Consortium to Develop a New Sequence VID Fuel Efficiency Test for Engine Oils

- Final Report -

October 15, 2008

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1. Executive Summary

Background and Approach For the last 30+ years, it has been recognized that engine oils can play a significant role in improving automotive fuel economy. The original protocol for measurement of engine oil fuel economy was developed in the early 1980's and incorporated the FTP test cycle run in five vehicle types. This protocol was replaced by a dynamometer-based ASTM standard test for evaluating lubricant fuel economy, known as the Sequence VI, in 1985. The Sequence VI was replaced by the Sequence VIA in 1995 as part of the update to the ILSAC GF-2 engine oil standard, and later by the Sequence VIB introduced in 1998 in conjunction with the introduction of the ILSAC GF-3 engine oil standard. Both the VIA and VIB tests used the Ford 4.6L 2V 1994 model year engine because it was believed that this particular modular engine was representative of future engine technology during the mid-to-late 1990s. The VIB test also included a fuel economy measurement for the aged oil (measured after 96 hours of aging), referred to as FEI 2, whereas the VIA had measured fuel efficiency only on new oils (measured after 16 hours of aging). The same VIB test was used in the latest ILSAC engine oil standard, GF-4, which was finalized in January of 2004.

Although the VIB test was being used in qualifying GF-4 oils, the suitability of the VIB for continued use was beginning to be questioned. Test precision was an issue, as well as the age of the engine and the ability of the test to discriminate friction modified from non-friction modified oils to the same degree as found in some other engines. As a result of these concerns, the ILSAC/Oil Committee established a GF-5 Fuel Economy Task Force in January 2005 to oversee the development of FTP data intended to serve as the field correlation database for a new fuel economy test and the development of a new test. In April, the task force recommended that a new VID engine/dynamometer test be developed to measure fuel economy improvement, and in October 2005 it was decided to establish a Consortium built around funding by interested companies to fund the test development effort. API agreed to serve as the Consortium Administrator and prepared an agreement that outlined the proposal for the Sequence VID Consortium. The proposal stipulated that Intertek Automotive Services and Southwest Research Institute would serve as the Consortium contractors. Ten companies ultimately agreed to participate in the Consortium, granting them access to data and information generated during the development of the test and an equal say in the direction of the development effort.

The Scope and Objectives originally adopted by the Consortium for the development of the new test were as follows:

Scope *Develop an engine dynamometer-based fuel economy test for ILSAC GF-5 that will replace the ILSAC GF-4 Sequence VIB fuel economy test. The new test should represent both viscometric and friction modifier oil effects on the fuel economy of current and future North American and Japanese engines.*

Objectives 1) *The test should be responsive to both viscometric and friction modifier effects in oils. 2) Ideally, the test should show improved test precision over the current Sequence VIB fuel economy test. This will be quantified by showing that the new test has a lower standard deviation of fuel economy improvement. 3) The new test should be developed to correlate with new FTP fuel economy vehicle data. Stage weighting/selection will be used to achieve the best correlation with FTP results. The test oils will be the GF-5 Fuel Economy Task Force Matrix Test Oils (A-K, Z), which are distributed by the Test Monitoring Center (TMC) and which are being used in the FTP fuel economy testing that is being conducted.*

As indicated above, a matrix of ten test oils (A-K) was established, representing three different DI chemistries, and consisting of non-friction modified oils of viscosity grades ranging from SAE 0W-20 to 10W-30, and oils containing either an organic friction modifier or a molybdenum-based friction modifier. A baseline SAE 20W-30 oil, Z, was also blended for use in establishing the variation which occurred in each engine. These test oils were used both in developing Federal Test Procedure (FTP) fuel economy data in a number of vehicles to serve as the correlation database and in developing the new VID dynamometer test.

Generation of FTP Data FTP fuel economy data were obtained on a total of 7 vehicles using some or all of these test oils. General Motors supplied data on four vehicles, Ford Motor Co. on two vehicles, and JAMA (the Japan Automobile Manufacturers Association) on one vehicle. Slightly different protocols were used in some of the FTP testing that was conducted in the various laboratories, and different aging conditions and mileages were also used by Ford in its testing. However, all testing consisted of evaluating the fuel economy performance of each oil tested in each vehicle compared with the fuel economy performance of the baseline oil, Z, which was tested both before and after each test oil. The fuel economy testing consisted of running the FTP-75 driving schedule followed by duplicate highway fuel economy tests. Fuel economy values were calculated from the FTP and Highway data based upon a weighting system described in the U.S. Code of Federal Regulations (CFR), Title 40, Parts 86 and 600. City, highway and combined fuel economy values were determined for each oil/vehicle combination using prescribed equations, and the improvements relative to the baseline oil were calculated from similar

FTP testing conducted on the baseline oil before and after each test oil run. This process was repeated following oil aging in the vehicles on chassis dynamometers (2,000 and 6500 miles for the General Motors and Japanese vehicles, and 500 and 5000 miles for the Ford vehicles).

Multiple linear regression analysis was used to estimate the effects of Vehicle Make, Vehicle Unit, Vehicle Odometer Miles, Vehicle Driver, Oil, Oil Miles, and their interactions on the GM Fuel Economy FTP Data. The conclusions from the statistical analysis of the oils' impact on Fuel Economy in the GM Field Trial are presented below.

- There is statistical evidence that the matrix oils are better in Fuel Economy performance than Baseline Oil Z
- There is no statistical evidence that the matrix oils differ from each other in performance
    - Estimated performance range is 0.2 to 0.3 miles per gallon
    - There appears to be more separation of oils under FTP (city) conditions than FFE (highway) conditions
- There is no statistical evidence that lighter viscosity grades offer any Fuel Economy improvement among the matrix oils
- While there is not enough statistical evidence to support the conclusion, it appears that friction modified oils offer a very slight Fuel Economy benefit over non-friction modified oils
- There is no statistical evidence that oils with lower HFRR differ in Fuel Economy performance from oils with higher HFRR
- There is not enough statistical evidence to support a decline in Fuel Economy performance of the matrix oils as they age from 2000 miles to 6500 miles.

Based on these findings, and the realization that direct correlation with the FTP data based on statistically significant results would not be possible, the Consortium agreed to modify Objective Number 3 listed earlier as follows:

> *Develop a VID engine test based on operating conditions mapped proportionally to FTP-75 and Highway Fuel Economy Tests, and which generally agrees with the FTP fuel economy data generated by the Consortium. Other data may be considered, as appropriate. The test should emulate aging observed during mileage accumulation at Xk miles from the*

FTP program, discriminate between Oil Z and the other matrix oils based on viscosity effects, and determine FM effects.

The mileage accumulation distance referred to in the modified Objective Number 3 (Xk miles) was later set at 6500 miles.

Throughout the VID development, a stage-gate process was used to manage the project. Advantages of this process included improved chance of success, ability to focus efforts on the most important outcomes and tasks, ability to identify and evaluate all alternatives at the beginning of the project, ability to identify key decisions and allowing stakeholders to provide guidance at critical decision points. Several stages were defined: Stage 1 included defining the project opportunity statement, objectives, scope, and plans. The deliverables in this stage were the Consortium agreement and initial project plan. This stage completed in 2006. Stage 2 included test scoping and defining alternatives with deliverables of completing the FTP testing and analysis and initial engine set-up, shake down, and scoping. Stage 2 completed in June 2007 with agreement to increase test spending and begin the Sequence VID test development process. Stage 3 included the core of the VID development activities. Deliverables included defining the aging conditions and stage selection. Stage 3 completed in May 2008. Stage 4 included the final prove-out of the test procedure and conditions developed in the first 3 Stages, including a demonstration that the test discrimination and test precision were sufficient to proceed with the precision matrix. Deliverables from this stage were a final recommendation of a new Sequence VID test to the ILSAC/Oil Committee and this research report. Stage 4 was completed in September 2008.

Engine Test Development The engine selected for the development of the Sequence VID test was the General Motors 3.6L V6, Code LY7. The LY7 was selected based upon it being a modern-day engine equipped with 4 valves per cylinder, and a variety of advanced engine technology. It was expected that the LY7 would be produced for many years after the introduction of the Sequence VID test to better ensure engine and parts availability for future testing. The original LY7 calibration that was selected was used in the 2006 Cadillac CTS. However, because of the timing for when a large number of engines could be purchased by OHT (the “Special Parts Supplier” designated by the Consortium), it was necessary to update the engine to the calibration planned for use in the 2008 Cadillac SRX, as discussed in more detail in the body of the report. OHT assisted in making this calibration change, as well as in fabricating several other special parts found necessary to increase the control of the engine and improve the precision of the resulting test. The details of these portions of the VID test development program are also covered in the body of the report.

One of the most important objectives of the VID engine test development effort was to identify potential VID operating conditions that can be run in steady state and provide the best possible discrimination for viscometric and friction modifying properties of oil without a significant deviation from the conditions found in the FTP data. This was accomplished by reviewing the FTP data from the selected 3.6L HF V6 engine, determining the range of conditions available to run in steady state in the current VID stand configuration, and identifying the combinations of conditions available in the VID stand configuration that would best represent the range of conditions seen in the FTP data. Data acquired during FTP testing on Buick-3, with a 3.6L HF V6, was provided by GM and reviewed to identify potential test conditions for the VID test. The analysis included modal analysis, K-Means Cluster Analysis, and Principal Components Analysis of 0.1 second data acquired during all four stages of FTP testing; this consisted of 26,452 data points for each variable. Initial stage selection for the VID test was based on the data reviewed and the known historical effect of speed, load, and oil/coolant temperature on fuel economy. Based on the strong correlation between oil and coolant temperature in the FTP data and the desire to identify stages that provide discrimination, nine stages were initially proposed, covering a range of parameters that accounted for the majority of FTP conditions and was within the capabilities of the current VID stand-engine configuration. Review at the consortium level ultimately resulted in one additional stage being added, making a total of ten stages being selected to go forward for additional testing.

These ten stages were subsequently evaluated in a series of “sense check” tests to determine the responses of various matrix oils in the various stages. Based upon the responses obtained, the members of the Consortium were encouraged that the proposed Sequence VID engine and initial operating conditions would be able to show differences among the oils related to the use of friction modifiers and viscosity grades. “Pseudo ZN/P” values were also calculated for each of the ten stages so that they could be related to the lubrication regime (boundary, mixed, or hydrodynamic) applicable to each stage. Z, the viscosity value in centipoise, was calculated from the engine oil sump temperature and the known kinematic viscosity at 40 and 100 C. For the speed term, N, engine speed in RPM for each stage was used. The manifold absolute pressure (MAP) in kPa, was used as the Load term, P. Calculation of the ZN/P values further enabled the creation of a “pseudo” Stribeck curve, for which the higher ZN/P values represented conditions more hydrodynamic-like in nature, while the lower ZN/P values represented conditions more boundary-like in nature, and the intermediate ZN/P values represented conditions normally associated with the mixed lubrication region of the Stribeck curve. The following table describes the ten stage conditions chosen to represent the FTP operating conditions, and their corresponding “pseudo ZN/P” values calculated as indicated:

Stage	1	2	3	4	5	6	7	8	9	10
Speed, RPM	2000	2000	2000	2000	1500	1500	695	695	695	695
MAP, kPa	34.9	35.5	56.6	55.9	58.1	44.7	35.3	34.7	42.8	40.6
Oil Temp	115	65	115	65	115	80	115	35	115	35
Viscosity at Oil Temp, cSt	8.56	34.6	8.56	34.6	8.56	20.9	8.56	133	8.56	133
Viscosity at Oil Temp, cP	6.88	29.1	6.88	29.1	6.88	17.4	6.88	115	6.88	115
ZN/P	394	1642	243	1043	178	583	136	2304	112	1969

Before these stage conditions could be evaluated further, it was necessary to determine the appropriate oil aging conditions and the number of hours to age the oil. To do this, used oil samples were taken under various steady state engine conditions every 25 hours and tested for DIR Oxidation, Viscosity at 40°C and HFRR. The results from these tests were compared with the used oil results from the GM FTP tests across vehicles and for FTP tests for one of the vehicles, a Buick Lacrosse, which utilizes the same engine as was chosen for VID development. Results were compared in a series of three experiments, including the constraints that aging test time should not exceed 100 hours, and that the test conditions should not deviate significantly from conditions occurring within the FTP spectrum of operating conditions. One of the steps taken to accomplish these objectives was to reduce the oil fill by 10% as a way to increase aging severity while still running at conditions similar to those used for FTP tests. Based on this analysis by the statistical group of the three experiments conducted, the Consortium agreed that the Sequence VID test oil aging conditions would be 120°C oil temperature, 110 Nm load and 2250 rpm for a total test aging time of 100 hours (not including time for actual fuel economy test). This set of conditions simulated aging of the oil under FTP mileage accumulations for a period of 6500 miles, which as indicated earlier had been chosen by the Consortium as the mileage accumulation distance for Objective Number 3.

At this point, a matrix was designed with the purpose of providing data to facilitate a decision to reduce the number of stages (Matrix II in this report). When this testing uncovered problems related to test repeatability and reproducibility, a number of changes to the test stands and the test engine were made. These were subsequently evaluated in another matrix (Matrix III in this report). Extended aging was not included in any of this testing so as to conserve funds for future testing.

The problems investigated in Matrices II and III (as detailed in the body of the report) included the lack of discrimination at the idle test stages, possible carryover effects, agreement between the two test laboratories, concerns regarding test repeatability, and the unknown relationship between the Matrix II and GM fuel economy test data. To counteract these problems, changes were made in the ECM and the throttle control mechanism of the engine. The revision to the ECM was to change from a variable spark timing at idle conditions (stock condition) to a fixed spark timing at idle. The change that was made in the throttle control mechanism was the implementation of a duel throttle or DT system to improve the degree of control at part throttle conditions. The reasons leading up to this change are detailed in the report. The effect of conducting a double baseline oil test before each candidate oil test (i.e., BLB1 and BLB2) was also evaluated, and while there was not enough statistical evidence to justify the use of double baselines to reduce variability, it was agreed by the Consortium members that this effect should be further evaluated in the final Prove-out Matrix.

Once these issues had been addressed, the Consortium agreed to reduce the number of stages in preparation for the final Prove-out Matrix. The statistical criteria used for the stage reduction and selection of the final stages were based on correlation and discrimination (since both were part of the original test development objectives). The Consortium members reviewed the GM fleet and Matrix II fuel economy discrimination and correlation analysis results to identify the stages that should be eliminated. Based on a discussion of the analysis results, a consensus was reached to drop stages 1, 2, 6, and 10. The rationale for eliminating these stages was:

- Stage 6 lacked discrimination for any of the candidate test oils.
- Stages 1 and 3 had similar discrimination, but Stage 3 correlated better with the GM fleet test data.
- Although Stages 8 and 10 had similar correlations to the GM fleet test data and neither provided statistical discrimination between the candidate test oils, Stage 8 had more favorable properties than Stage 10.
- Stage 4 was retained instead of Stage 2 because the discrimination and correlation for Stage 4 was better than that for Stage 2.

The retained stages for follow-on testing in Matrix IV therefore included 3, 4, 5, 7, 8, and 9. These stages corresponded to 3 high-load and high-speed and 3 low-load and low-speed conditions.

The purpose of the Prove-Out Matrix was to demonstrate that the test run under final conditions (number of stages, aging, engine test hardware and protocols) was capable of discriminating fuel economy performance between oils differing in viscometric properties or friction modifying capabilities. Therefore, oils were selected to test these capabilities - in particular, Oils A, B and E were selected as the test oils. By doing this, the FEIs of Oils B and A could be compared to determine the FM effect, and those of Oils A and E could be compared to determine the viscosity grade effect. Having all oils from one supplier allowed for a minimum number of tests to be performed given a number of repeats as each of the oils had the same DI package and, therefore, could use the same "control" oil. The test matrix design was composed of 16 tests performed in two labs (8 tests per lab). The "control" oil (Oil A) was tested 6 times and Oils B and E were each tested 5 times.

The Statistical Group (SG) analyzed the Prove-out Matrix data with the objective of determining discrimination and at the same time recommending the final baseline and stage weighting to be used in the VID procedure. Several analyses were presented by the various statisticians, and the SG came up with a number of agreements. The most significant of these were:

- Significant fuel consumption (FC) and fuel economy improvements (FEI) differences and baseline (BL) variability exist between the two test laboratories (SwRI and IAR).
- No friction modifier (FM) carry-over was identified. However, consecutive BL FC differences appear to be oil dependent.
- All three BL runs (i.e., BLB1, BLB2 and BLA) are required for minimum RMSE and maximum discrimination.
- Baseline Weighting should be in the following ranges:
    - FEI1: 0-20 BLB1, **80 BLB2** & 0-20 BLA
    - FEI2: **0 BLB1**, 10-50 BLB2 & 50-90 BLA
- With regard to Discrimination:
    - Practical stage weights exist that discriminate FM and viscosity (VG) for FEI1
    - The same stage weights discriminate for VG for FEI2, while the FM effect in FEI2 is directionally correct
- Guidelines for oil pressure, MAP, and/or baseline fuel consumption should be established for test validity (BLB1, BLB2), and interpretability (BLB2, BLA) before the precision matrix.
    - BLB1-BLB2 FC shift: -0.20% to 0.40%
    - If outside range, run a third baseline test (BLB3) and compare with BLB2

However, the Statistics Group could not completely agree on BL weights or stage weights.

