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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 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].

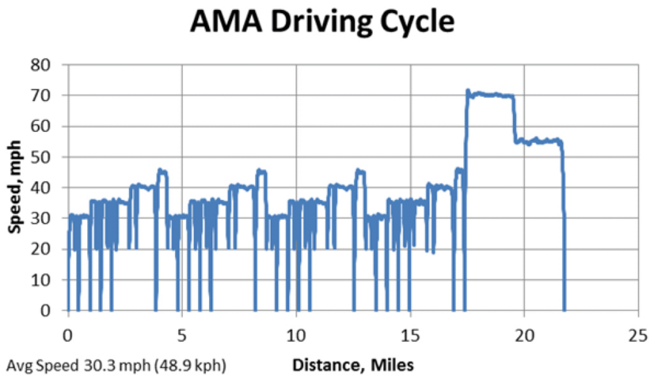

Figure 1. EPA AMA Vehicle Aging Driving Schedule

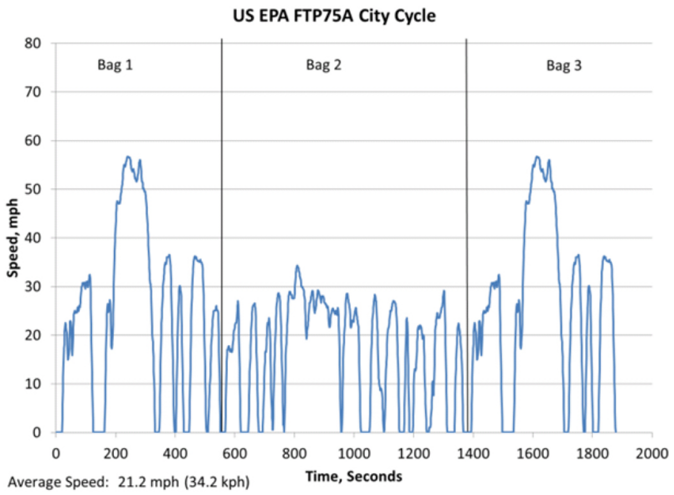

Figure 2. US EPA FTP 75A City Driving Emission Cycle

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[1] The 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.

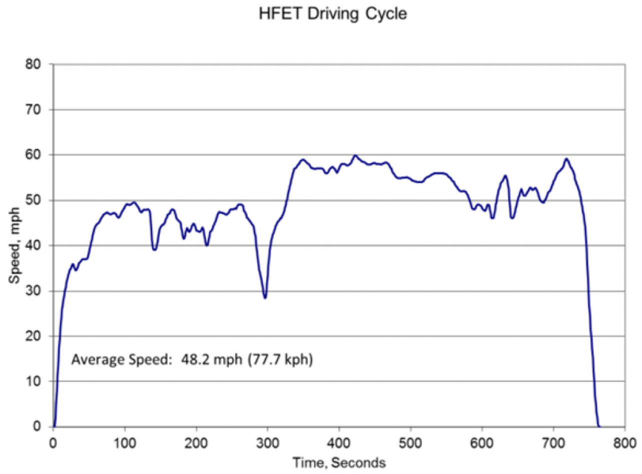

Figure 3. US EPA Highway Fuel Economy Driving Cycle

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.

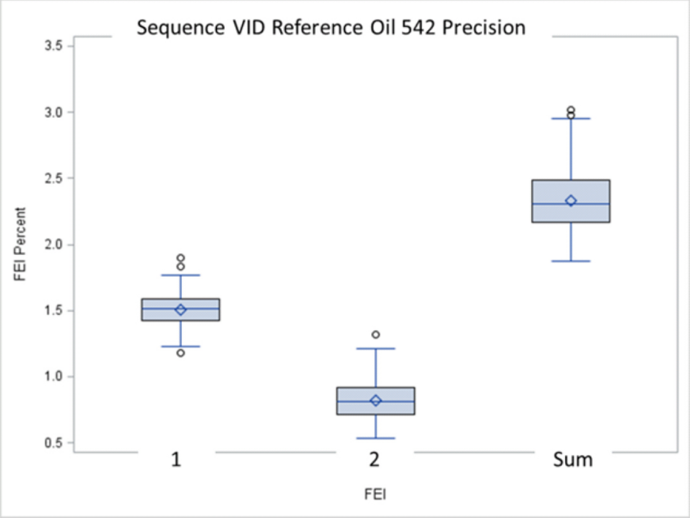

Figure 4. Example of Reference Oil Precision

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 conditions". 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 FTP[2]. 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.

