therefore fails to meet the first driving cycle selection criterion. Its average speed is also too low to produce an acceptable daily mileage rate and thus fails the second criterion. As with the US FTP, while it is essential to demonstrating emissions and fuel economy for compliance purposes, it was not deemed suitable to meeting the author's goals.

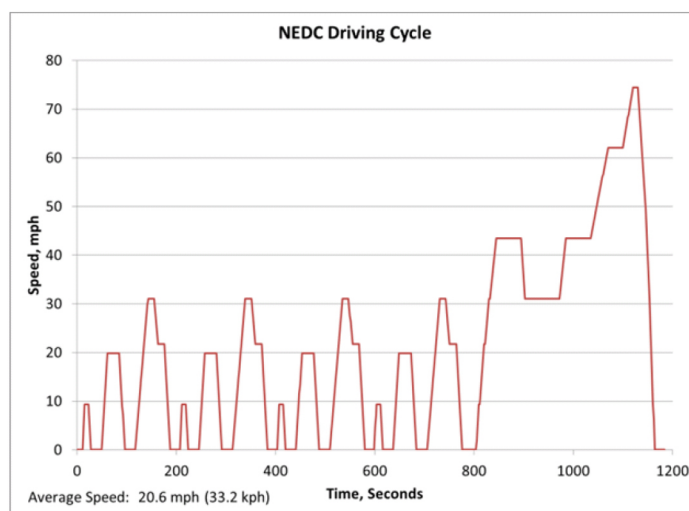


Figure 8. NEDC Driving Cycle

²The US06 test is designed to represent high speed highway driving and aggressive (i.e., rapid accelerations and decelerations) urban driving. The SC03 test is designed to represent the impact of air conditioner operation at high temperatures and the testing is performed with simulated solar loading at 90°F (32°C). The Cold FTP, which is conducted at 20°F (-7°C), is designed to reflect the impact of cold temperatures.