In subsequent discussion within the Consortium, it was agreed that the baseline weightings should be as follows:

- FEI1: 0% BLB1, 80% BLB2, 20%BLA
- FEI2: 0% BLB1, 10% BLB2, 90%BLA

The stage weightings should be those corresponding most closely to the FTP operating conditions. Those weightings are:

- Stage 3: 30%
- Stage 4: 3.2%
- Stage 5: 31%
- Stage 7: 17.4%
- Stage 8: 1.1%
- Stage 9: 17.2%

Based on the Prove-out Matrix results and analysis, these stage weightings provide statistical discrimination for FM and viscometric effects in FEI1 (p-Value of 0.025 and 0.015, respectively, with a RMSE at 0.225), and viscometric effects in FEI2 (p-Value of 0.029 with a RMSE of 0.264). The FM effect in FEI2 was directionally correct (p-Value of 0.279). These baseline and stage weightings, combined with the final test procedure developed for the VID test, represent the final recommendations of the Consortium for a VID fuel efficiency test.

2. Purpose

The purpose of the effort described in this report was to develop a dynamometer-based engine test to measure the fuel efficiency improvement offered by an engine oil. The intent was to develop Federal Test Procedure (FTP) fuel economy data in a number of vehicles to serve as the correlation database for developing the new test. The new test was intended to replace the existing Sequence VIB fuel efficiency test, to show discrimination of both viscometric and friction modifier effects, and to show improved precision over the Sequence VIB test.

3. Conclusions and Recommendations

The following conclusions were reached in this work:

1) Given the number of repeat FTP fuel economy tests conducted and the precision of the FTP fuel economy tests, it was not possible to obtain data which showed

statistical discrimination between test oils ranging in viscosity from SAE 0W-20 to SAE 10W-30 based on either viscometric or friction modifier effects. The test oils could be differentiated from a high viscosity baseline oil (SAE 20W-30), but not from each other.

2) While there was not enough statistical evidence to support the conclusion, it appeared that friction modified oils offer a very slight fuel economy benefit over non-friction modified oils.

3) The Consortium was successful in developing an engine dynamometer test, based on the General Motors 3.6L V6 engine (Code LY7), which met the objectives set forth by the Consortium of:

   a. *being responsive to both viscometric and friction modifier effects in oils.*
   b. *showing improved test precision over the current Sequence VIB fuel economy test.*
   c. being *based on operating conditions mapped proportionally to FTP-75 and Highway Fuel Economy Tests, and which generally agree with the FTP fuel economy data generated by the Consortium.*

4) Based on achieving these three objectives, the final VID test developed by the Consortium consisted of six discrete steady state conditions or stages weighted as follows:

   - Stage 3: 30%
   - Stage 4: 3.2%
   - Stage 5: 31%
   - Stage 7: 17.4%
   - Stage 8: 1.1%
   - Stage 9: 17.2%

5) The corresponding baseline weightings decided upon were:

   - FEI1: 0% BLB1, 80% BLB2, 20%BLA
   - FEI2: 0% BLB1, 10% BLB2, 90%BLA

Recommendation:

The VID Consortium recommends, based on the data generated during test development and in the final Prove-out Matrix, that 1) a new Sequence VID fuel economy test to determine the fuel efficiency of engine oils be finalized in a Precision Matrix to be conducted by ASTM, 2) the new Sequence VID test incorporate the six stages identified in this work weighted as follows:

- Stage 3: 30%
- Stage 4: 3.2%
- Stage 5: 31%
- Stage 7: 17.4%
- Stage 8: 1.1%
- Stage 9: 17.2%

And 3) the corresponding baseline weightings be:

- FEI1: 0% BLB1, 80% BLB2, 20%BLA
- FEI2: 0% BLB1, 10% BLB2, 90%BLA.

4. Introduction

4.1. Improving vehicle fuel economy is a major goal for automotive manufacturers, both to meet government mandated fuel economy requirements and to satisfy consumers' desires for improved fuel efficiency. One of the methods of improving fuel economy is through the use of fuel efficient engine oils. Thus, as part of the International Lubricant Standardization and Approval Committee (ILSAC) engine oil category requirements, a fuel efficiency requirement is included in the current ILSAC category, ILSAC GF-4, and one is planned for inclusion in the next category, GF-5. The test used for quantifying the fuel efficiency of engine oils is the Sequence VI Test. GF-5 is under development and planned for introduction in the fourth quarter of 2010 and is expected to include an updated Sequence VI Test, the Sequence VID. The US EPA requires that automobile manufacturers use engine oils for emission certification and fuel economy testing that are readily available to consumers, and that these oils are representative of the general marketplace oils in regard to fuel efficiency. To judge the suitability of these oils the EPA uses the fuel efficiency limit requirements contained within the current ILSAC GF category. Therefore, the development and adoption of a suitable test for measuring the fuel efficiency of engine oils is important for automobile manufacturers to assist in selection of appropriate oils to help meet their fuel economy goals, but also to provide a common test method that EPA can use for approval of oils for emission and fuel economy certification.

4.2. **History** In the mid 1970's, the lubricants industry recognized that engine oils could play a significant role in improving automotive fuel economy. The auto industry was required to run a Federal Test Procedure (FTP) for emissions purposes on all new vehicle models to certify them for sale in the US. The original protocol for measurement of engine oil fuel economy was developed in the early 1980's and incorporated the FTP test cycle run in five vehicle types. This ASTM test method (ASTM 5-Car Test) served as the industry standard for the measurement of engine oil effects on vehicle fuel economy until the mid 1980's.

In 1979, ASTM had begun development of a laboratory dynamometer-based engine test procedure in an effort to improve precision, plus reduce test time and cost relative to the 5-car procedure. This effort led to the introduction of the dynamometer-based ASTM standard test for evaluating lubricant fuel economy, known as the Sequence VI, in 1985. This test used a 1982-84 model year 3.8L Buick carbureted engine. The Sequence VI was the first dynamometer-based ASTM test designed to measure the fuel efficiency performance of engine oils under conditions analogous to the Federal Test Procedure. The Sequence VI consisted of two steady state operating conditions, one to emphasize viscometric effects and one to emphasize boundary effects. Results from the two test conditions were weighted (65% / 35%, respectively) as this gave the best correlation with 5-car results.

The Sequence VI was replaced by the Sequence VIA in 1995 as part of the update to the ILSAC GF-2 engine oil standard. This test type used the Ford 4.6L 2V 1994 model year engine which was selected as the desired engine for this test method because it was believed that this particular modular engine was representative of future engine technology during this time period. The Sequence VIA test utilized six steady state test conditions that simulated the operation of the Ford 4.6L engine running in an FTP cycle. The test stage weightings were selected based on a modal analysis of the FTP operation.

The next generation fuel efficiency test was the Sequence VIB introduced in 1998 in conjunction with the introduction of the ILSAC GF-3 engine oil standard. This test used the same engine as the Sequence VIA. The major revisions from the Sequence VIA were the inclusion in the procedure of 80 hours of aging at 2,250 RPM and 135°C oil temperature to reflect 6400-9600 km vehicle aging of the lubricant, addition of a new stage 1 and elimination of stages 3 & 6. It also included a fuel economy measurement for the aged oil, referred to as FEI 2 (FEI 1 was retained as the measurement of "new" oil fuel efficiency improvement, measured after 16 hours of aging).

The same VIB test was used in the latest ILSAC engine oil standard, GF-4. An attempt was made during the development of GF-4 to extend the 80 hour aging period to promote enhanced fuel efficiency retention. This new procedure was to be designated as

Sequence VIC. However, when no differences were found between the FEI 2 values after 80 and 120 hours of aging for a number of oil chemistries, the effort to develop a Sequence VIC test procedure was abandoned and the Sequence VIB test with 80 hours of aging was retained for ILSAC GF-4.

5. Consortium Process

5.1. Reasons for Consortium The ILSAC/Oil Committee established a GF-5 Fuel Economy Task Force in January 2005 to oversee the development of FTP data intended to serve as the field correlation database for a new fuel economy test and the development of a new test. Both bench and engine sequence tests were to be considered by the task force. At the April 2005 ILSAC/Oil meeting, the task force recommended that a new engine/dynamometer test be developed to measure fuel economy improvement. The task force named this test, intended as a successor to the Sequence VIB fuel efficiency test, the Sequence VID. In October 2005, ILSAC recommended to ILSAC/Oil that the best approach for developing the Sequence VID would be to establish a consortium to fund the test development effort, and requested that API serve as the Consortium Administrator. Limited resources within the ILSAC-member companies prevented any one company from undertaking the effort. Several possible funding mechanisms were considered, and API sent out a survey in late October 2005 to determine the interest level in various possible Consortium funding options. Based on the input received from the survey and follow up discussions with several of the respondents, the GF-5 Fuel Economy Task Force decided to proceed with a Consortium proposal built around funding by interested companies.

5.2. Description of Consortium Agreement API prepared an agreement that outlined the proposal for the Sequence VID Consortium, the rules of participation, and the levels of entry. The final agreement is included as Appendix A. The rules included provisions for confidentiality of data and information generated by the Consortium and a requirement for regular release of information to interested organizations such as ASTM and SAE. The agreement also stipulated that Intertek Automotive Services and Southwest Research Institute would serve as the Consortium contractors.

API distributed the agreement to interested companies and trade associations for their consideration. Those choosing to participate signed a copy of the agreement and returned it to API for compilation with the other signed agreements. Each agreement was signed in multiple counterparts that together constituted a single agreement.

5.3 **Make-up of Consortium** Ten companies agreed to participate in the Consortium. Eight (Shell, Chevron, ExxonMobil, Lubrizol, Afton, R.T. Vanderbilt, Oronite, and Infineum) joined as cash-contributing participants by committing to pay $300,000 each for entry into the Consortium, and two (Ford and General Motors) joined as original equipment manufacturer participants by agreeing to provide FTP field correlation data. Membership in the Consortium granted each member access to data and information generated during the development of the test and an equal say in the direction of the development effort. Each member had one equally-weighted vote.

5.4 **Funding – Budget** The Consortium raised $2.4 million for the development of the Sequence VID. API agreed to serve as Secretary to the Consortium and act as contracting authority with the test labs. The budget for the Consortium effort is summarized in Appendix B.

5.5 **Reporting Structure** The Sequence VID Consortium reported to the GF-5 Fuel Economy Task Force, a group established by the ILSAC/Oil Committee. However, the Consortium Chair routinely reported test development status to ILSAC/Oil and interested organizations such as ASTM and SAE.

5.6 **Scope and Objectives** The GF-5 Fuel Economy Task Force charged the Consortium with developing an engine dynamometer-based fuel economy test for ILSAC GF-5 that would replace the GF-4 Sequence VIB fuel economy test. The new test was intended to represent both viscometric and friction modifier oil effects on the fuel economy of current and future North American and Japanese engines. The Scope and Objectives originally adopted by the Consortium for the development of the new test were as follows:

> **Scope** *Develop an engine dynamometer-based fuel economy test for ILSAC GF-5 that will replace the ILSAC GF-4 Sequence VIB fuel economy test. The new test should represent both viscometric and friction modifier oil effects on the fuel economy of current and future North American and Japanese engines.*
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> **Objectives** 1) *The test should be responsive to both viscometric and friction modifier effects in oils. 2) Ideally, the test should show improved test precision over the current Sequence VIB fuel economy test. This will be*

quantified by showing that the new test has a lower standard deviation of fuel economy improvement. 3) The new test should be developed to correlate with new FTP fuel economy vehicle data. Stage weighting/selection will be used to achieve the best correlation with FTP results. The test oils will be the GF-5 Fuel Economy Task Force Matrix Test Oils (A-K, Z), which are distributed by the Test Monitoring Center (TMC) and which are being used in the FTP fuel economy testing that is being conducted.

These Scope and Objectives were modified at a meeting of the Consortium members on July 11, 2007, when it became apparent based on the results from the FTP Testing work that direct correlation with the FTP data based on statistically significant results would not be possible. At that meeting, the Consortium agreed to modify Objective Number 3 as follows:

Develop a VID engine test based on operating conditions mapped proportionally to FTP-75 and Highway Fuel Economy Tests, and which generally agrees with the FTP fuel economy data generated by the Consortium. Other data may be considered, as appropriate. The test should emulate aging observed during mileage accumulation at Xk miles from the FTP program, discriminate between Oil Z and the other matrix oils based on viscosity effects, and determine FM effects.

The mileage accumulation distance referred to in the modified Objective Number 3 (Xk miles) was later set at 6500 miles.

6. Test Oils

6.1. Selection Process The test oils used in the Sequence VID Development program were, for the most part, the same oils previously selected by General Motors for FTP fuel economy test work. Following discussions within ILSAC early in 2005, General Motors made the decision and commitment to conduct FTP testing in a number of vehicles utilizing a number of oils. These FTP data were to serve as the correlation base for developing a new engine oil fuel efficiency test that could demonstrate differences among viscosity grades and the effectiveness of friction modifiers for the ILSAC GF-5 standard.

In selecting the oils to be used in the FTP test program, General Motors contacted each of the four major additive suppliers and asked if they would be willing to supply oils for the program and their recommendations for test oil properties. Based on the input received, two additive companies were selected to supply test oils. One company would supply three SAE 5W-20 viscosity grade oils containing the same DI package; one with no friction modifier, a second one with an organic friction modifier, and a third one with a molybdenum friction modifier. It was decided to use oils containing only an organic or a molybdenum friction modifier to try to separate the effects of these types of friction modifiers on fuel efficiency, even though it was recognized that many companies use a combination of the two types of friction modifiers in their formulations. The first company was also asked to supply an SAE 5W-30 and an SAE 10W-30 oil containing the same DI package with no friction modifier (and later an SAE 0W-20 oil with no friction modifier), as well as a baseline oil – nominally an SAE 10W-30 oil without a viscosity modifier – also with the same DI package. This baseline oil, because of viscometric constraints, turned out to be an SAE 20W-30 oil. A flush oil containing five times the amount of detergent in the baseline oil was also provided for flushing the engines between test oils.

The second additive company was asked to provide three SAE 5W-30 oils containing a second DI package – one with no friction modifier, a second one with an organic friction modifier, and a third one with a molybdenum friction modifier. The intent was for these three oils to provide a second DI chemistry and a comparison between SAE 5W-20 and SAE 5W-30 oils containing friction modifiers.

These eight oils formed the core matrix of test oils. Two additional oils, containing a third DI chemistry (designated as DI-3), were added later in the program at the request of ILSAC to represent Japanese initial fill chemistries, bringing the total number of oils to ten. These additional oils, an SAE 0W-20 and an SAE 5W-20, were supplied by JAMA, and contained a molybdenum friction modifier at a higher Mo concentration level than either DI-1 or DI-2. These ten matrix test oils, which are shown in Table 1, were subsequently agreed to by the Fuel Economy Task Force of the ILSAC/Oil Committee, and later by the Sequence VID Development Consortium, as the Test Oil Matrix to be used in the development of the Sequence VID Engine Oil Fuel Efficiency Test.

Table 1. Test Oils

DI Package –1	
A	5W-20 (No FM)
B	A + Organic FM-1
C	A + Moly-FM-1 (200 ppm Mo)
D	A as 5W-30 (No FM)
E	A as 10W-30 (No FM)
L *	A as 0W-20 (No FM)
F	Z + 5X Detergent
Z	Baseline Oil

DI Package –2	
G	5W-30 with DI-2 (No FM)
H	G + Organic FM-2
I	G + Moly-FM-2 (600 ppm Mo)

DI Package –3	
J	0W-20 + Moly-FM-3 (1000 ppm Mo)
K	5W-20 + Moly-FM-3 (1000 ppm Mo)

*Oil L added during test development

- **Matrix of ten (initially) test oils assembled covering range of viscosities, types, and levels of friction modifiers**
- **Baseline Oil (Z) SAE 20W-30, No VM, No FM**
- **Flush Oil - Baseline Oil with 5X Detergent**

Both additive suppliers (i.e., the two additive suppliers chosen originally) were asked to blend their oils to be "GF-4 capable." That is, it was intended that each of the oils would pass the GF-4 performance tests, if they were to be tested. The only caveat to this was that each additive supplier was allowed to select the phosphorus level of their test oils. This was permitted because the phosphorus level being proposed for ILSAC GF-5 at the time was uncertain, there being some discussion of a 0.05% P maximum, and some discussion of retaining the GF-4 maximum of 0.08% P maximum.