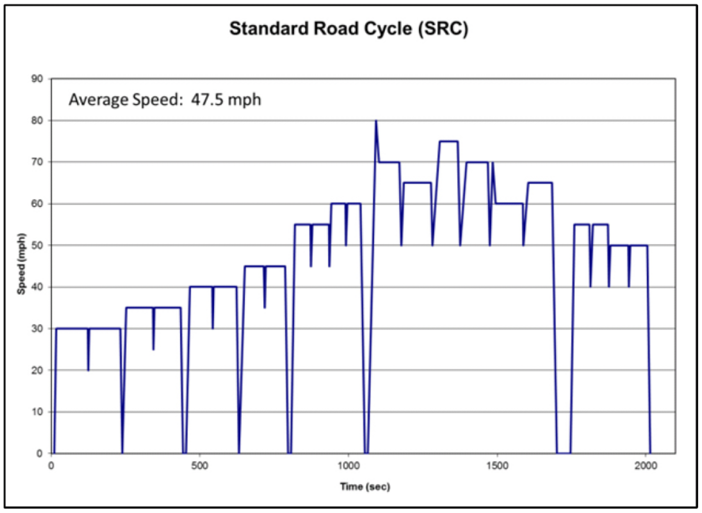

Figure 5. US EPA Standard Road Cycle for Vehicle Aging

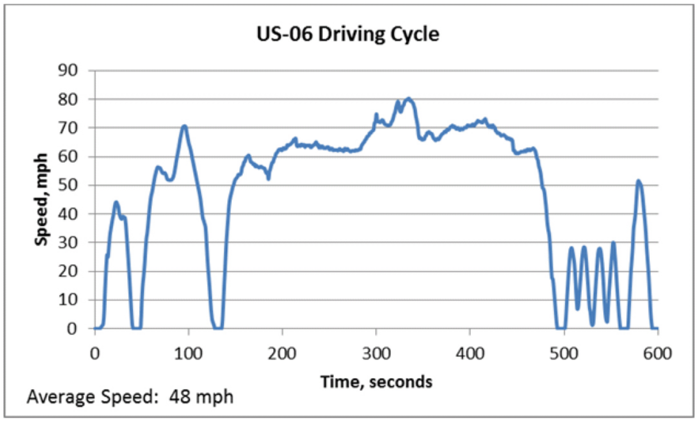

Figure 6. US EPA US-06 Aggressive Driving Schedule

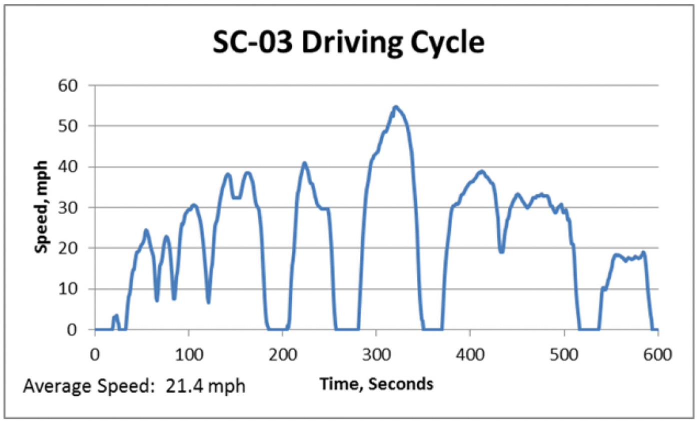

Figure 7. US EPA SC03 Air Conditioner Test Driving Cycle

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, it's 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.

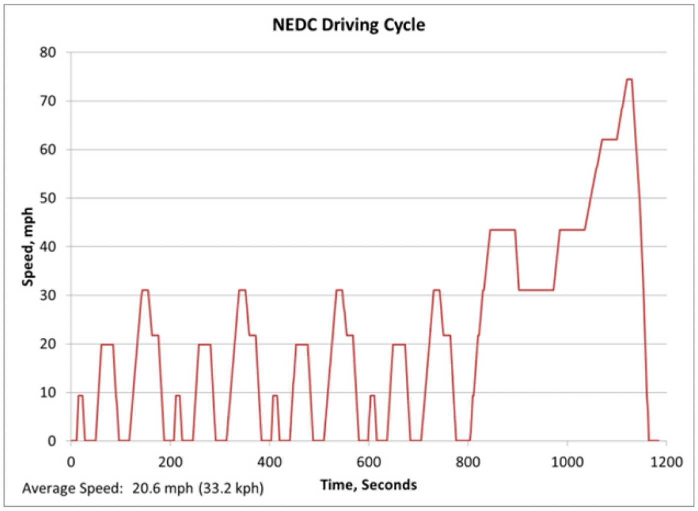

Figure 8. NEDC Driving Cycle

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[2] The 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.

The Artemis Cycle

In the year 2000 the European Commission with the 5th Framework Research Programme funded a research program called the Assessment and Reliability of Transport Emission Models and Inventory Systems project, or ARTEMIS, for short, with two principle objectives. The first related to developing a fundamental understanding of the uncertainties in emission modeling and the second was to develop a harmonized methodology for estimating emissions. The results of this project are summarized in their final report [8]. During the development of harmonized methodology several large-scale in-use vehicle studies were conducted which examined driving patterns in various settings - urban (city), rural, and motorway (highway). The dataset covers 77 private vehicles in 4 countries, covering 10,300 trips, and driven by their owners in actual use during 2200 hours covering 88,000 km (54,560 mi). While it is beyond the scope of this paper to summarize the statistical analysis and selection methodology employed by the research team, the outcome was three cycles known collectively as the Common ARTEMIS Driving Cycles (CADC). The CADC has three segments described in Table 3 and shown in Figures 9, 10, 11. The figures are annotated with the distinct type of driving represented in that portion of the cycle.

The authors chose to use this cycle because it satisfies both of the primary objectives for aging cycle selection: it is a real world transient cycle based on the ways people drive, and the average speed for the CADC is high enough to provide some amount of accelerated aging without being unrealistically fast. Regarding average speed, in its Final Technical Support Document[1] the EPA reported on the average driving speeds from a variety of in-use studies conducted in several cities around the United States as part of a report on mobile source emissions. The comprehensive analysis of these data may be found in the MOVES2004 Highway Vehicle Population and Activity Data Draft Report, EPA420-P-04-020, December 2004. In this report, based on the descriptions of city and highway driving the average speeds were reported as 19.9 mph and 57.2 mph, respectively. Vehicle fuel economy is a complex calculation based on the five test methods referenced earlier but the historical label value uses a 55/45 breakdown of city and highway driving. Using the EPA breakdown for the average speeds would result in a value of 36.5 mph and this is in remarkably close agreement with the 36.2 mph average of the CADC shown in Table 3. This satisfies the first selection criterion. An average of 36.2 mph would also yield over 800 miles per day in continuous use and thus satisfying the second criterion for accumulation rate.

Table 3. ARTEMIS Cycle Statistics

Cycle	Distance, mi (km)	length, sec	Average speed, mph (kph)	Max Accel Rate, kph/sec (mph/sec)
Urban	3.0 (4.8)	993	11.0 (17.7)	6.4 (10.3)
Rural	10.7 (17.3)	1082	35.7 (57.5)	5.3 (8.5)
Motorway	17.9 (28.8)	1068	60.2 (96.8)	4.3 (6.9)
Combined	31.6 (50.9)	3143	36.2 (58.4)	6.4 (10.3)

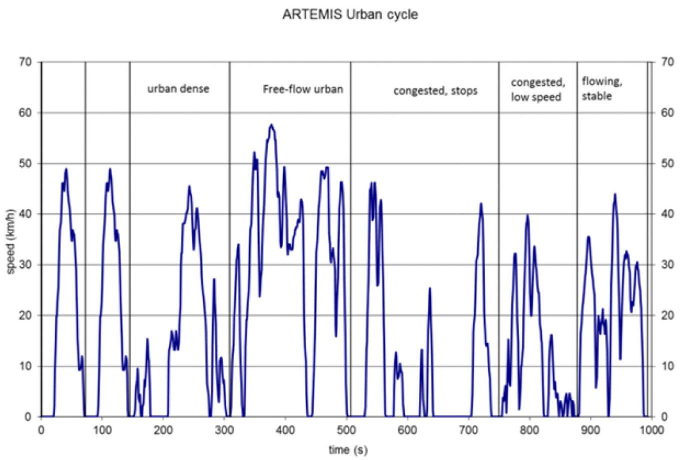


Figure 9. ARTEMIS Urban Cycle Showing Breakdown of Steps

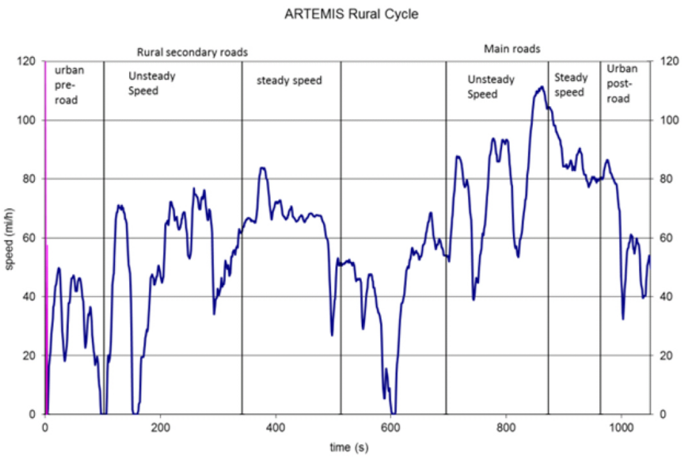


Figure 10. ARTEMIS Rural Cycle Showing Breakdown of Steps

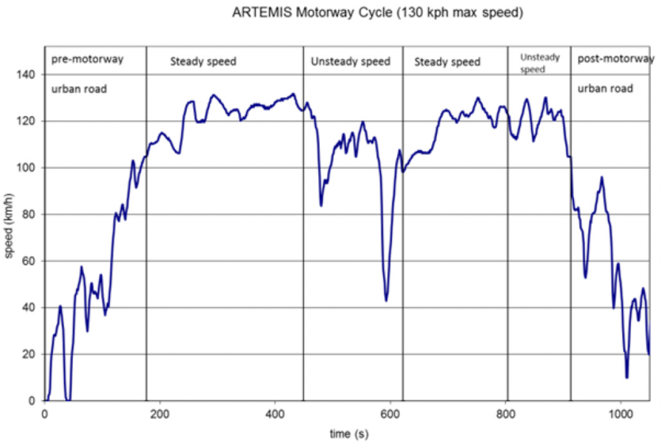


Figure 11. ARTEMIS Motorway Cycle Showing Breakdown of Steps

When the CADC was put into service by the authors they inserted three short periods of steady-state driving at 30, 50 and 70 mph (48.4, 80.6 and 112.9 kph) after each CADC cycle to help monitor the performance of the chassis dynamometer by laboratory operators. Data from these periods were not used in any of the calculations of fuel economy but were useful in assuring the accuracy of dynamometer load controls and calibration.

Vehicle Testing Dynamometer

High-precision vehicle tests are typically conducted indoors in order to reduce the amount of variation due to ambient variables on engine and vehicle performance. Intake air temperature, relative humidity and barometric pressure are some of the factors that laboratory engineers take into account when conducting performance testing. In an uncontrolled setting such as an outdoor Mileage Accumulation Dynamometer (MAD) it is not readily possible to control these variables but it is still possible to correct for them, provided a sufficient quantity of data is collected to characterize the effect. Due to the anticipated long-term nature of the envisioned testing the authors chose to use readily-available MAD's for this work, and to rely on statistical regressions to correct for ambient variation. The subject dynamometers had been recently retrofitted with proprietary, advanced feedback control hardware and software for speed, throttle and vehicle load control. The gear box used to change the direction of rotation was fitted with an oil heater and controlled to a set point to minimize the impact of temperature variation on drag. Pillow block shaft support bearings between the gearbox and variable drive motor were also instrumented for temperature measurement and use as a diagnostic tool. Vehicle-specific road load coefficients were used by the dynamometer load control software which came from the US EPA Annual Certification and Test Results web page [9]. In Figure 12 a schematic of the MAD is shown and in Figure 13 a test vehicle is shown on the dynamometer platform. Transient vehicle speed was controlled by an automated driver that depressed the accelerator pedal with feedback control. Vehicle road-load control was accomplished using the vehicle-specific road load coefficients (adjusted for parasitic losses) as applied by the variable speed drive motor. In order to closely follow the programmed vehicle speed trace, the variable speed drive motor was used for vehicle braking instead of using the vehicle's braking system.