For the ten test oils, targets were established for both the high-temperature, high-shear viscosity at 150°C, and the friction coefficient by the HFRR procedure. These targets, as shown in Table 2, were established to provide an acceptable range for these oil properties as they had been tied to fuel efficiency from previous studies. All ten of the original test oils, the SAE 0W-20 oil added later (Oil L), as well as the baseline oil (BL) and the flush oil (FO) were sent to the ASTM Test Monitoring Center which had agreed to handle the control and distribution of the oils for the Test Development Consortium.

6.2. Oil Characteristics Table 3 shows the final viscometric properties for the test oils. Table 4 shows the base oil properties for the test oils. Except for Oils J and K, all of the original matrix oils were blended from Group II base oils. Oils J and K were blended using mixtures of Groups III and IV, and Groups I and III, respectively.

Table 2. Test Oil Matrix – Viscosity and Friction Coefficient Targets

Decreasing Friction Coef →

↑ Decreasing Viscosity

		J [2.6, 0.06]
		K [2.6, 0.06]
A [2.6, 0.12]	**B** [2.6, 0.09]	**C** [2.6, 0.06]
G [2.9, 0.12]	**H** [2.9, 0.09]	**I** [2.9, 0.06]
D [2.9, 0.12]		
E [3.2, 0.12]		
Z [3.7, 0.12]		

[ ] = [HTHS @ 150C, HFRR friction coefficient] nominal values

Table 3. Test Oil Properties

Oil Code	DI Package	SAE Viscosity Grade	Friction Modifier	KV40, cSt	KV100, cSt	HTHS at 100°C, cP	HTHS at 150°C, cP	CCS, cP
VID-A	1	5W-20	none	45.29	8.06	5.82	2.53	5760 (-30°C)
VID-B	1	5W-20	Organic	44.33	7.92	5.74	2.51	6360 (-30°C)
VID-C	1	5W-20	Mo-containing	45.06	8.11	5.84	2.54	6000 (-30°C)
VID-D	1	5W-30	none	56.07	9.59	6.37	2.88	5790 (-30°C)
VID-E	1	10W-30	none	71.40	10.83	7.53	3.21	5920 (-25°C)
VID-G	2	5W-30	none	61.14	10.55	6.84	3.05	5420 (-30°C)
VID-H	2	5W-30	Organic	61.42	10.47	6.84	3.03	5410 (-30°C)
VID-I	2	5W-30	Mo-containing	61.54	10.59	6.73	3.06	2980 (-25°C)
VID-J	3	0W-20	Mo-containing	41.14	9.36	5.39	2.51	5140 (-35°C)
VID-K	3	5W-20	Mo-containing	41.84	8.66	5.66	2.59	4050 (-30°C)
VID-L	1	0W-20	none	45.84	8.78	5.54		5200 (-35°C)
VID-BL	1	20W-30 (No VM)	none	102.00	12.06	9.88	3.70	6530 (-15°C)
VID-FO	1 + 5X Detergent	20W-40 (No VM)	none	114.70	13.26	10.70	4.10	7100 (-15°C)

Note: All Matrix Oils, other than J and K blended using Group II Base Oils

Table 4. Sequence VID Matrix Oils – Base Oil Properties

Matrix Oil	A	B	C	D	E	F	G	H	I	J		K		L		Z
API Base Oil Group	II	II	II	II	II	II	II	II	II	III	IV	I	III	II	II	II
Saturates, wt %	95.4	95.4	95.4	95.4	95.9	96.2	94	94	94	99.7	99.7	72.4	98.7	95.4	98.1	96.2
Sulfur, wt %	0.001	0.001	0.001	0.001	0.001	0.001	<0.005	<0.005	<0.005	<0.01	<0.01	0.14	<0.01	0.001	<0.001	0.001
Viscosity Index	116.7	116.7	116.7	116.9	111.7	99.6	116	116	116	121	123	102	119	116.7	112	99.4

Table 5. Baseline Oil Comparison

Property	HR	BC	BL
Applicable Test	5-Car and Sequence VI	Sequence VIA and VIB	Sequence VID
SAE Viscosity Grade	20W-30	5W-30	20W-30
KV100, cSt	9.5	10.3	12.06
CCS, cP	6000 at -20°C	3350 at -25°C	6690 at -15°C
Sulfated Ash, %	0.85	1.2	0.78
Zinc, %	0.13	0.13	0.05
Phosphorus, %	0.12	0.12	0.05
Magnesium, %	0.13	0	0
Calcium, %	0	0.29	0.21
Molybdenum, %	0	0	0
Sodium, %	0	0	0
Base Oil	Group I	Groups IV and V	Group II
API Performance Category	SE	SH/SJ	SM
VM Type	none	none	none

Note:
HR refers to High Reference
BC refers to Baseline Calibration
BL refers to BaseLine

Table 5 shows a comparison of properties of the baseline oil BL with those of the baseline oil used in the original 5-Car and Sequence VI test, as well as the baseline oil used in the Sequence VIA and Sequence VIB tests.

Figure 1 shows the friction coefficients as measured by the HFRR method at various temperatures for the fresh (unaged) oils. HFRR data on the same oils after accumulating 2000 miles and 6500 miles will be shown later in the report. As noted in Table 2, Oils C, I, J and K were targeted to have an HFRR value at 140°C of 0.06. Oils B and H were targeted to have values of 0.09, and Oils A, D, E, G, and Z were targeted to have values of 0.12. While some of the final blends of the oils had values slightly higher than the targeted values, in general the oil matrix achieved the desired spread in frictional properties as measured by HFRR.

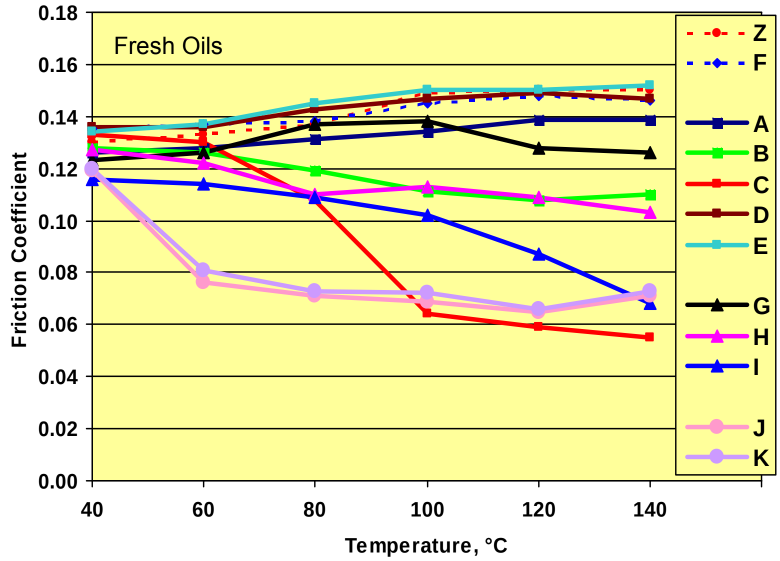


Figure 1. Friction Coefficients of VID Matrix Oils using HFRR

6.3. Used Oil Analyses As the FTP program progressed, it was agreed in a meeting of the two suppliers of DI packages 1 and 2 and General Motors personnel, that the analyses indicated in Table 6 would be performed on the oil samples by Intertek Automotive Research, and that Southwest Research Institute would perform HFRR analyses on the oil samples at the conditions indicated in Table 7. Protocols were established for the volumes of samples to be taken at each interval during the FTP testing, to accommodate the analyses required.

Table 6. Oil Analysis Procedures

Test	Procedure	Notes
FTIR	ASTM E168	Oxidation peak height
Kinematic Vis at 40C	ASTM D445	
Kinematic Vis at 100C	ASTM D445	
HTHS at 100C	ASTM D4683	
HTHS at 150C	ASTM D4683	Only on NEW, FRESH, and 6.5K-USED samples
TAN	ASTM D664	
TBN	ASTM D4739	
Elementals	ASTM D5185	
CCS	ASTM D5293	
Fuel Dilution	ASTM D3525	
Water Dilution	Karl Fischer	Only on 6.5K-USED samples

Table 7. HFRR Friction Test Conditions

Parameter	Conditions	Notes
Temperatures	40, 60, 80, 100, 120, 140 °C	
Speed of ball	20 Hz	
Ball path	1 mm	
Load	400g (~4N)	
Time at each Temp	10 minutes	
Test Specimens	Standard disk and ball specimens	PCS can supply 200 disks and balls from same batch of material
Ball	- AISI-E 52100/535A99 - Hardness : 58-66 Rockwell C - Roughness : Ra < 0.050 microns	
Disk	- AISI-E 52100/535A99 - Hardness : 190-210 Hv30 (~12 Rockwell B) - Roughness : Ra < 0.020 microns	

7. Vehicle Testing

7.1. General Motors Vehicle Testing As part of the development of the Sequence VID test, GM agreed to supply vehicle fuel economy comparisons of the Sequence VID Matrix oils using two vehicles. Based upon the expectation that additional vehicles could be tested with the matrix oils, without adding substantially to the test timeline, if testing and mileage accumulation could be coordinated, GM also agreed that additional vehicle testing would be made available to the Consortium to the extent that this additional vehicle testing would not interfere with the original commitment of data from two vehicles.

Four different vehicles equipped with four different engines were selected for use by GM. These four original vehicles were tested for fuel economy response to engine oil formulation on fuel economy to determine which vehicles would be selected for inclusion in the FTP testing of the matrix oils. In addition to the original four vehicles, a fifth vehicle, a Buick LaCrosse, was added to the initial evaluation series for reasons explained below. The five vehicles are listed in Table 8. The five engines listed in Table 8 are all equipped with roller followers except for the Saab which uses a slider follower configuration in the valve train mechanism.

Table 8. GM Vehicles used in Initial Evaluation

Vehicle Make	Vehicle Model	Engine Description
Pontiac	G6	3.5L V6 Code LX9
Cadillac	DHS	4.6L V8 Code L37
Chevrolet	SSR	3.5L V8 Code LS1
Saab	9.5 Aero Turbo	2.3L L4 Turbocharged
Buick	LaCrosse	3.6L V6 Code LY7

Two engine oils, previously used in a study of engine oil fuel efficiency (Tseregounis et al., ***Engine Oil Effects on Fuel Economy in GM Vehicles – Separation of Viscosity and Friction Modifier Effects,*** SAE 982502, October, 1998) were used to evaluate the responsiveness of the five vehicles. One of the oils was an SAE 5W-30 labeled as Oil DD, and the second oil, Oil BB, was Oil DD with a Molybdenum-containing friction modifier added to it to equal about 1000 ppm of Mo. The vehicles were run in FTP/Highway tests that compared Oil DD to Oil BB. The testing consisted of four complete FTP/Highway tests for each vehicle/oil combination. The testing did not include any mileage accumulation on either of the test oils, other than those miles accumulated during the actual fuel economy testing. Results of those comparisons are shown in Table 9.

Table 9. Percent Fuel Economy Improvement in GM Vehicles - Oil DD vs. Oil BB

Vehicle	City	Highway	Combined 55/45
Pontiac	2.48	3.90	2.91
Cadillac	1.48	2.45	1.79
Chevrolet	0.41	1.96	0.95
Saab	0.41	0.89	0.56
Buick LaCrosse	1.16	2.30	1.48

Based upon the results in this initial study, the Pontiac G6 and the Cadillac DHS were selected as GM's primary vehicles. Another reason for inclusion of the Pontiac G6 was that, at that time GM, expected to propose the LX9 used in the Pontiac G6 as the Sequence VID engine. Subsequently, GM decided to recommend the use of the 3.6L V-6 (Code LY7) engine that was used in the Buick LaCrosse for use in the Sequence VID, and the Cadillac was dropped from the vehicle testing program. GM decided that the Chevrolet SSR and the Saab 9.5 Aero would be included in the vehicle evaluation of the Sequence VID Matrix oils as time and equipment allowed. After the full test program was begun, GM decided that it would be unable to run all of the test oil/vehicle combinations in the time frame originally planned. To eliminate that issue, two additional vehicles were added to the program, a second Buick LaCrosse, and a second Pontiac G6. With the additional two vehicles, all of the matrix oils would be run in the Buick LaCrosse model and the Pontiac G6 model, in addition to the oils run in the SSR and the Saab. Table 10 shows which oils were tested in each of the vehicles. In addition to the six vehicles listed in Table 10, a third Buick LaCrosse was used for measuring and recording various engine and vehicle parameters during FTP and Highway tests.

Table 10. GM Vehicle/Oil Combinations Tested

Vehicle	Oils Evaluated
Buick LaCrosse-1	A, B, C, D, E, I, J
Buick LaCrosse-2	C, E, G, H, I, J, K
Pontiac G6-1	A, B, C, D, E, G, I
Pontiac G6-2	C, E, G, H, I, J, K
Chevrolet SSR	A, B, C, D, E, G, H, I, J, K
Saab 9.5 Aero	A, B, C, D

Prior to the beginning of the test program, the vehicles had been broken in under normal day-to-day customer driving to about 5,000 miles or greater. Each of the vehicles was examined by technicians to ensure that all components were functioning properly. Thermocouples were installed in the engine oil drain plug for each of the vehicles. The thermocouple tip extended one-half inch past the end of the drain plug. A thermocouple was also inserted into the engine coolant at the junction of the coolant hose and top of the engine radiator. Fuel lines were installed on the vehicle to provide connections to the Pierburg fuel meter.

GM Test Facility Description All of the vehicle preparation, mileage accumulation and testing of the GM vehicles was done at the GM Milford Proving Ground. The Milford PG is a nearly 4,000 acres site located about 40 miles northwest of Detroit containing 132 miles of test roads and more than 106 buildings. The vehicle fuel economy test work was done at the Research and Development facility at the PG. All of the fuel economy testing was done using one 48" single-roll Burke-Porter chassis dynamometer. The dynamometer test room is temperature and humidity controlled. The soak area for overnight vehicle storage is also temperature controlled. Fuel economy determinations were made using Pierburg fuel meters. One fuel meter was used for all of the GM vehicles except for the Saab, which required a fuel meter of a different configuration because the Saab used a recirculating fuel injection system. The other GM vehicles use a non-recirculating fuel injection system. Most fuel economy test programs run at the GM R&D facility are designed to use only one driver for all testing; however, in a test program as large as the vehicle testing for the Sequence VID development, it was not possible to limit the driving to one individual. To the extent possible, one driver was responsible for driving the fuel economy tests. When that was not possible, a second driver was used. Differences between the drivers were noted, and as described later in the report, those differences were accounted for in the fuel economy comparisons.

Mileage Accumulation Mileage accumulation was accomplished using Labeco mileage accumulation dynamometers. The driving schedule for the mileage accumulation is shown in Figure 2. Average speed for the mileage accumulation was about 30 miles per hour, and had a maximum speed of about 70 miles per hour. During mileage accumulation the drive axle tires for each of the vehicles were swapped with the non-driving axle tires to ensure that the tires used during the actual fuel economy testing did not have to be replaced during the entire test program. In the case of the Chevrolet SSR a separate set of drive axle tires and wheels were purchased and used for mileage accumulation since the rear tires (drive axle) are a different size than the front tires.

Test Schedule and Fuel Economy Calculations The fuel economy testing consisted of running the FTP-75 driving schedule followed by duplicate highway fuel economy tests. Figures 3a and b show the vehicle speed during the FTP and Highway tests, respectively. Included in Figures 3a and b are the engine oil, coolant and ambient temperatures from one of the test vehicles during a typical test. The FTP-75 consists of 23 driving cycles. Cycles 1-5 are often referred to as the Cold Start or Bag 1, related to emission testing. Cycles 6-18 are referred to as the Stabilized Phase or Bag 2. Following Cycle 18 the vehicle engine is turned off, and the vehicle sits for 10 minutes. After this 10-minute hot soak, the vehicle is restarted and Cycles 19-23 (Hot Start or Bag 3) are driven. Cycles 19-23 are the exact same driving schedule as Cycles 1-5, the only difference is the warmed-up conditions of Cycles 19-23. In the GM testing, at the completion of the FTP, Cycle 23, the vehicle engine is again turned off, and another 10-minute hot soak takes place, followed by the Highway test. The GM testing included duplicate Highway tests, as shown in Figure 3b, although only the second Highway test fuel consumption data was used in calculation of the fuel economy value.