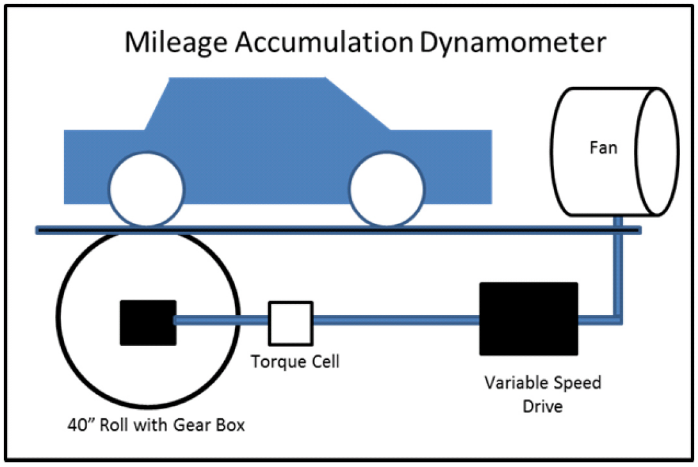


Figure 12. Schematic of Mileage Accumulation Dynamometer

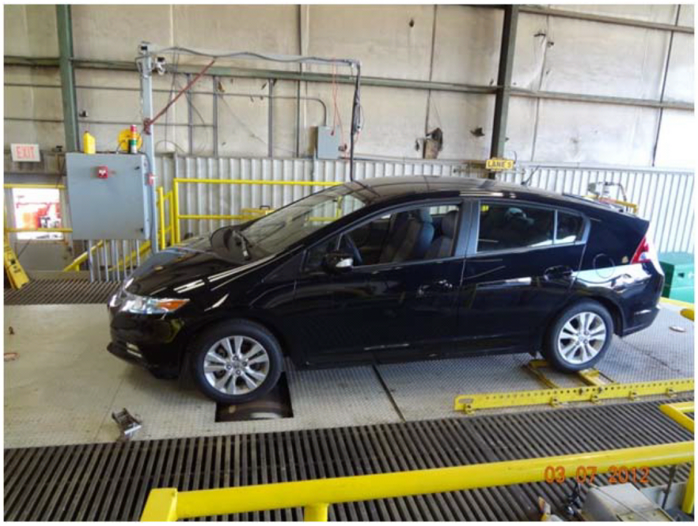


Figure 13. Test Vehicle Shown on MAD Lane

Vehicle Instrumentation

The test vehicles were instrumented to measure several parameters from the on-board OBDII computer including: rpm, load, throttle, mass air flow, and manifold absolute pressure. The vehicle's engine was instrumented to measure sump temperature, block temperature (coolant), and intake air temperature. Ambient condition data were monitored including barometric pressure, temperature and relative humidity. From the dynamometer control hardware the following were recorded: wheel speed, torque, horsepower, and several parameters associated with the dynamometer performance to assure constant, high-precision operation. Fuel flow and temperature were measured on a volumetric basis using a positive displacement flow meter with a flow range of 10 to 10,000 cc/minute and accuracy of 0.2% of the reading.

Data from all of the input and output variables were logged at 1Hz. One cycle of the CADC plus steady-state (CADC+SS) generated approximately 3500 observations and for a typical 10,000 mile (16,129 km) test data files routinely exceeded 1,000,000 observations. There was a heavy reliance on user-developed software for data reduction, analysis, and reporting.

Test Vehicles

This paper will summarize the results of four gasoline-fueled vehicles that were used for oil aging and fuel economy measurement. All vehicles were purchased new for this study and were not driven on the road except for delivery from the dealer. For dynamometer testing purposes they were necessarily equipped with two-wheel drive chassis and automatic transmissions. Since the goals included evaluating as many different types of technology as possible, with global applicability, the following vehicles were used as summarized in Table 4:

Table 4. Vehicles Used in Test Program

Model Year	ID	Vehicle Type	Country of Origin	Engine Type	Technology
2010	NA V6	SUV	North America	V6 3.5L	Cam in Block
2010	NA V8	Full-Size Sedan	North America	V8 4.6L	SOHC PFI
2010	JP I4	Compact	Japan	I-4 2.4L	SOHC PFI
2011	DE I4	Sports Compact	Germany	I-4 2.0L	DOHC, DIG/Turbo

Each new vehicle was instrumented as described above for operation on the MAD lane and operated for several 2500 mi (4062 km) tests using a baseline lubricant. It was possible to determine when the vehicle was broken-in by comparing the average fuel consumption across tests and plotting these versus vehicle mileage. This technique is described in the Statistical Analysis section, below.

RESULTS

Statistical Analysis

Recognizing the impact of uncontrolled ambient test conditions on the test vehicles and dynamometer hardware, the authors took the approach of estimating and reducing their impact by performing linear regressions on the second-by-second data files. The extremely large amount of data collected during testing enabled the use of a linear regression modeling, along with engineering judgment, to estimate the effects of air temperature on engine operation and vehicle load measurement. These effects, though very small, could then be regressed from the average cycle-by-cycle data with a high degree of statistical confidence. In practical terms, due to the long-term nature of the testing and the transient mode of operation the effect of ambient air temperature on fuel economy was relatively small and very consistent across all vehicles. The same response held true for the effect of barometric pressure and relative humidity which were only found to be significant at their extremes. An example of test stability is Figure 14 which shows the typical response of MPG during the three ARTEMIS cycles to the observed range of ambient temperature. This graph contains the data from thirteen 5,000-mile (8,000 km) test runs and represents more than 60,000 miles (97,000 km) of operation over a 12-month period. The other three vehicles behaved in a similar, predictable fashion but having slightly different slopes. The authors believe this test stability is due to the relative consistency of oil temperature throughout the testing. In spite of ambient temperature fluctuations during tests, average oil temperature was found to be fairly consistent between adjacent runs, usually less than 2°C. These statistics represent data collected over the course of 12 months where ambient temperature spanned a range from −5 to +35°C. For all vehicles and for all tests conducted over a 24-month period, oil temperature averaged 100.0°C.

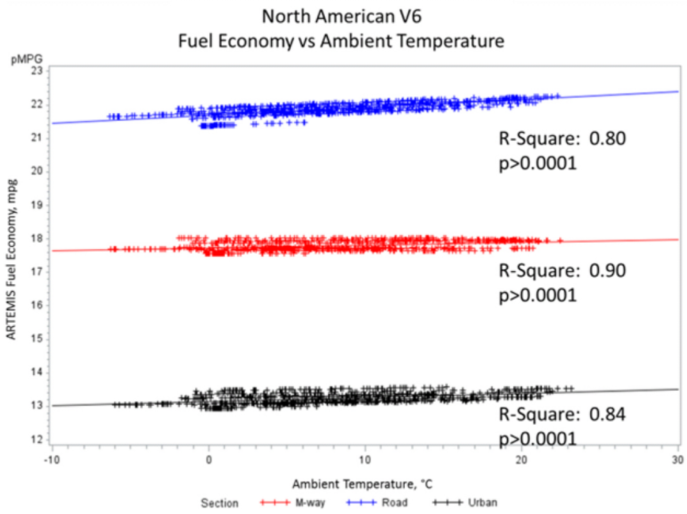


Figure 14. Effect of Ambient Temperature on Fuel Economy

Data Reduction Techniques

Four data reduction techniques were employed on the very large raw temperature-adjusted data files and they fall into the following hierarchy:

1. Simply summarize the total fuel consumed for all ARTEMIS sections and divide by distance to compute MPG.

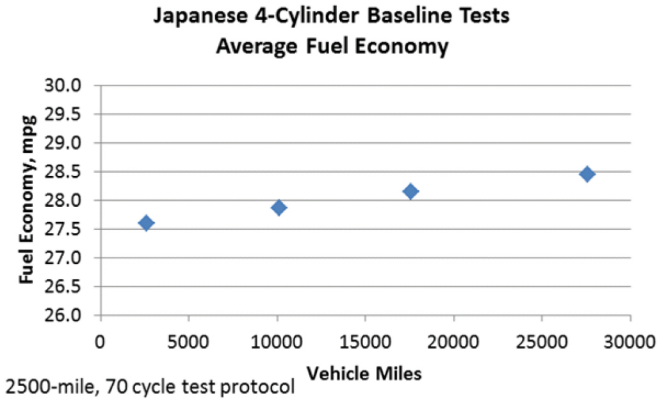
2. Calculate fuel consumption rate for each full cycle through the CADC and plot versus distance.

3. Break the CADC down into its three segments and analyze by driving pattern and engine operation condition.

4. Perform a second-by-second analysis, correlating engine operation and fuel economy.

First level

The highest level analysis technique is shown in Figure 15. This type of analysis is useful for showing overall trends like the expected increase in fuel economy with vehicle miles[3]. For this figure the test vehicle's average fuel consumption was calculated for four individual tests using a baseline formulation and plotted versus vehicle mileage at the start of oil aging. Each point in Figure 15 represents 2500 miles (4032 km) of driving (the average of 70 cycles of the CADC comprised of 240,000 observations) on the same oil formulation.



2500-mile, 70 cycle test protocol

Figure 15. Japanese I-4 Fuel Economy Break-in Trend

Second level

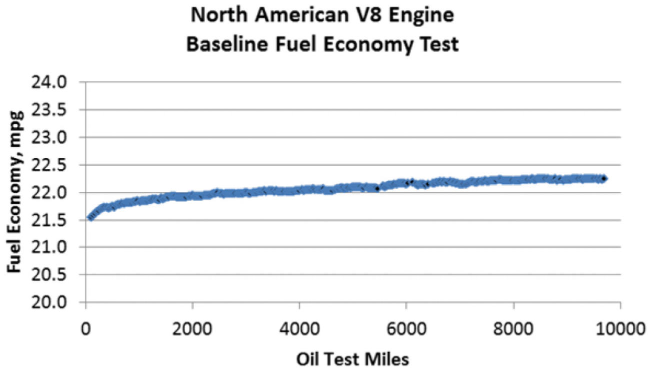


Figure 16. NA V8 10,000 Mile Fuel Economy Data

The second level involves calculating an average fuel economy value for each full cycle of the CADC. The data from a 10,000 mile test using an SAE 5W-20 viscosity grade oil meeting the dexos1™ specification is shown in Figure 16. Each point on the plot is an average value for one of the approximately 280 cycles of CADC operation. In this figure the subtle increase in fuel economy with oil age can be observed. It should be noted that this increase in fuel economy is consistent throughout all of the testing that took place during this program and is consistent with the vehicle data on Sequence VID correlation matrix oils discussed in the final Sequence VID Consortium report [2].

Third level

The third level of analysis involves breaking the CADC down into its three elements: Urban, Rural and Motorway Driving. For illustration purposes the values for fuel economy in Figure 17 are plotted with reduced frequency (every 10 cycles). Each point represents the average fuel economy for one cycle of the CADC. This type of analysis allows for driving pattern comparisons of oils. The figures summarizing the three ARTEMIS test cycles, Figures 9, 10, 11, show a further breakdown of each cycle into distinct driving components and while outside of the scope of this paper, an analysis of these modes is possible, relating the trends back to the large-scale consumer driving study.

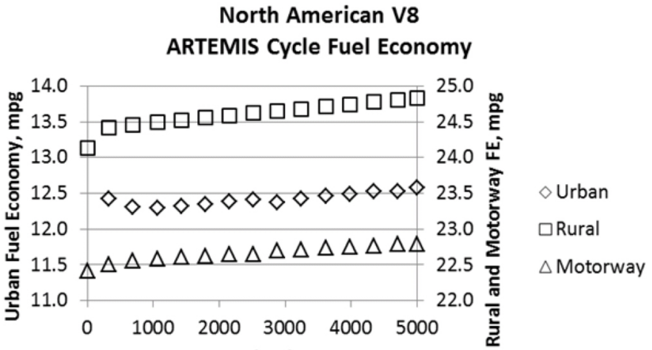


Figure 17. ARTEMIS Section Fuel Economy

Fourth level

The fourth and final method of data reduction is second-by-second analysis of cycle performance where the data from each cycle of CADC are aligned according to each of the 3143 seconds of operation and the fuel totaled on a second-by-second basis. This facilitates comparisons of different engine oils to the baseline and increases understanding of how different lubricants perform in different parts of the CADC. Figure 18 shows one type of analysis where the fuel flow derived from the operation with two oils is deviated from baseline oil fuel flow and the differences plotted versus cycle miles. The CADC is also plotted for reference purposes. The performance differences are clearly evident showing Oil A having a cumulative difference from the baseline oil approaching 0.5% and Oil B having a cumulative difference of about −1.0%.

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[3] On the US EPA's website, http://www.fueleconomy.gof/feg/topten.jsp, they cite the following fact regarding fuel economy and vehicle age: "A vehicle that is properly maintained will retain its efficiency for many years. The EPA tests vehicles with about 5,000 miles (8064 km) on the odometer to account for the break-in period since a vehicle's fuel economy will typically continue to improve over the first several years of ownership. Vehicles that are 10 or even 15 years old will experience little decrease in fuel economy if properly maintained."