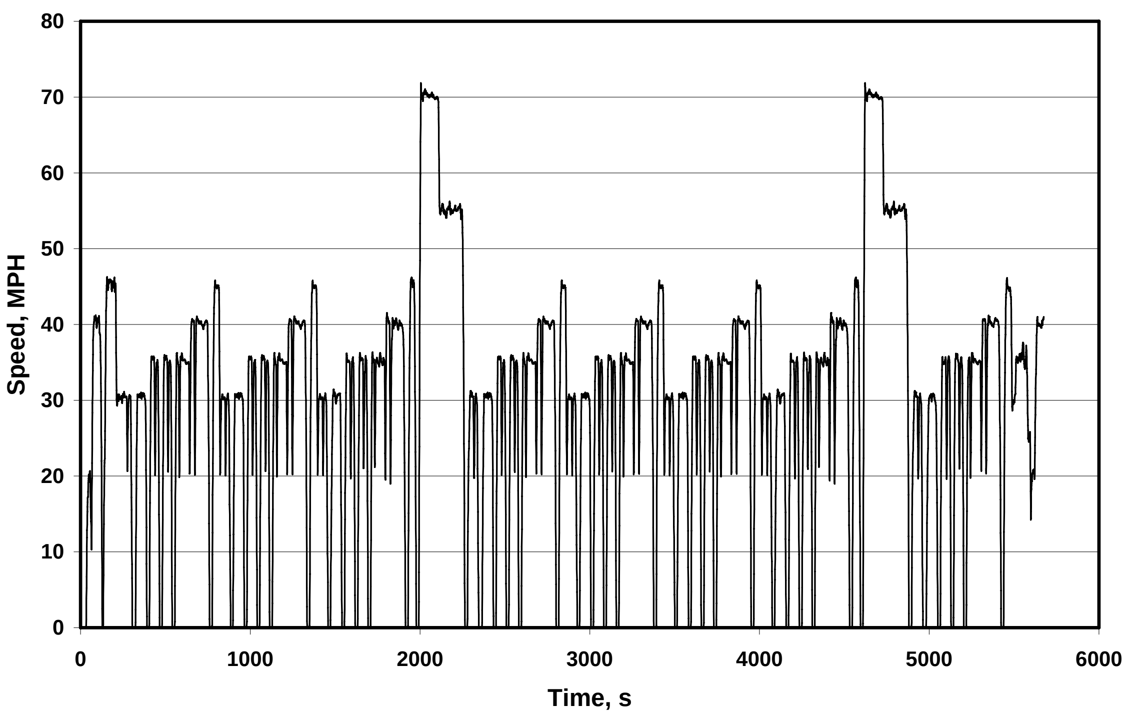


Figure 2. AMA Mileage Accumulation Schedule Used for GM Vehicles

Fuel Economy Calculations Fuel economy values calculated from the FTP and Highway data are based upon a weighting system described in the U.S. Code of Federal Regulations (CFR), Title 40, Parts 86 and 600. The weighting for the City (FTP) is 43% of the cold start (Cycles 1-5), and 57% of the hot start (Cycles 19-23) combined with the Stabilized Phase (Cycles 6-18). The actual equation from EPA for emissions calculations is:

$$Ywm = 0.43 \left((Ycs + Yst) / (Dst + Dst) \right) + 0.57 \left((Yhs + Yst) / (Dhs + Dst) \right) \qquad \text{Eq (1)}$$

where:

Ywm = weighted mass emission of each pollutant (CO, CO_2, NOx, HC) in grams per vehicle mile

Ycs = mass emission of each pollutant in the Cold Start

Yst = mass emission of each pollutant in the Stabilized Phase

Yhs = mass emission of each pollutant in the Hot Start

Dcs = driving distance in Cold Start

Dst = Driving distance in Stabilized Phase

Dhs = Driving Distance in Hot Start.

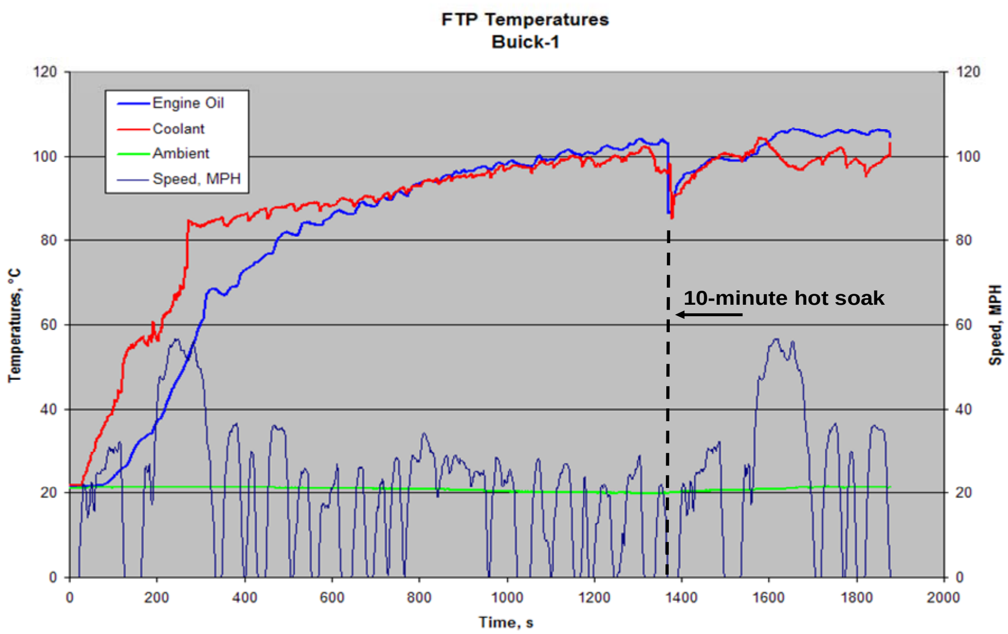


Figure 3a. FTP-75 (City Test) Driving Schedule and Temperatures

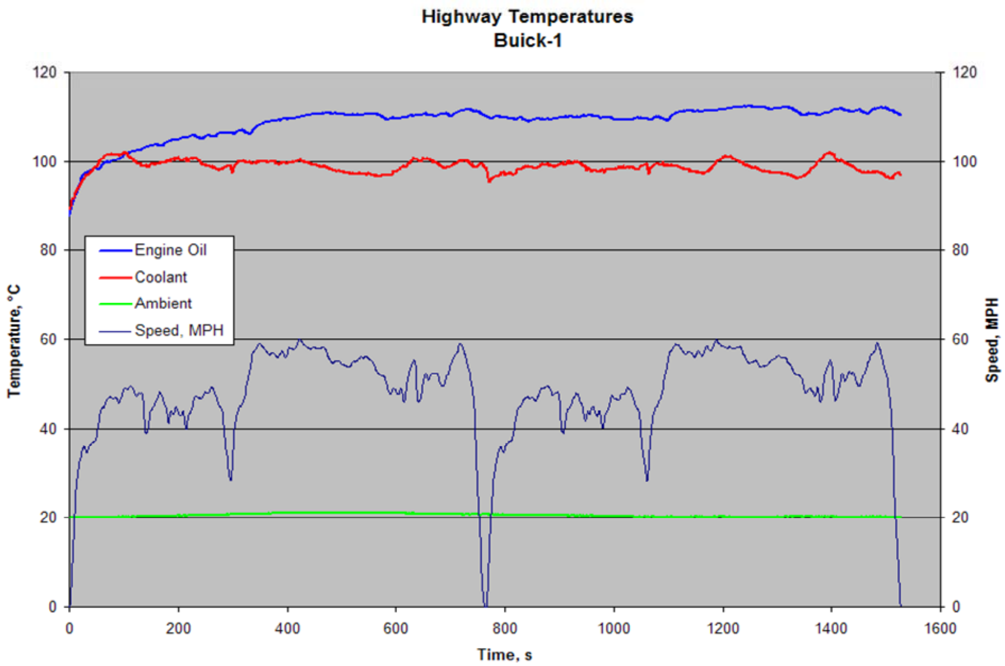


Figure 3b. Highway Test Driving Schedule and Temperatures

Because the GM fuel economy data was based upon measured fuel consumed using a fuel meter rather than calculating fuel economy from emission data using a carbon balance method, the volume of fuel consumed in the various phases was substituted for the emission data in the above equation.

For the Combined fuel economy value, the weighting of the City and Highway are 55% and 45%, respectively. The Combined (sometime called EPA 55/45) is calculated as a Harmonic Average using the following equation:

MPG combined = 1 / ((0.55/ City Fuel Economy) + (0.45 / Highway Fuel Economy)). Eq (2)

Figure 4 is an example of the data file developed for each vehicle during the FTP and Highway testing. The data files were supplied to the statisticians for their review and analysis.

25ZP4427 Pontiac G6-2
Pierburg Dual Meter
Black Pontiac G6

Pontiac G6-2

	driver	date	run #'s	odometers	---Metered Fuel Economy--- FTP	FFE	Combined	---Metered Fuel Economy--- 1-5	6-18	19-23	Pre-Cond
B-P 48" Roll Dyno	**Scott**	04/04/06	2/3	12956	21.52	34.81	25.984	19.99	21.02	23.97	34.08
Series 1	**Scott**	04/05/06	4/5	12988	21.51	34.64	25.933	20.03	20.92	24.14	34.16
Baseline Oil "Z"	**Scott**	04/06/06	6/7	13020	21.49	34.73	25.940	20.06	20.90	24.05	34.18
Baseline -1	**Scott**	04/07/06	8/9	13053	21.66	34.92	26.124	20.12	21.16	24.13	34.48
	Scott	04/08/06	10/11	13085	21.53	34.81	25.992	20.02	20.97	24.13	34.26

Test Condition- Oil, Miles

FTP (Federal Test Procedure) is the City portion of the EPA defined emission test

FFE is the Highway portion of the test (aka HWY, HWFET)

Combined is the harmonic average (55%-45%) of the FTP and FFE

1-5, 6-18, 19-23 are the three parts of the FTP (aka Cold Start, Stabilized, and Hot Start, respectively)

Pre-Cond is a "warm-up" cycle for FFE, (not used in Fuel econ calculation)

Figure 4. Example of Fuel Economy Data File

Figure 5 shows how fuel economy differences between the baseline and a matrix oil results were originally planned to be calculated. A linear regression is determined from the "baseline before" and the "baseline after" data. A calculated baseline fuel economy value is then determined from the regression equation at the odometer mileage corresponding to that after 2,000-miles of matrix oil testing, and that after at the 6,500-miles of matrix oil testing. The fuel economy differences are then determined between the calculated baseline at 2,000 miles and the matrix oil at 2,000 miles, and between the baseline at 6,500 miles and the matrix oil at 6,500 miles.

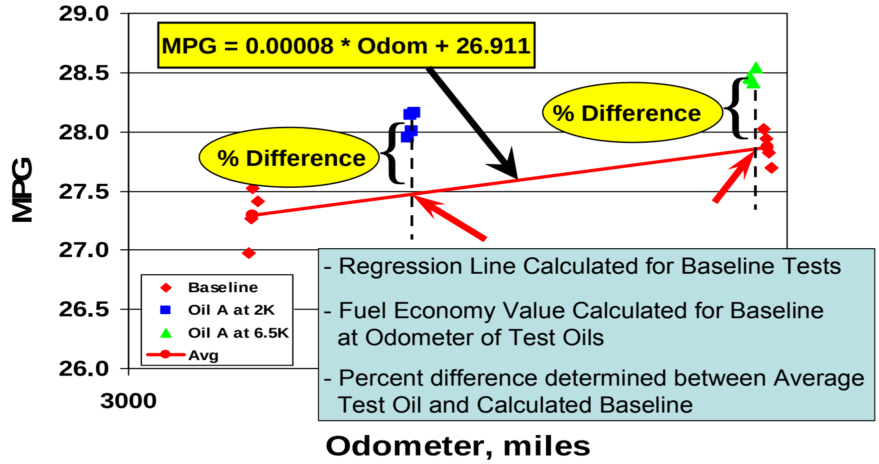


Figure 5. Example of Calculation Method for Determining Fuel Economy Differences

A test protocol was developed for the testing of the matrix oils in each of the vehicles. A diagram of the test protocol is shown in Figure 6. As previously noted the vehicles had been driven for break in purposes for about a minimum of 5,000 miles. To minimize fuel differences effects on testing, the vehicle fuel tank was drained prior to fuel economy testing and refilled with RFG Tier 2 Unleaded Test fuel. To minimize fuel costs, the RFG Tier 2 Unleaded Test fuel was not used for mileage accumulation. The vehicle engine oil was drained, refilled with Oil F (flushing oil) and driven at 55 MPH for about 10 miles (two laps on the PG Circular Track). The oil was again drained and the engine refilled with baseline oil (Oil Z), and driven again for about 10 miles. The drain, refill, drive procedure was repeated, followed by a final drain and refill to Oil Z. An oil sample was saved from the first drain, and another oil sample was taken from the engine of the final refill prior to testing. At the conclusion of the oil flush/change procedure, the vehicle was prepped for the fuel economy test by driving the FTP-75 and HWFET, referred to as the Prep Test, and then allowed to soak at room temperature. Overnight soak times were controlled to minimize differences in soak times between tests. No more than one test per vehicle could be run per day. The Prep Test was followed by four FTP and Highway fuel economy repeat tests. In some case the number of tests conducted was more than four, and in a very few cases the number of tests was only three. A typical test series would be to have the Prep test run on Monday followed by four repeat tests run Tuesday through Friday. At the completion of the Baseline testing, the vehicle oil was changed using the same flush/fill procedure described above, but substituting one of the matrix oils for Oil Z. The vehicle was then sent to the mileage accumulation dynamometers (MADs) for accumulation of 2,000 miles. After 2,000 miles, the vehicle had a Prep Test run, followed by four FTP and Highway fuel economy repeat tests. An oil sample was taken from the engine after the 2,000-mile tests were completed. The vehicle was returned to the MADs for an additional 4,500 miles, before being returned for testing at the 6,500 mile point. After the 6,500-mile testing, the engine was switched back to the baseline oil, and a series of four repeat baseline tests were run. All of the 6,500-mile used oil drained from the engine was saved for analysis and possible future testing. The baseline testing after the matrix oil completed the evaluation of that matrix oil in that vehicle, and this baseline test also used as the "baseline before" testing of the next matrix oil. Also shown in Figure 6 are the points during the testing when oil samples were collected for later analysis that was described in the Test Oil section (Section 6.3) of this report.

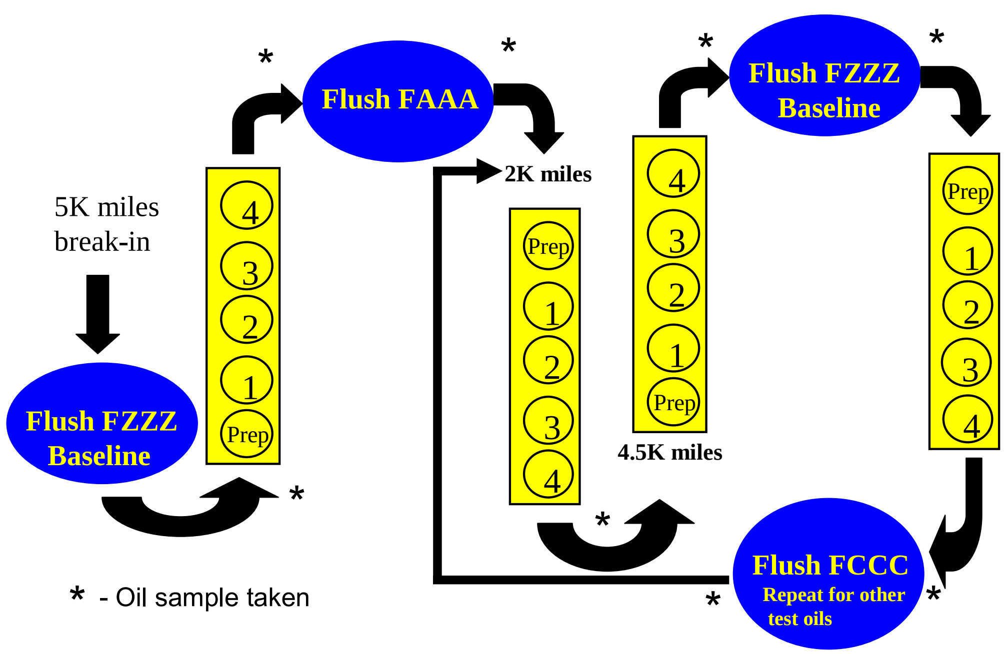


Figure 6. Schematic of Vehicle Test Protocol for One Vehicle

7.2. Ford Vehicle Testing The vehicle fuel economy testing contributed by Ford Motor Company consisted of running three VID Consortium oils in a Ford F-150 (1) and five VID

Consortium oils in a Ford Fusion (2). Data was generated on a second Ford Fusion (3) using a GF-4 5W-20 motor oil.