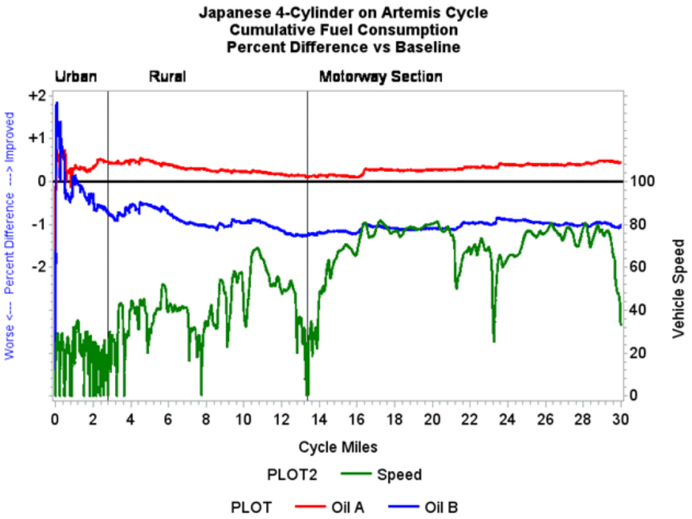

Figure 18. Second-by-Second Comparison Breakdown

Fuel Dilution and Viscosity Changes

The relatively rapid increase in observed fuel economy within the first 1000 miles (1600 km) in Figure 16 is related to a small decrease in the oil's kinematic viscosity. This is caused by shearing of polymers such as viscosity index improvers (VII) used to produce cross-graded oils. VII's may be categorized according to their shear stability, and oils formulated with VII's of differing Shear Stability Index (SSI) will display markedly different shear-thinning rates during the first 1000 miles of operation. Fuel dilution is another possible source of viscosity loss but the authors found that oils aged according to the ARTEMIS protocol experience very little fuel dilution, on the order of 0.3 to 1.5%. To better understand the impact of shear-thinning on fuel economy, a 1000-mile (1600 km) test was conducted using the German 4-cylinder vehicle using oil with an SAE Grade of 5W-30. Oil was sampled and analyzed for change in viscosity (as measured at 40°C) at 100-mile (161 km) intervals. Figure 19 shows the percent viscosity loss during this 1000-mile (1600 km) investigation. This decrease in viscosity is consistent with experience in the Sequence VID at 16 hours where FEI 1 is recorded, as shown in Figure 20. This figure summarizes the results of many SAE 5W-30's tested in the Sequence VID.

To better understand the context of the ARTEMIS driving cycle, viscosity change with mileage was compared to oils aged according to the AMA protocol and oils aged in the Sequence VID. Since the initial change in viscosity is governed in part by the SSI of the VII the authors compared changes in viscosity from the intermediate reading to end-of-test (EOT) reading. Figure 21 compares the change in viscosity from the intermediate reading to EOT for oils aged using the ARTEMIS cycle, the AMA cycle, and the Sequence VID. All oils in this comparison are Viscosity Grade SAE 5W-20 and the bars are the average of all available tests. The vehicles were sampled at 2000 miles and EOT while the Sequence VID was sampled at the 2000-mile equivalent (16-hours) and the 6500-mile equivalent (100-hours). The EOT mileage was 10,000 for the ARTEMIS sample and 6,500 for the AMA cycle. While there is good agreement between oils aged in vehicles, the Sequence VID shows a more severe rate of viscosity increase and this likely explains the lower fuel economy at EOT relative to vehicle tests. The authors believe this is related to the accelerated oil aging conditions of the Sequence VID which employs oil temperature that is 20°C higher than the 100°C average observed in all of the vehicles tested by the authors. The observed oil consumption in the vehicles is also less than half of that observed in a typical Sequence VID test and considering the higher oil temperature of the Sequence VID, this suggests distillation as a predominant mechanism for the viscosity increase in Figure 21.

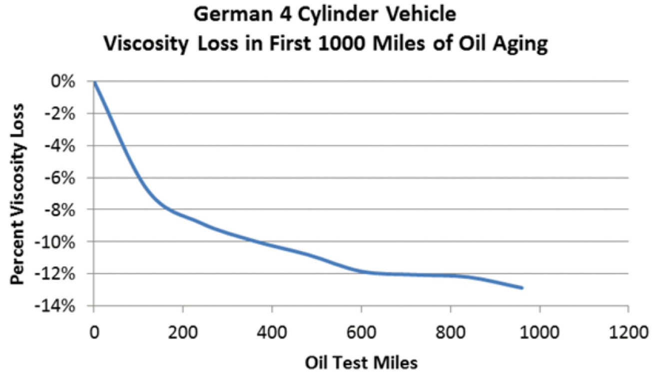

Figure 19. Viscosity Loss During First 1000 Miles of Aging

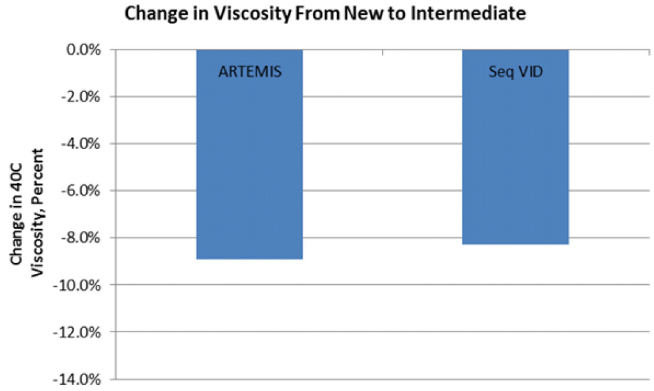

Figure 20. Change in Viscosity from New to Intermediate for SAE 5W-30 Oil

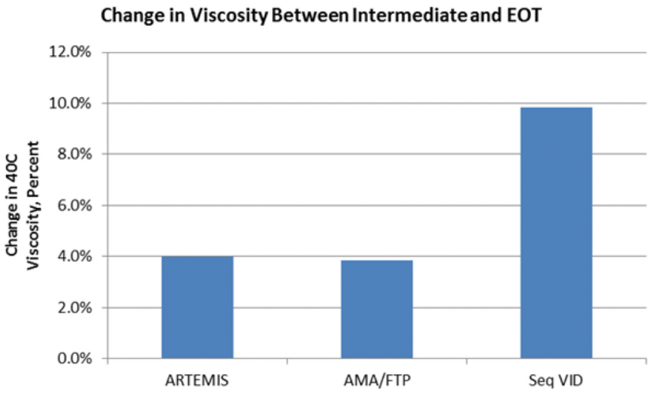

Figure 21. SAE 5W-20 Oils Aged in Three Tests

Test Precision

Many test programs were conducted using the four test vehicles over the course of 24 months and an essential element of each program was to run bookend-baseline oil tests at the beginning and end of every program. Comparison of the two baseline results helped to estimate the discriminating power of the test and estimate vehicle aging drift like that shown in Figure 15. An example test matrix including test results is shown in Table 5. All of the oils in this matrix pass their respective requirements in the Sequence VI engine test and are commercial products. Test results are expressed in terms of a mean and standard deviation, and a statistical box and whisker plot treatment of the data is shown in Figure 22. In practical terms the baseline oil No. 1 gave essentially the same fuel economy in both tests and oil No. 5 is different from the other three at the 95% confidence level.