Vehicle description Vehicle 1 was a 2006 Ford F-150 5.4L 3 valve per cylinder engine with a roller-follower valvetrain and a 4R75E automatic transmission. The vehicle had approximately 4692 miles at the beginning of the testing. Vehicle 2 was a 2006 Ford Fusion 2.3L 4 valve per cylinder engine with a direct-acting mechanical bucket valvetrain and an FNR5 automatic transmission. The vehicle had approximately 5483 miles at the beginning of the testing. Vehicle 3 was a 2006 Ford Fusion 2.3L 4 valve per cylinder engine with a direct-acting mechanical bucket valvetrain and an FNR5 automatic transmission. The vehicle had approximately 11710 miles at the beginning of the testing.

Facility description The Ford Fusion was run at the Light Duty Vehicle Emission Laboratory at Southwest Research Institute (SwRI). The Ford F-150 testing was conducted at Allen Park Test Laboratory. All testing was conducted on a Horiba 48 inch single roll chassis dynamometer. Mileage accumulation was run on the Fusion and F-150 on the mileage accumulation chassis dynamometer at SwRI and the Labeco chassis dynamometer at Ford's Michigan Proving Grounds, respectively. All Federal Test Procedure 75 (FTP-75) and Highway Fuel Economy Tests (HwFET) on the Fusion were conducted in the same test cells with the same drivers. The F-150 testing was done in three test cells, using two different operators and robot drivers.

Test Schedule The fuel economy was determined utilizing Federal Test Procedure 75 (FTP-75) and Highway Fuel Economy Test (HwFET) driving cycles as specified in the U.S. Code of Federal Regulations (CFR), Title 40, Parts 86 and 600. The fuel economy evaluations consisted of a precondition run of one FTP-75 and one HwFET, followed by three FTP-75 + HwFET evaluations. In these three runs fuel economy was determined by the CFR-specified carbon balance method. Additional FTP-75 + HwFET evaluations were run if the coefficient of variation of the three combined FTP-75 + HwFET fuel economy results from the original three tests was greater than 0.5%. The precondition run plus three FTP-75 + HwFET evaluations accumulated approximately130 miles on the vehicle.

Haltermann EEE emissions certification fuel was used for all fuel economy preconditions, FTP-75 and HwFET tests. A single batch of EEE emissions fuel was used for all the testing conducted at SwRI.

The entire test schedule consisted of a baseline run conducted on Oil Z (four FTP-75 + HwFET), followed by an engine oil flush, mileage accumulation of 500 miles, fresh oil fuel economy testing (four FTP-75 + HwFET), mileage accumulation of 4500 miles, aged oil fuel economy testing (four FTP-75 + HwFET), followed by an engine oil flush. Then the cycle was repeated for the next test oil. The sequence is indicated in Table 11.

The engine oil flush consisted of a 15 minute run, at idle, with oil F, drain oil F, then two 15 minute runs, at idle, with the test oil. The test oil was drained after each run and the oil filters were replaced. The engine was then refilled with test oil and a new oil filter was installed for the fuel economy testing. Oil samples were taken as shown in Table 11.

Table 11. Ford Oil Sampling Schedule

Description	Oil sample	Miles
Baseline Fuel Economy	8-oz. fresh & after FE	130
Mileage Accumulation	8-oz. fresh after flush	500
"Fresh Oil" Fuel Economy	4-oz. used after FE	130
Mileage Accumulation	4-oz. 2000 miles	4500
5K "Aged Oil" Fuel Economy	8-oz. after FE	130

Table 12 shows the oils that were evaluated in each of the Ford vehicles. All oils were compared to the matrix baseline oil, Z.

Table 12. Ford Vehicle/Oil Combinations

Vehicle	Oils Evaluated
F-150 Pick up	A, C, GF-4 Ford Factory Fill
Fusion -1	A, B, C, D
Fusion - 2	GF-4 Ford Factory Fill

Mileage accumulation   For the Ford Fusion, mileage accumulation was performed on mileage accumulation dynamometers at SwRI. For the Ford F-150 mileage accumulation was performed on a Labeco chassis dynamometer at the Ford Michigan Proving Grounds. Commercially available 87-octane fuel was supplied to the vehicles during mileage accumulation. The Ford Fast AMA driving profile was used for mileage accumulation. A cycle in the Ford Fast AMA driving profile consisted of a low speed stop and go portion and a high speed portion. It averages approximately 46 mph and each cycle is approximately 45 minutes long. The cycles are repeated until the desired mileage is accumulated.

Fuel economy calculation process Fuel economy was determined by the carbon balance method specified in CFR, Title 40, Parts 86 and 600 from the exhaust emissions concentrations measured during the tests and the carbon weight fraction of the fuel.

$$mpg = (5174 \times 10^4 \times CWF \times SG)/[((CWF \times HC) + (0.429 \times CO) + (0.273 \times CO_2)) \times ((0.6 \times SG \times NHV) + 5471)] \quad \text{Eq. (3)}$$

where:

CWF = Carbon weight fraction of test fuel

SG = Specific Gravity of test fuel

HC = Grams per mile of hydrocarbon

CO = Grams per mile of Carbon monoxide

CO_2 = = Grams per mile of Carbon dioxide

NVH = Net heating value, by mass, of test fuel.

Bagged exhaust emission concentrations were determined using methods specified in CFR, Title 40, Parts 86 and 600. Three bags were collected during the FTP-75 and one bag was collected during the HwFET.

7.3. JAMA Vehicle Testing Although JAMA, as an organization, was not a member of the Consortium, nor was any JAMA-member company a member of the Consortium, JAMA were interested in supplying vehicle fuel economy evaluations of several of the Matrix oils. JAMA selected a Nissan Altima for their test work. The Altima was equipped with a 2.5L L4 multi-point injection, engine equipped with a slider-follower valve train configuration. The JAMA fuel economy testing was done at the Japanese Automotive Research Industry (JARI) lab, using the same procedure for prepping and running the vehicle. The JAMA testing included the FTP-75 and Highway tests and the Japan 10-15 driving schedule. Oils A, C and J were evaluated and were compared to the Oil Z baseline oil in the JAMA vehicle testing. Fuel economy calculations and percent changes in fuel economy relative to Oil Z were calculated using the same method described in the GM vehicle testing section. JAMA evaluated the matrix oils after 2,000 and 6,500 miles of mileage accumulation similar to the AMA driving schedule used by GM. Oil samples of the fresh and used oils were collected and analyzed using the same protocols followed in the GM testing.

7.4. Vehicle Fuel Economy Test Results – GM Vehicles As previously mentioned, two drivers were used for the GM vehicle testing, a primary driver, Driver-1, and a secondary driver, Driver-2, for the occasions when the primary driver was unavailable. Although both drivers were consistent in their respective tests, there appeared to be a consistent difference between Driver-1 and Driver-2 in some vehicle models. Review of the driver differences were analyzed by the statistical group and a correction factor was determined for Driver-2 results to bring them in line with results from Driver-1. Use of the correction factor is illustrated in Figure 7a and b. Figure 7a shows the results for one of the Pontiac G6 vehicles with the results of Driver-2 circled. Results for Driver-1 and Driver-2, individually, are very repeatable; however, they are not consistent between the two drivers. Using the driver correction factor, the data in Figure 7a are re-plotted in Figure 7b. The driver-corrected data are much more consistent. The driver correction factors for the GM vehicles were used in plotting the data in Figures 8 through 12.

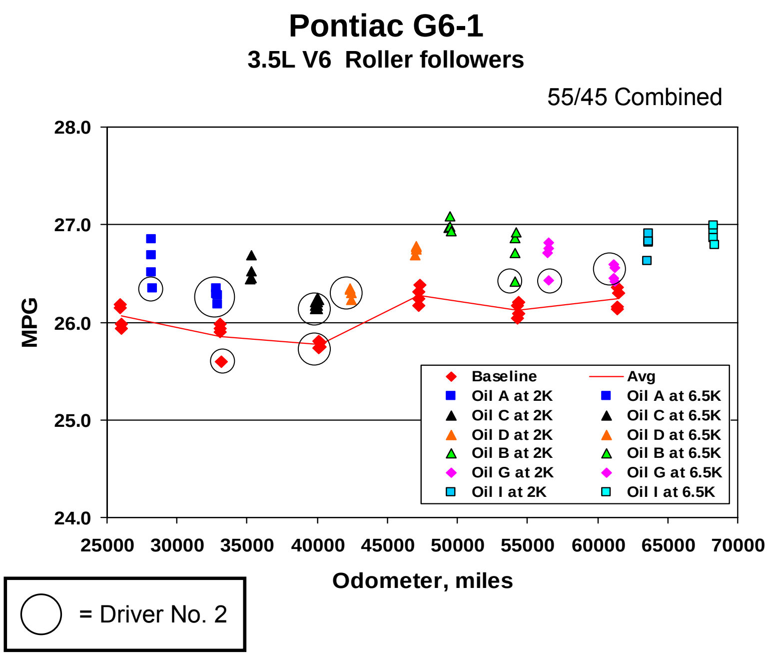


Figure 7a. Fuel Economy Results for Both Drivers

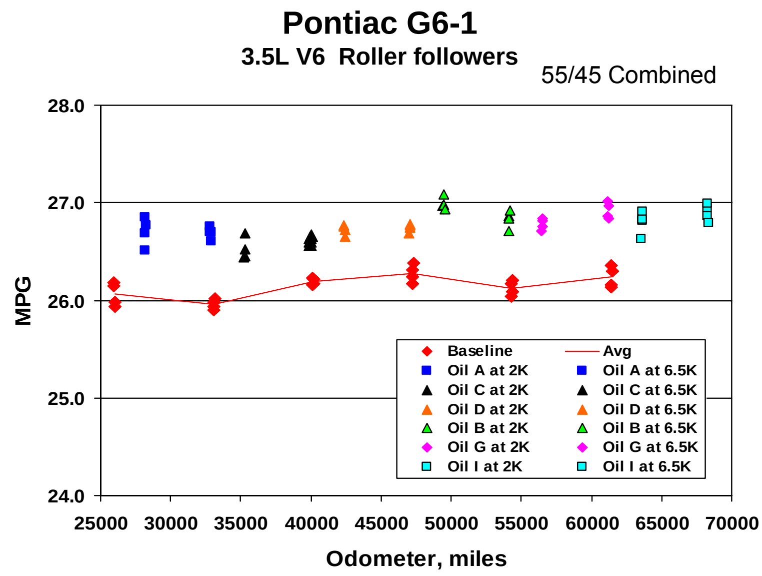


Figure 7b. Fuel Economy Results using Driver Correction Factor- Pontiac G6-1

The results from the vehicle fuel economy testing in the GM vehicles are illustrated in Figures 8 through 12. Data are displayed for the Combined 55/45 comparisons.

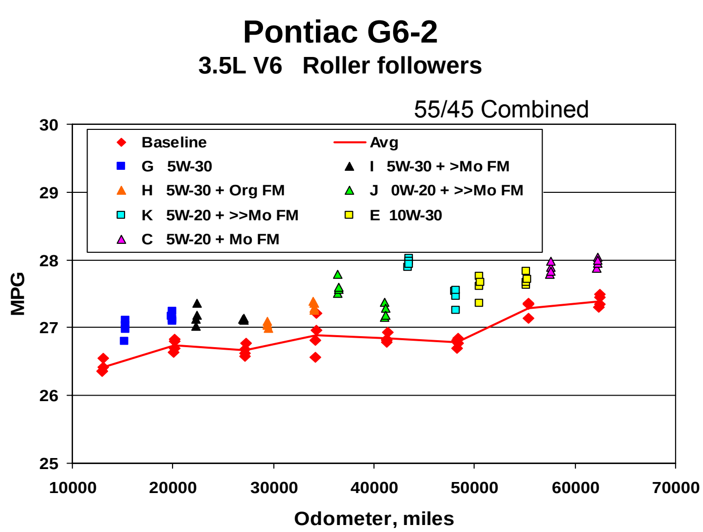


Figure 8. Fuel Economy Results - Pontiac G6-2

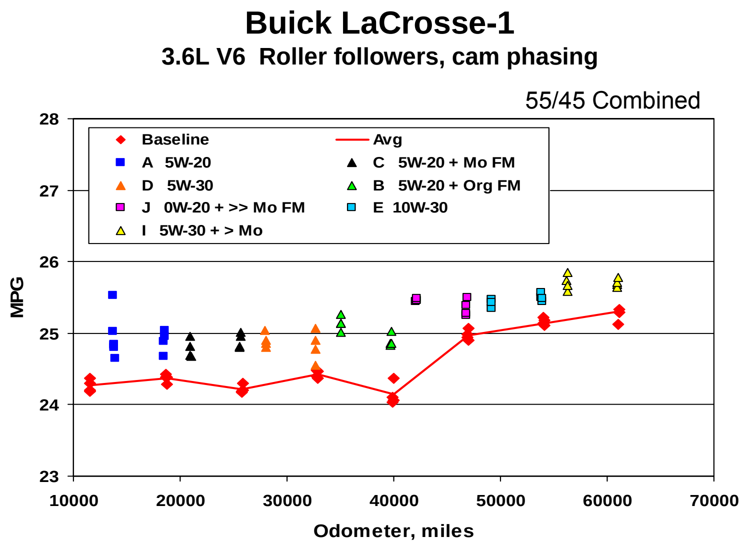


Figure 9. Fuel Economy Results - Buick LaCrosse-1

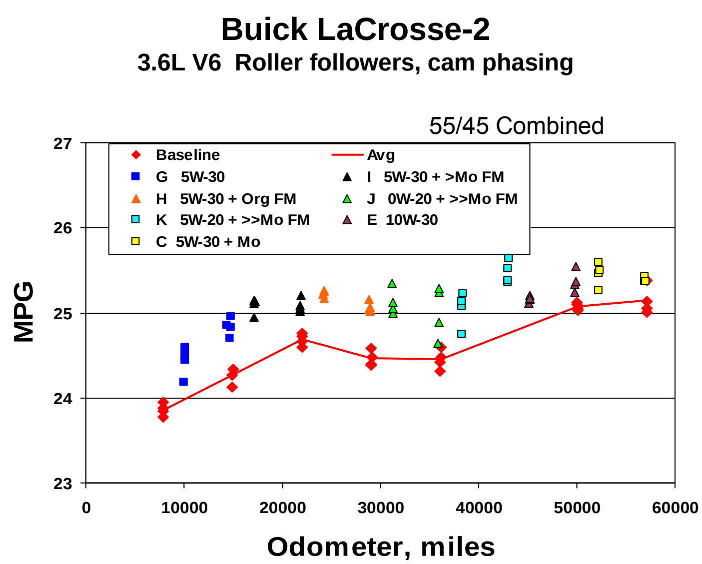


Figure 10. Fuel Economy Results - Buick LaCrosse-2

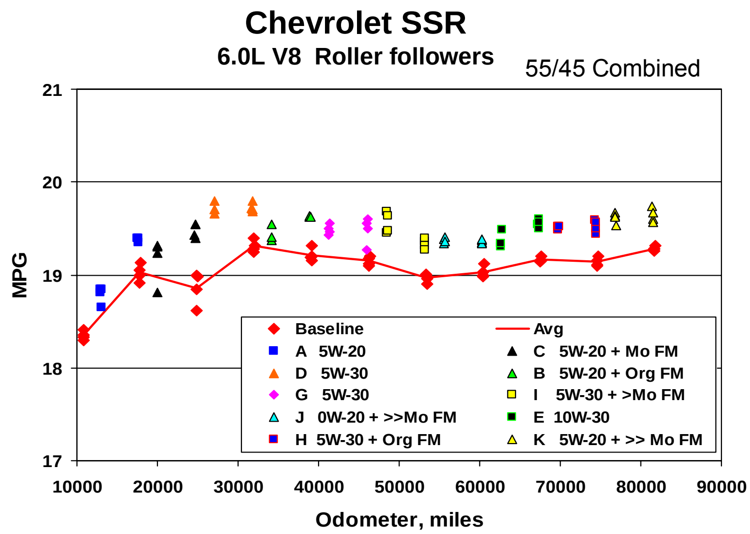


Figure 11. Fuel Economy Results - Chevrolet SSR

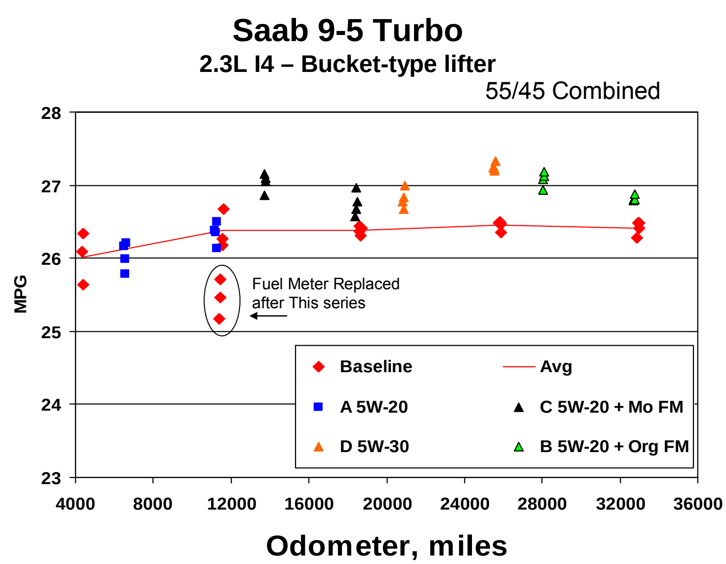


Figure 12. Fuel Economy Results - Saab 9.5 Aero

The fuel economy test results using the Ford vehicles are shown in Figures 13 through 15.

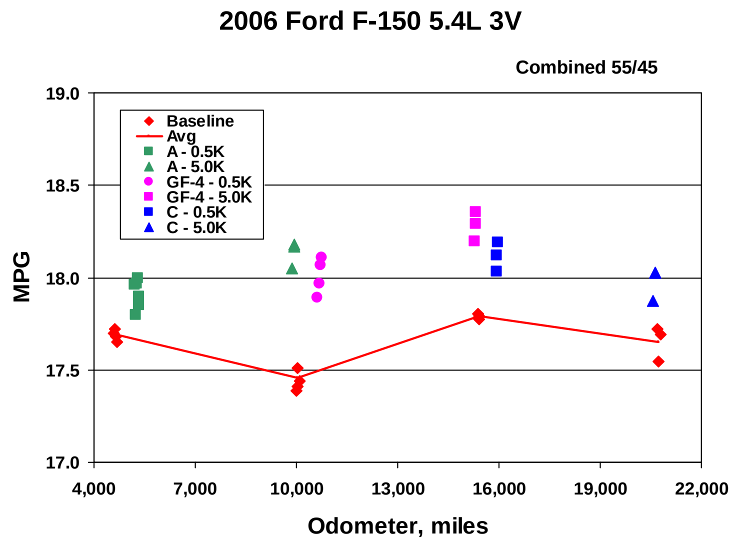


Figure 13. Fuel Economy Results – Ford F-150

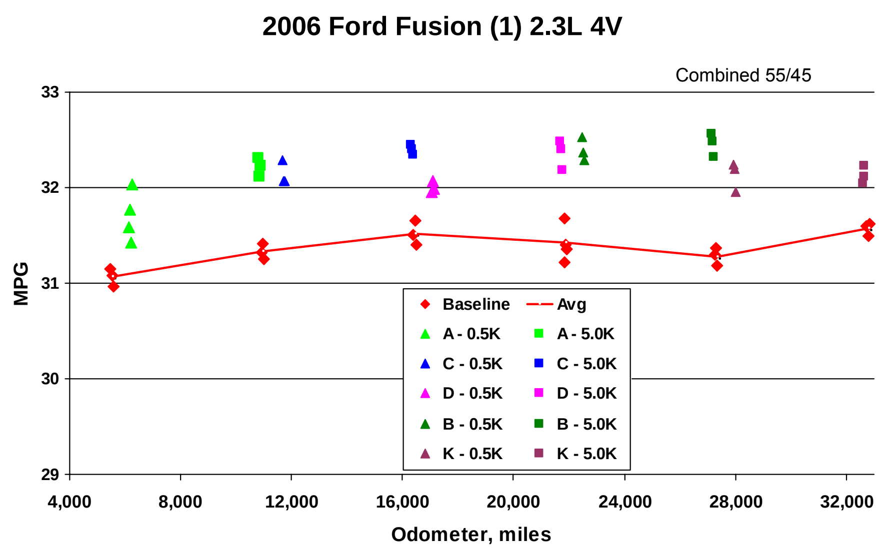


Figure 14. Fuel Economy Results – Ford Fusion-1

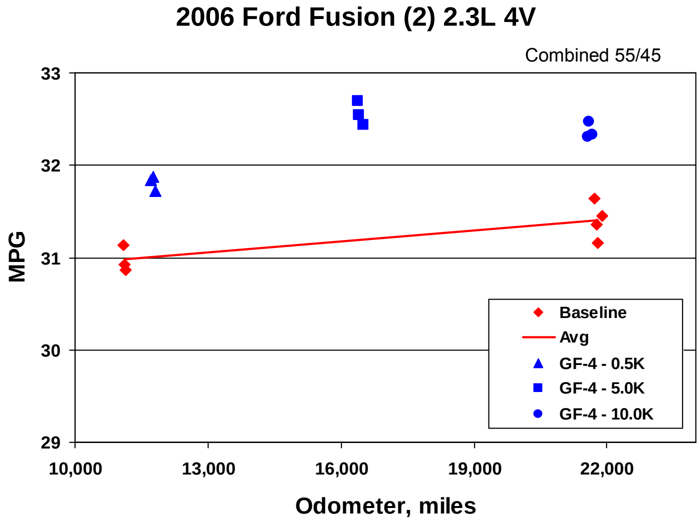


Figure 15. Fuel Economy Results – Ford Fusion-2

The test results for the Nissan Altima (provided by JAMA) are shown in Figures 16 and 17 for the Combined 55/45 testing and Japanese 10-15 Mode testing, respectively, for Oils A, C, and J.

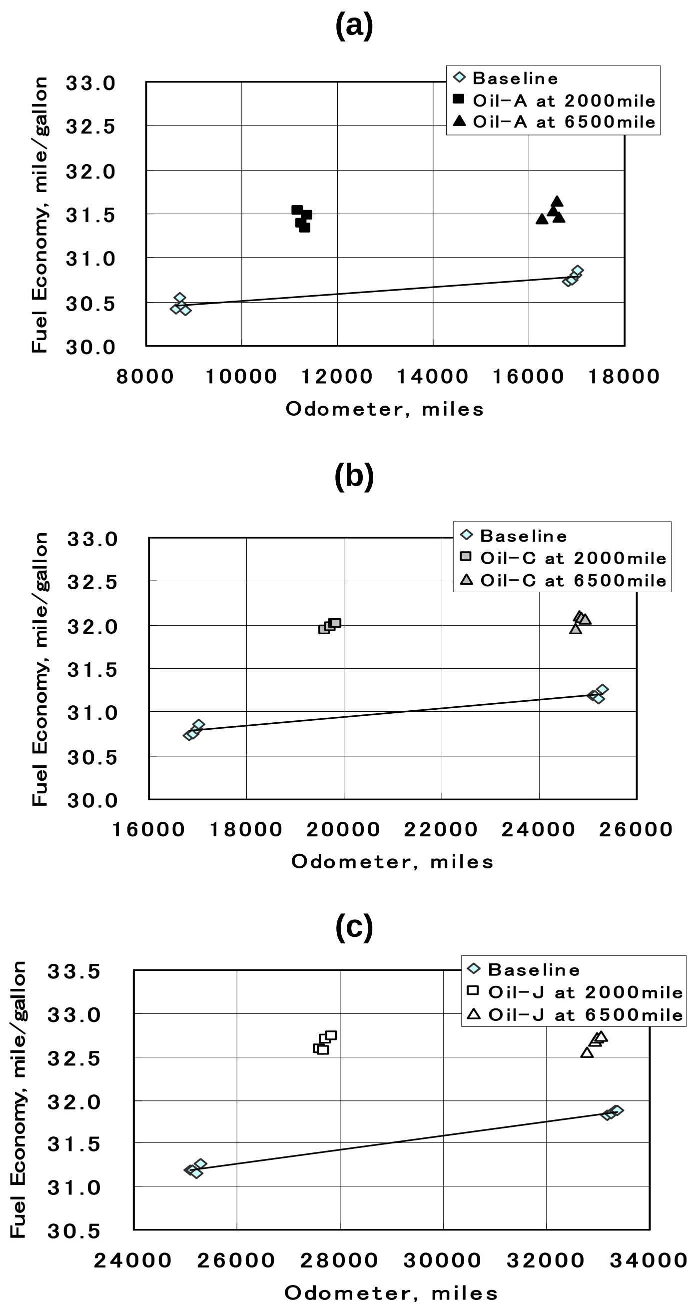


Figure 16. Combined 55/45 Results for Oil A (a), C, (b), and J (c) – Nissan Altima

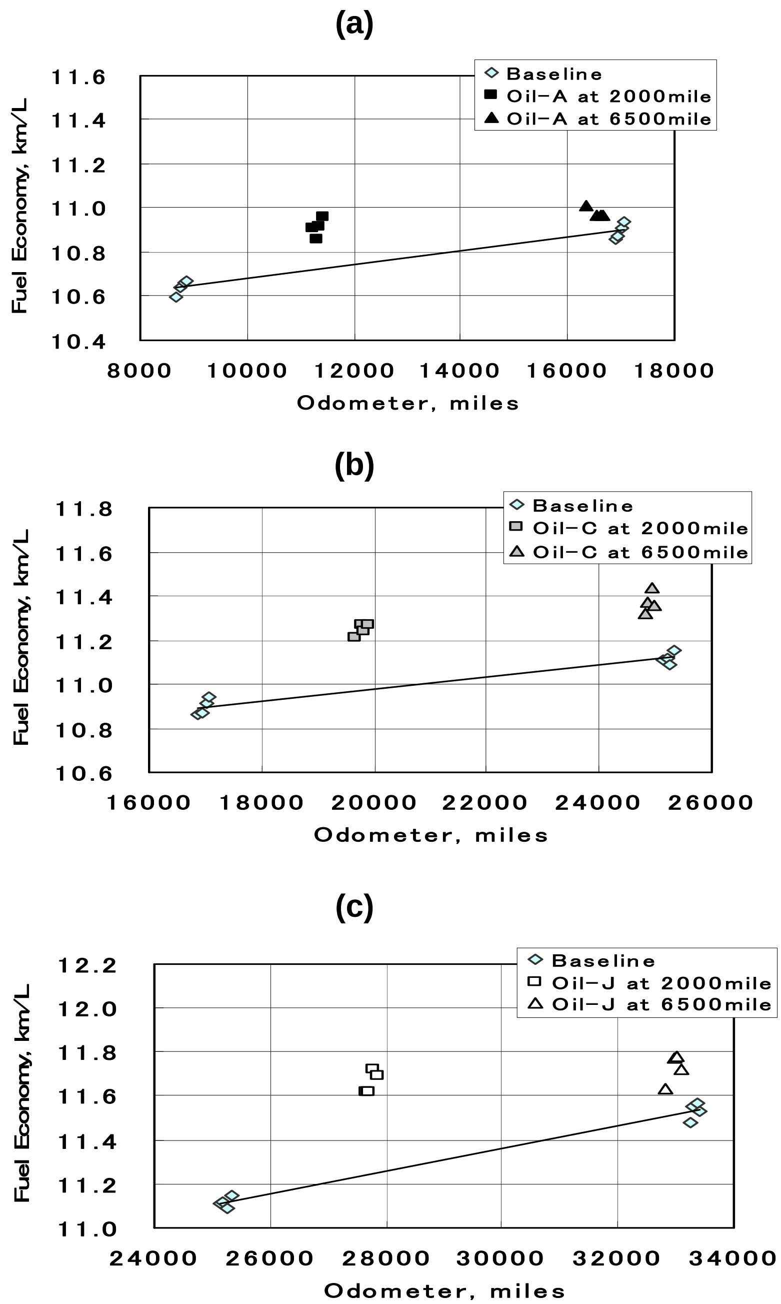


Figure 17. Japanese 10-15 Mode Results for Oil A (a), C, (b), and J (c) – Nissan Altima

Statistical Analysis of GM Vehicle Testing Multiple linear regression analysis was used to estimate the effects of Vehicle Make, Vehicle Unit, Vehicle Odometer Miles, Vehicle Driver, Oil, Oil Miles, and their interactions on the GM Fuel Economy FTP Data.

The data used in the analysis and the summary of the regression analysis is included in Appendix C. It is important to understand that the Fuel Economy results from the GM Vehicle Testing are not just a function of the crankcase oil and the miles on the oil, but also a function of the GM Vehicle Model, the Model Unit, the Vehicle Miles, the Driver of the Vehicle, and other factors and covariates not listed and/or measured. That is why the statistical analysis must, and does, take these additional variables and factors into account when making the comparisons of Oil impact on GM Vehicle Fuel Economy.

From the analysis, there is statistical evidence that Fuel Economy improves as Vehicle Miles increase. The relationship is not linear, but is transformed to be approximately linear by taking a double Natural Log of the Vehicle Miles. This relationship, adjusted for each GM Vehicle, is then taken into account when comparing oils. The fact that GM Vehicle Models differ in Fuel Economy performance is also taken into account.

From the analysis, there is statistical evidence that the Vehicle Driver impacts Fuel Economy. Not only does the Driver impact Fuel Economy, but impact is dependent upon the GM Vehicle. This relationship is taken into account when comparing oils.

As mentioned earlier, the covariates are taken into account when assessing the effects of Oil and Oil Aging on Fuel Economy performance. The Oils tested in the GM vehicle tests include Z (Baseline Oil as a 20W-30 with no Friction Modifier), A (Z technology, but a 5W-20), B (A with organic friction modifier), C (A with low level of molybdenum friction modifier), D (A as a 5W-30), E (A as a 10W-30), G (second technology with no friction modifier as a 5W-30), H (G with organic friction modifier), I (G with high level of molybdenum friction modifier), J (third technology with very high level of molybdenum friction modifier as a 0W-20), K (J as a 5W-20). While Oil Z was not aged in the GM vehicle tests, the other matrix oils were aged to 2000 miles and 6500 miles. The conclusions from the statistical analysis of the oils' impact on Fuel Economy in the GM Field Trial are presented below.

- There is statistical evidence that the matrix oils are better in Fuel Economy performance than Baseline Oil Z
- There is no statistical evidence that the matrix oils differ from each other in performance
    - Estimated performance range is 0.2 to 0.3 miles per gallon
    - There appears to be more separation of oils under FTP (city) conditions than FFE (highway) conditions

- There is no statistical evidence that lighter viscosity grades offer any Fuel Economy improvement among the matrix oils
- While there is not enough statistical evidence to support the conclusion, it appears that friction modified oils offer a very slight Fuel Economy benefit over non-friction modified oils
- There is no statistical evidence that oils with lower HFRR differ in Fuel Economy performance from oils with higher HFRR
- There is not enough statistical evidence to support a decline in Fuel Economy performance of the matrix oils as they age from 2000 miles to 6500 miles.

Difference from Baseline The following bar charts (Figures 18-20) depict the standardized difference between each Matrix Oil and Oil Z. This standardized difference, represented by T, is broken down by City Fuel Economy (FTP), Highway Fuel Economy (FFE), and Combined Fuel Economy, and by 2000 miles and 6500 miles. Any bar that is higher than the bars on the extreme left of the bar chart, labeled 'Significance', indicates a statistically significant difference between the Matrix Oil and Oil Z. As mentioned earlier, discrimination occurs more frequently under FTP conditions than under FFE conditions.