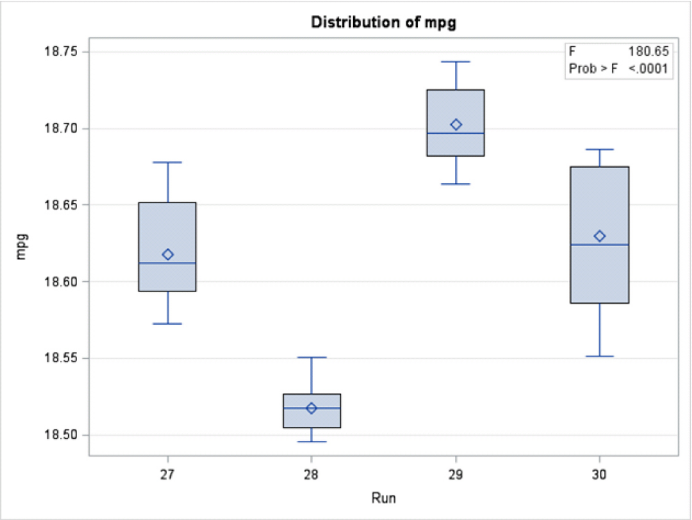

Figure 22. Fuel Economy versus Run Number

Table 5. Summary of Baseline Oil Test Precision

Oil No.	Oil Code	Test No.	Mean	Std. Dev
1	Baseline 5W-20	27	18.62	0.032
5	Oil A 5W-30	28	18.52	0.014
2	Oil B 5W-30	29	18.70	0.026
1	Baseline 5W-20	30	18.63	0.044

Test Sensitivity

With any new test, users want to understand the limits of discrimination, precision and repeatability. Several experiments were undertaken to understand the sensitivity of this test to engine oil formulation changes as summarized in Table 6. The oils listed in Table 6 contained the same commercial detergent-inhibitor package (DI) and viscosity modifier (VM) type and differed only in their SAE viscosity grade, presence of friction modifier (FM), and VM Shear Stability Index (SSI). Oils 1 - 3 all have passing results in the Sequence VI engine test. Using a broken-in vehicle with a North American V6 engine the oils were tested in the order shown in the table.

Table 6. Test Sensitivity Matrix

Oil No.	Viscosity Grade	FM	VII SSI	Test Order
1	SAE 5W-20	Yes	Higher	1
2	SAE 5W-30	Yes	Higher	4
3	SAE 5W-30	Yes	Lower	2
4	SAE 5W-30	No	Lower	3

Table 7 presents comparisons versus baseline for the four oils listed in Table 6. Fuel economy for each 5000-mile test was calculated and the percent differences calculated versus the comparison baseline. For the viscosity grade comparison the SAE 5W-20 averaged 0.5% better than the SAE 5W-30. For the FM comparison the friction-modified oil averaged 0.4% better than the non-friction-modified oil. VM shear stability indicates the expected increase in fuel economy with decreasing shear stability (increasing SSI). The results are statistically compared in Figure 23 using a box and whisker methodology, where the whiskers extending from the plot represent the range of results used in the analyses.

Table 7. Test Sensitivity Matrix Result Summary

Oil No.	Quality Level	Viscosity Grade	FM	VII SSI	FM % Improv.	Vis Grade % Improv	VM % Impact
1	ILSAC	SAE 5W-20	Yes	Higher	--	0.5	--
2	ILSAC	SAE 5W-30	Yes	Higher	--	**Baseline**	0.5
3	ILSAC	SAE 5W-30	Yes	Lower	0.4	--	**Baseline**
4	ILSAC	SAE 5W-30	No	Lower	**Baseline**	--	--