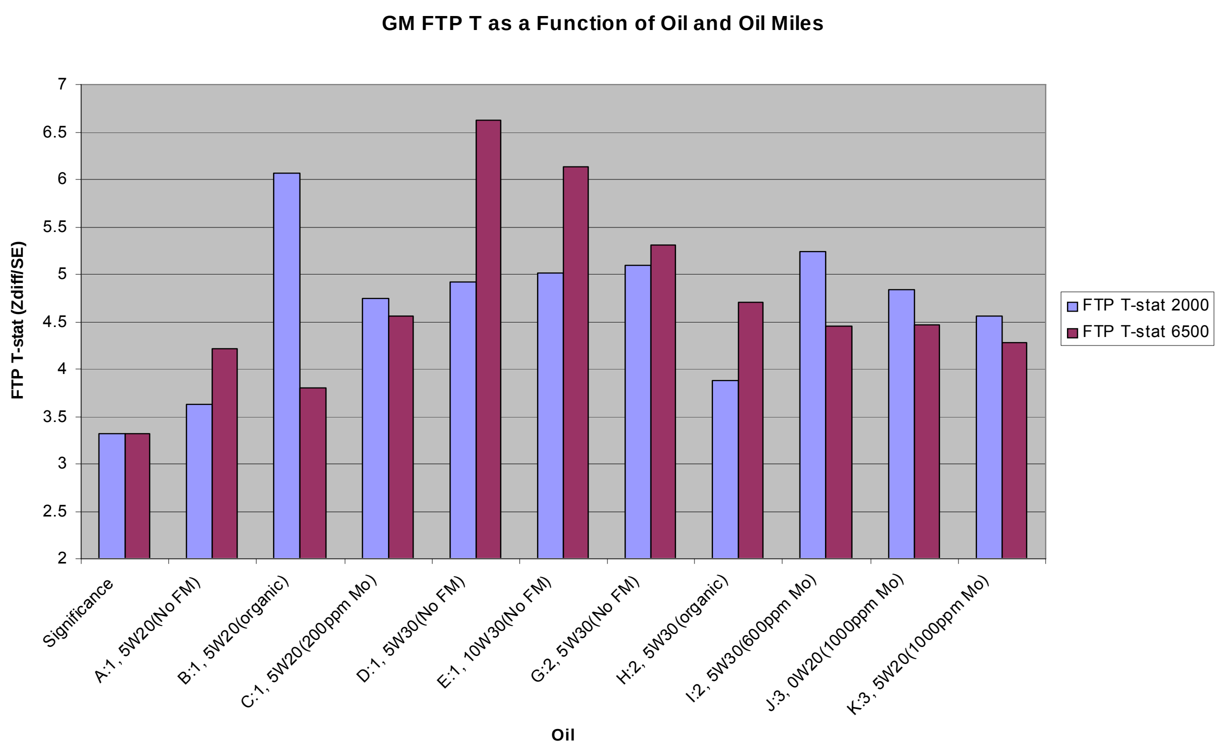


Figure 18. T-Statistic as a Function of Oil and Oil Miles for GM City Test Data

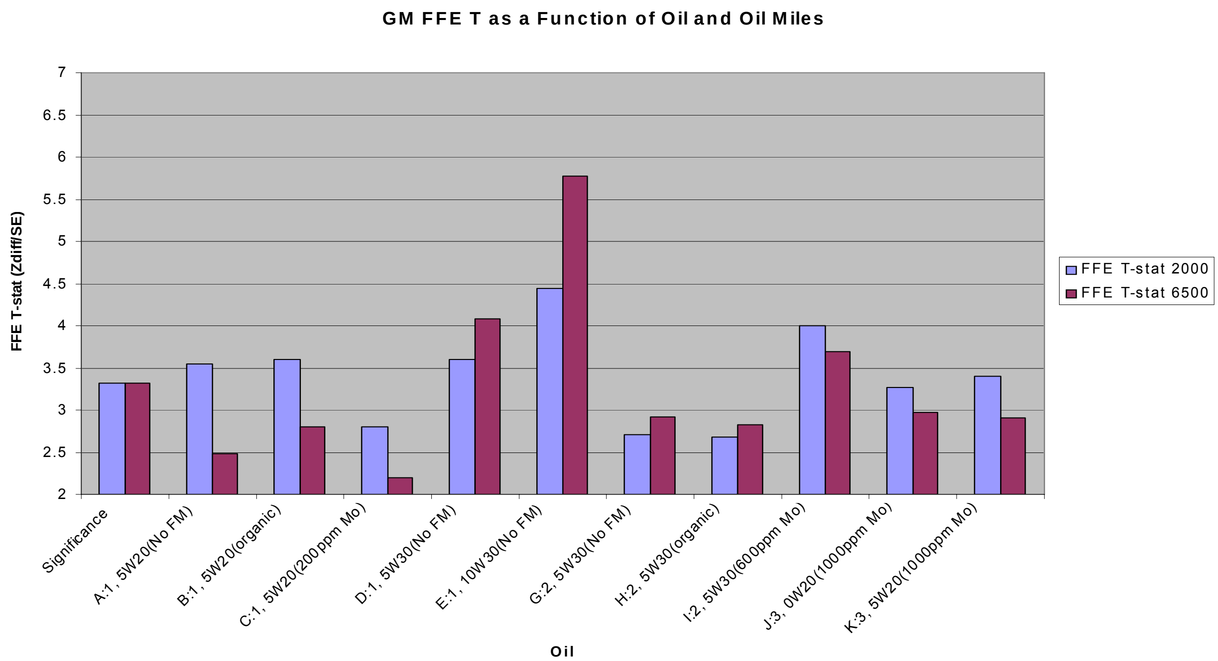


Figure 19. T-Statistic as a Function of Oil and Oil Miles for GM Highway Test Data

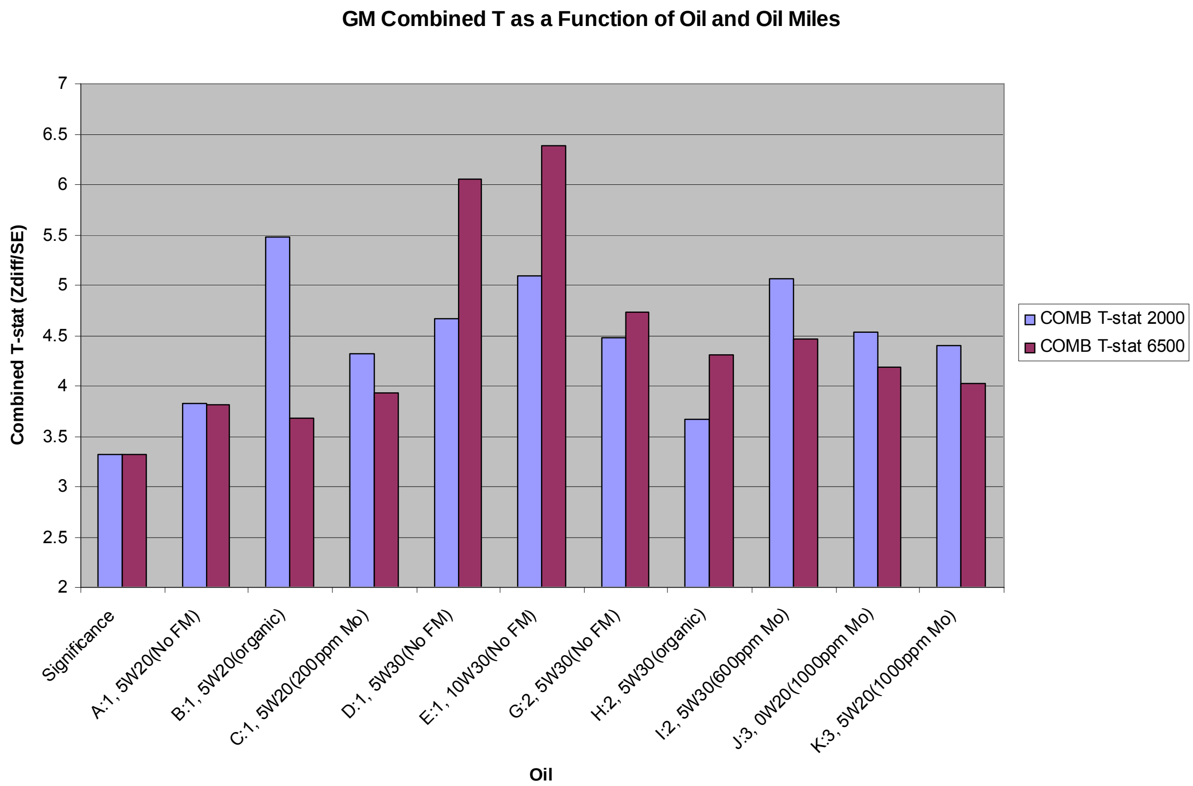


Figure 20. T-Statistic as a Function of Oil and Oil Miles for GM 55/45 Test Data

Matrix Oils Differences The following bar charts (Figures 21-23) depict the estimated Percent Fuel Economy Improvement over Oil Z for each Matrix Oil. As stated earlier, there is no statistical evidence that the oils differ from each other, and there is no statistical evidence of an effect due to friction modifier, viscosity grade, or oil aging. The graphs are presented for observational use only.

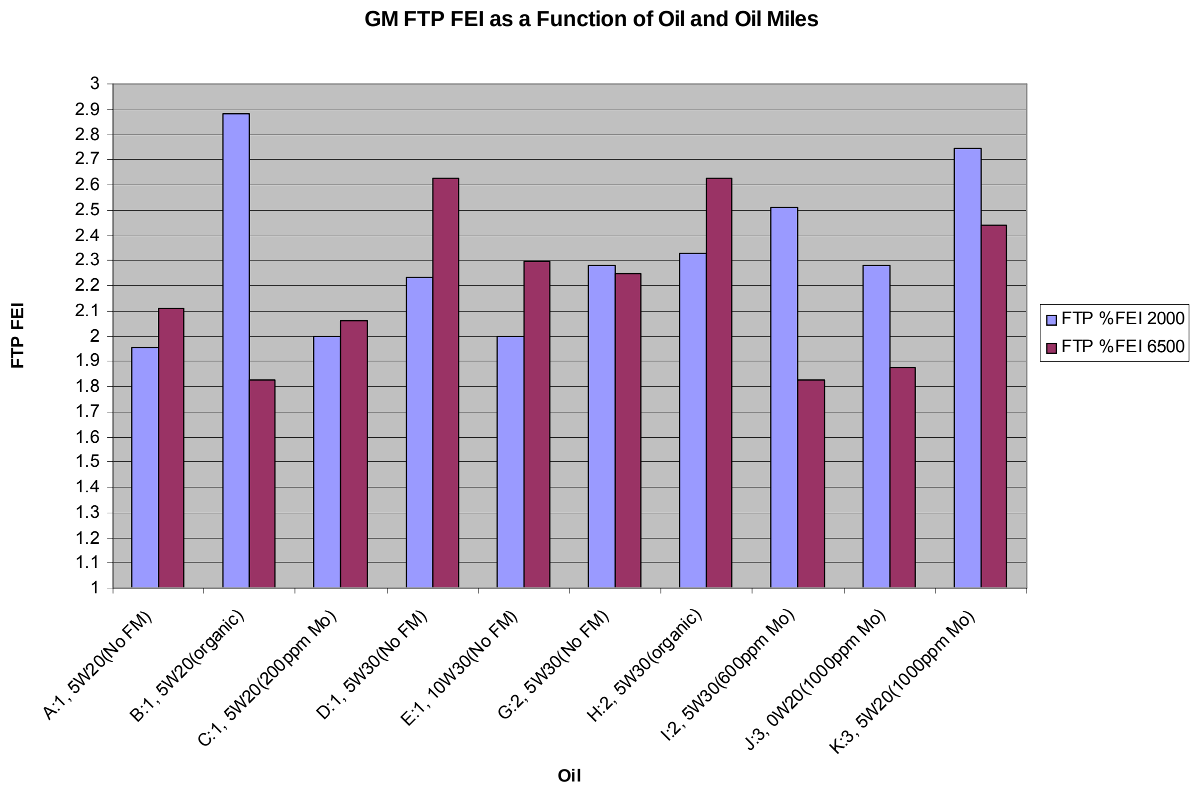


Figure 21. Percent Fuel Economy Improvement as a Function of Oil and Oil Miles for GM City Test Data

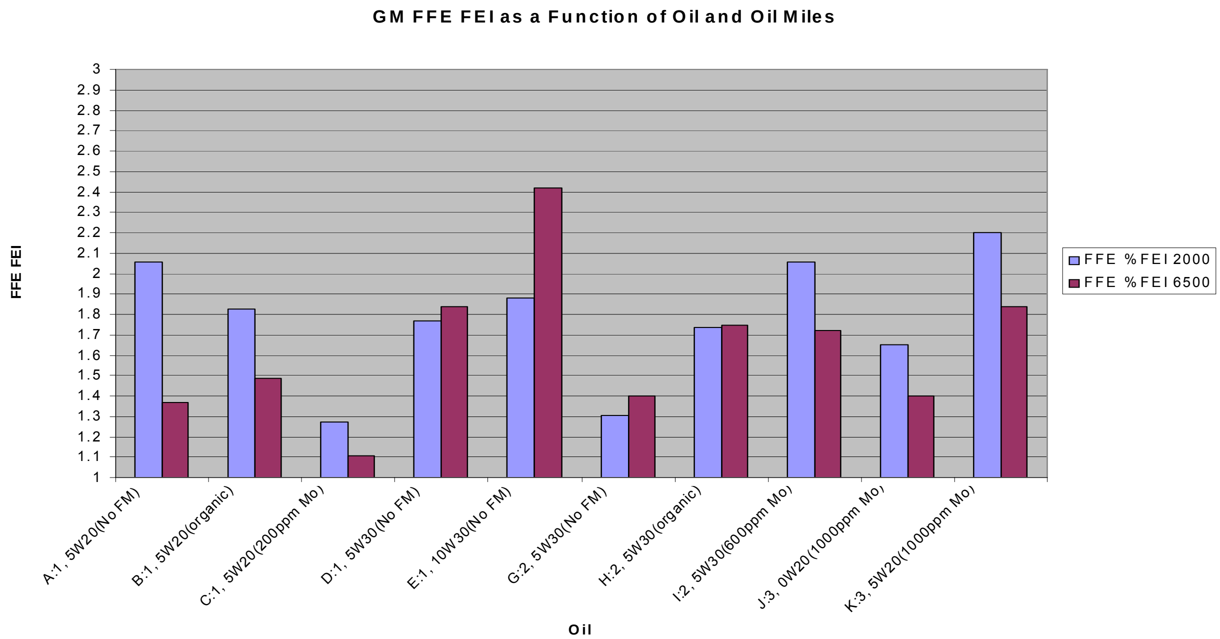


Figure 22. Percent Fuel Economy Improvement as a Function of Oil and Oil Miles for GM Highway Test Data

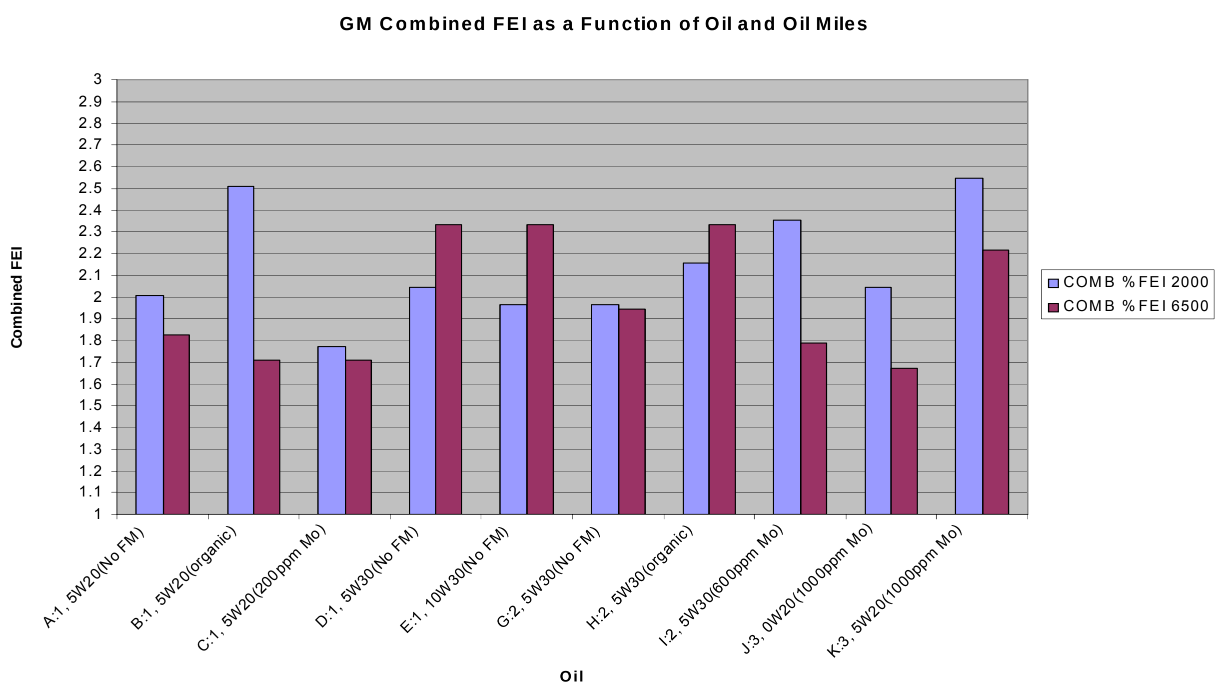


Figure 23. Percent Fuel Economy Improvement as a Function of Oil and Oil Miles for GM 55/45 Combined Test Data

There is no statistical evidence to support a correlation between Oil HFRR (at 140°C) and Fuel Economy performance in this particular study. The lack of correlation is evident in Figures 24-27.