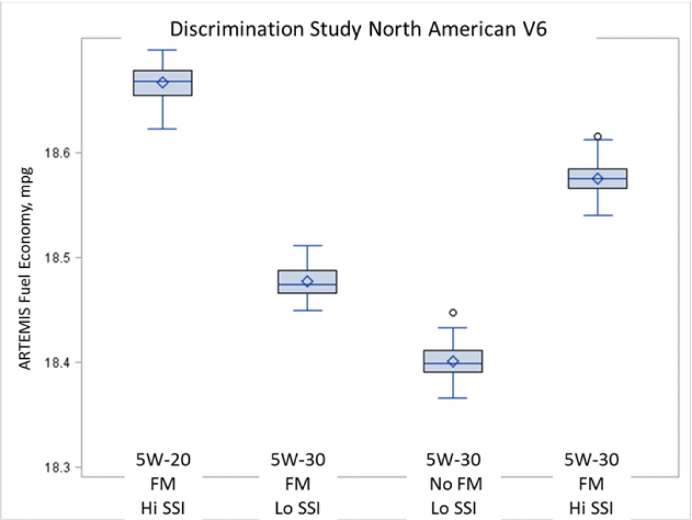

Figure 23. Statistical Study of Sensitivity Data

Vehicle Aging Effects

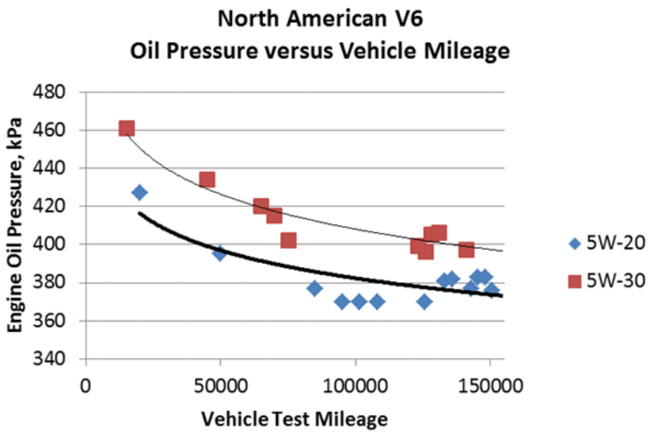

Figure 24. Oil Pressure versus Vehicle Test Mileage

The reader will note that the data summarized in Table 5 show that the SAE 5W-30 oil No. 2 was directionally higher in performance than the two baseline runs on the SAE 5W-20, and this is a reversal from the performance summarized in Table 7 where oil No. 1, the SAE 5W-20 was 0.5% higher. As miles accumulated on this vehicle's engine the authors found that its discrimination of kinematic viscosity changed from when the vehicle had fewer miles. Where the SAE 5W-30 Oil No. 2 performed worse than the 5W-20 baseline at 50,000 miles, it performed better at 150,000 miles. The authors believe engine age and increasing clearances within the engine account for this difference. Starting vehicle odometer mileage for the first matrix was 50,000 while the starting odometer mileage for the second matrix was 140,000 miles. Figure 24 shows the decreasing trend of average oil pressure SAE 5W-20 and 5W-30 oils versus vehicle test mileage for tests conducted during the 150,000 mile period and this supports the assumption that clearances within the engine were likely increasing. Changing journal bearing clearances affect thin-film friction, boundary friction and viscous drag [11].

Correlation with EPA Window Sticker Fuel Economy

The authors were interested in seeing how closely the ARTEMIS test protocol correlates with EPA Window Sticker Fuel Economy [10] (WSFE). WSFE is calculated from the results of five types of controlled laboratory emission tests: The FTP, HFET, US06, SC03 and 20°F FTP. The FTP and HFET have historically been used in 55/45 harmonic average and since 2005 the additional tests account for the factors of aggressive driving, air conditioner use and low-temperature operation. The WSFE numbers shown in Table 8 come directly from the EPA database for these vehicles and are shown as reported - rounded to the nearest whole MPG number. In Table 8 the authors have summarized all tests run on all OEM-recommended viscosity grades on the four vehicles. The data set represents a mixture of technologies, from commercial to research, from friction modified to non-friction modified, at all stages in the vehicle's life, across 24 months of operation. The data set includes 40 separate tests ranging in length from 2500 to 10,000 miles with a combined total of 115,000 miles. The results are tabulated in Table 8 and graphically depicted with their range in Figure 25. The authors are encouraged by the nearly 1:1 correlation and a Y-intercept that is essentially zero. While this is only a sample of four vehicles the authors have other vehicles on-test to expand this range to beyond 50 mpg, including hybrid technology.

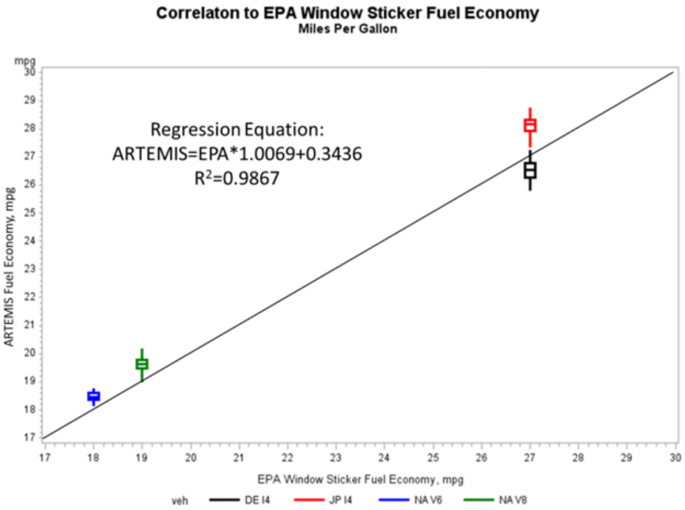

Figure 25. Correlation of ARTEMIS Protocol to EPA Fuel Economy

Table 8. Correlation of ARTEMIS to EPA Window Sticker

Model Year	Country/ Engine	EPA Window Sticker Fuel Economy	ARTEMIS Fuel Economy	Difference, %
2010	NA V6	18	18	0.0%
2010	NA V8	19	20	5.3%
2011	JP I4	27	28	3.7%
2010	DE I4	27	27	0.0%

SUMMARY/CONCLUSIONS

The authors have demonstrated the feasibility of simultaneously aging engine oils and measuring fuel economy under real-world driving conditions using a continuous measurement system and the application of statistical regressions. The value of this type of testing cannot be overstated as it opens the door to the quick and reliable development of OEM and vehicle-specific engine oil fuel efficient formulations that are not possible using standardized engine tests like the Sequence VID. The authors have explained why they chose the European ARTEMIS driving cycle and correlated its results with the US EPA window sticker fuel economy. And while not an expressed objective, the findings provide a mechanism to interpret the differences between oils tested in the Sequence VID and results obtained under real-world driving conditions. The following items are thoroughly discussed and examined:

- A novel and robust chassis dynamometer fuel economy test procedure that can accommodate nearly any vehicle while being operated in a transient mode.
- The utility of the ARTEMIS driving cycle for developing and in-depth understanding of oil-related fuel economy effects
- Correlation of this vehicle-based method with EPA window sticker fuel economy.
- A demonstration of how statistical techniques may be used to reduce the observed variation in vehicle operation associated with outdoor dynamometer testing.
- A demonstration of the impact of vehicle age and engine age on viscosity-related fuel economy.
- Vehicle-based observations about average oil temperature and oil consumption that help form a better understanding of why Sequence VID-aged oils produce an increase in fuel consumption.

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DEFINITIONS/ABBREVIATIONS

ARTEMIS - Assessment and reliability of transport emission models and inventory systems

ASTM - American Society for Testing and Materials

CADC - Common ARTEMIS Driving Cycles

CFR - Code of Federal Regulations

DI - Detergent Inhibitor System

FTP - Federal Test Procedure

FM - Friction Modifier

HFET - Highway Fuel Economy Test

ILSAC - International Lubricant Standardization and Approval Committee

KPH - Kilometers Per Hour
KV - Kinematic Viscosity
MPG - Miles Per US Gallon
MPH - Miles Per Hour
NEDC - New European Driving Cycle
SAE - Society of Automotive Engineers
SRC - Standard Road Cycle
SSI - Shear Stability Index
VII - Viscosity Index Improver
VM - Viscosity Modifier
US EPA - United States Environmental Protection Agency
WSFE - Window Sticker Fuel Economy