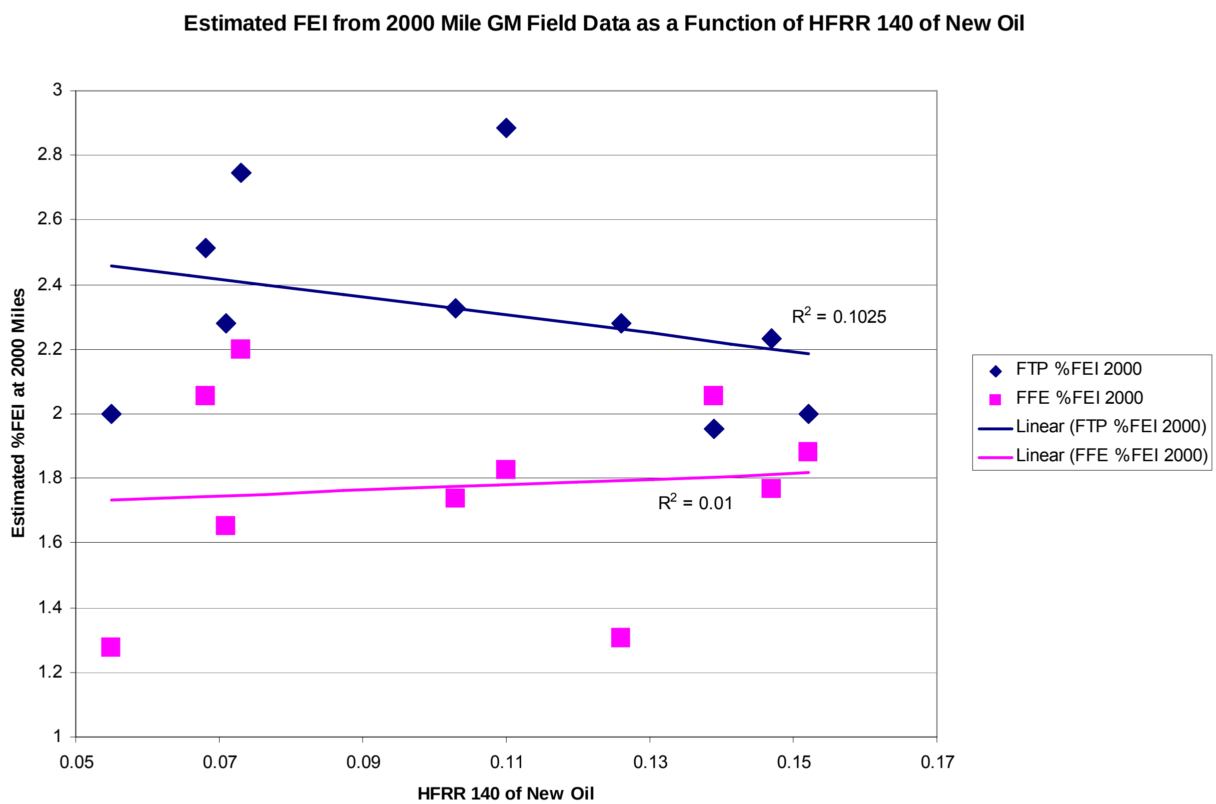


Figure 24. Estimated FEI from 2000 Mile GM Vehicle Data as a Function of HFRR 140 of New Oil

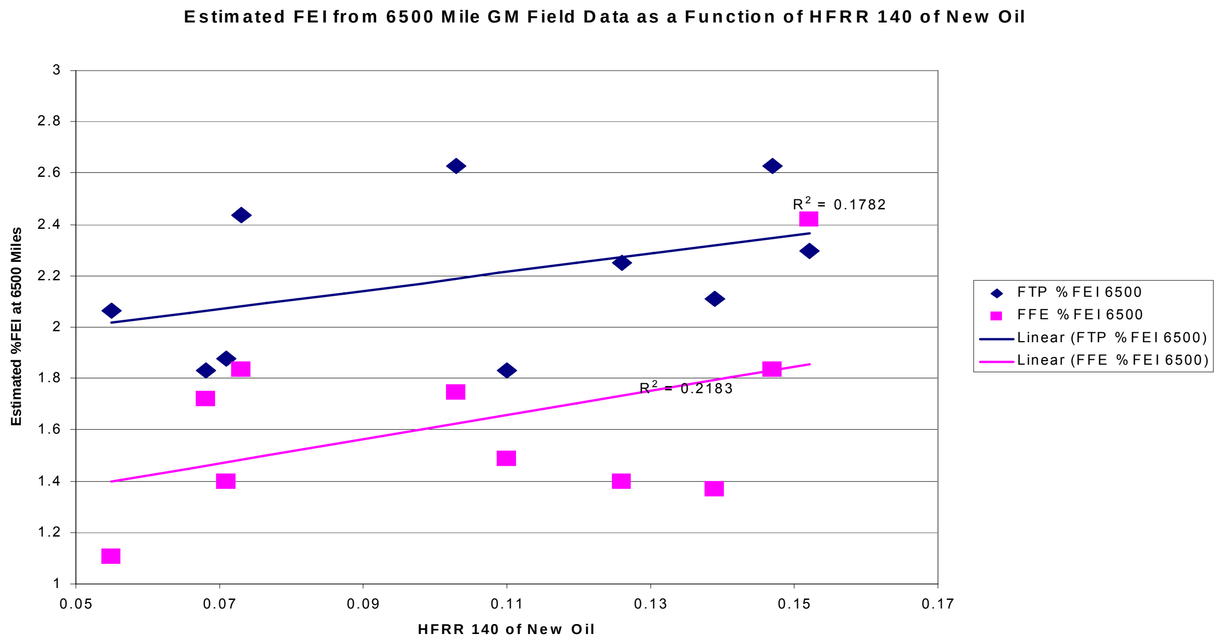


Figure 25. Estimated FEI from 6500 Mile GM Vehicle Data as a Function of HFRR 140 of New Oil

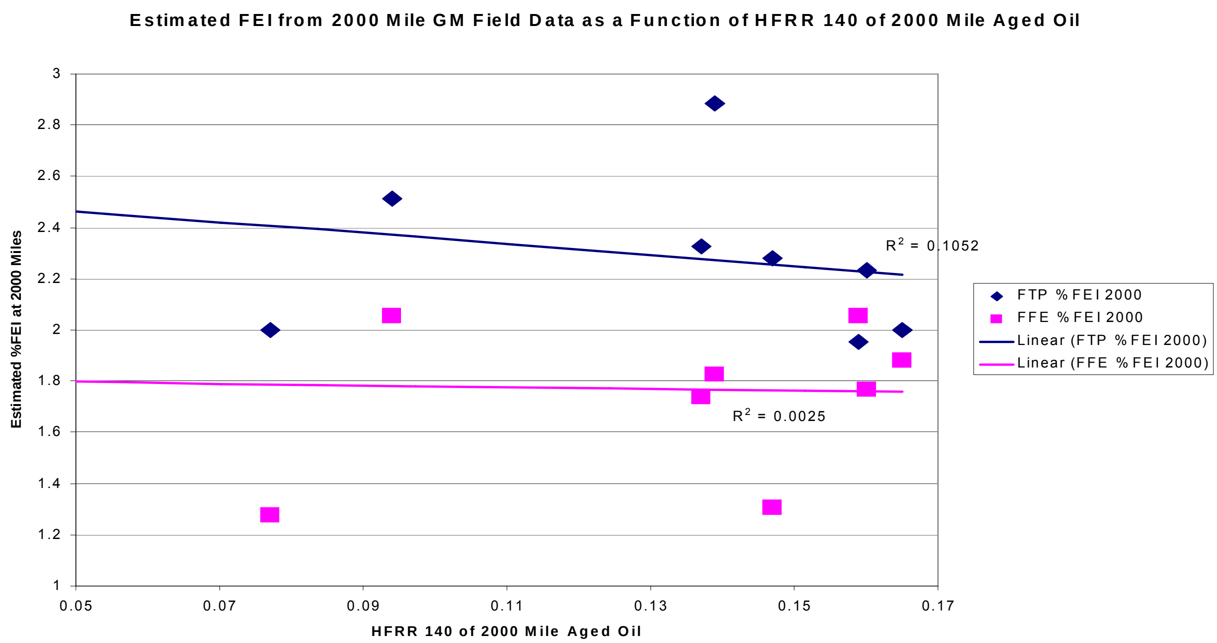


Figure 26. Estimated FEI from 2000 Mile GM Vehicle Data as a Function of HFRR 140 of Aged Oil

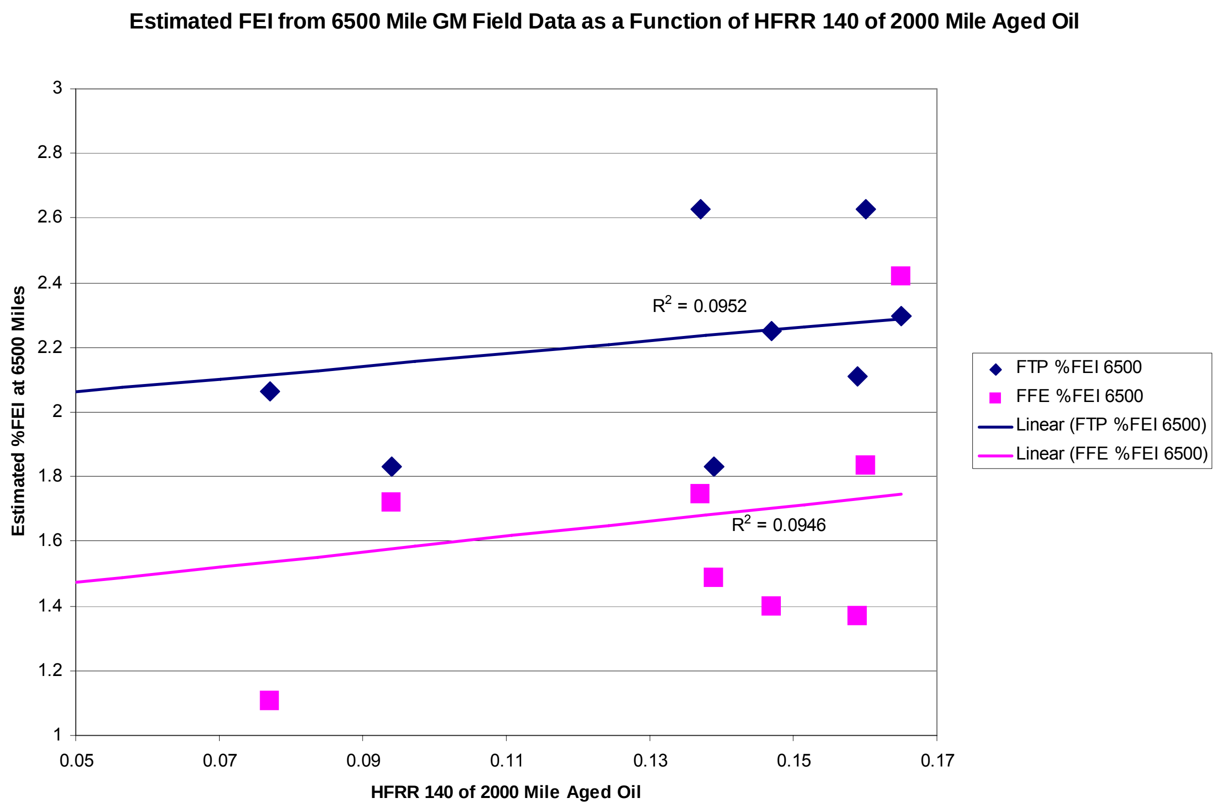


Figure 27. Estimated FEI from 6500 Mile GM Vehicle Data as a Function of HFRR 140 of Aged Oil

Statistical Analysis of Ford Vehicle Testing Multiple linear regression analysis was used to estimate the effects of Vehicle Make, Vehicle Unit, Vehicle Odometer Miles, Oil, Oil Miles, and their interactions on the Ford Fuel Economy FTP Data. The data used in the analysis and the summary of the regression analysis is included as Appendix D. It is important to understand that the Fuel Economy results from the Ford Vehicle Testing are not just a function of the crankcase oil and the miles on the oil, but also a function of the Ford Vehicle Model, the Model Unit, the Vehicle Miles, and other factors and covariates not listed and/or measured. That is why the statistical analysis must, and does, take these additional variables and factors in account when making the comparisons of Oil impact on Ford Vehicle Fuel Economy.

From the analysis, there is some statistical evidence that Fuel Economy improves as Vehicle Miles increase. The relationship is not linear, but is transformed to be approximately linear by taking a double Natural Log of the Vehicle Miles. This relationship is taken into account when comparing oils. The fact that Ford Vehicle Models differ in Fuel Economy performance is also taken into account.

As mentioned earlier, the covariates are taken into account when assessing the effects of Oil and Oil Aging on Fuel Economy performance. The Oils tested in the Ford Field Trial include Z (Baseline Oil as a 20W-30 with no Friction Modifier), A (Z technology, but a 5W-20), B (A with organic friction modifier), C (A with low level of molybdenum friction modifier), D (A as a 5W-30), K (third technology with very high level of molybdenum friction modifier as a 5W-20), and a GF-4 reference oil (specifics unknown). While Oil Z was not aged in the Ford Field Trial, the other matrix oils were aged to 500 miles and 5000 miles. The conclusions from the statistical analysis of the oils impact on Fuel Economy in the Ford Field Trial are presented below.

- At 500 miles
    - There is statistical evidence that the matrix oils B and C are better in Fuel Economy (city and highway) performance than Baseline Oil Z
    - There is some statistical evidence that the matrix oils D and K are better in Fuel Economy (city and highway) performance than Baseline Oil Z
    - There is statistical evidence that the GF-4 matrix oil is better in FTP (city) and Combined Fuel Economy performance than Baseline Oil Z
    - There is no statistical evidence that the matrix oils differ from each other in performance
        - Estimated maximum performance range is approximately 0.5 miles per gallon (matrix oil B versus matrix oil A)
        - There appears to be more separation of oils under FTP (city) conditions than FFE (highway) conditions
- At 5000 miles
    - There is statistical evidence that the matrix oils (except for K) are better in Fuel Economy (city and highway) performance than Baseline Oil Z
    - There is no statistical evidence that the matrix oils differ from each other in performance
        - Estimated maximum performance range is approximately 0.5 miles per gallon (matrix oil GF-4 versus matrix oil K)

- There is no statistical evidence that lighter viscosity grades offer any Fuel Economy improvement among the matrix oils
- While there is not enough statistical evidence to support the conclusion, it appears that friction modified oils offer a very slight Fuel Economy benefit over non-friction modified oils
- There is no statistical evidence to support a decline in Fuel Economy performance of the matrix oils as they age from 500 miles to 5000 miles.

Difference from Baseline The following bar charts (Figures 28 through 30) depict the standardized difference between each Matrix Oil and Oil Z. This standardized difference, represented by T, is broken down by City Fuel Economy (FTP), Highway Fuel Economy (FFE), and Combined Fuel Economy, and by 500 miles and 5000 miles. Any bar that is higher than the bars on the extreme left of the bar chart, labeled 'Significance', indicates a statistically significant difference between the Matrix Oil and Oil Z.

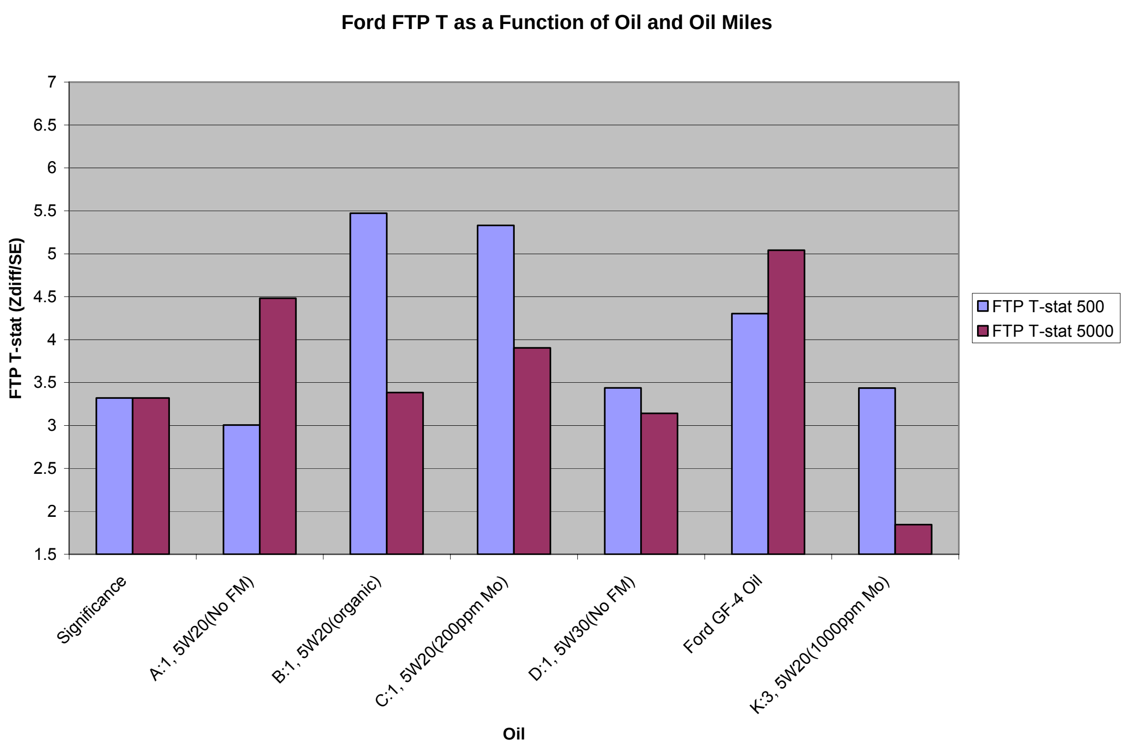


Figure 28. Ford FTP T as a Function of Oil and Oil Miles

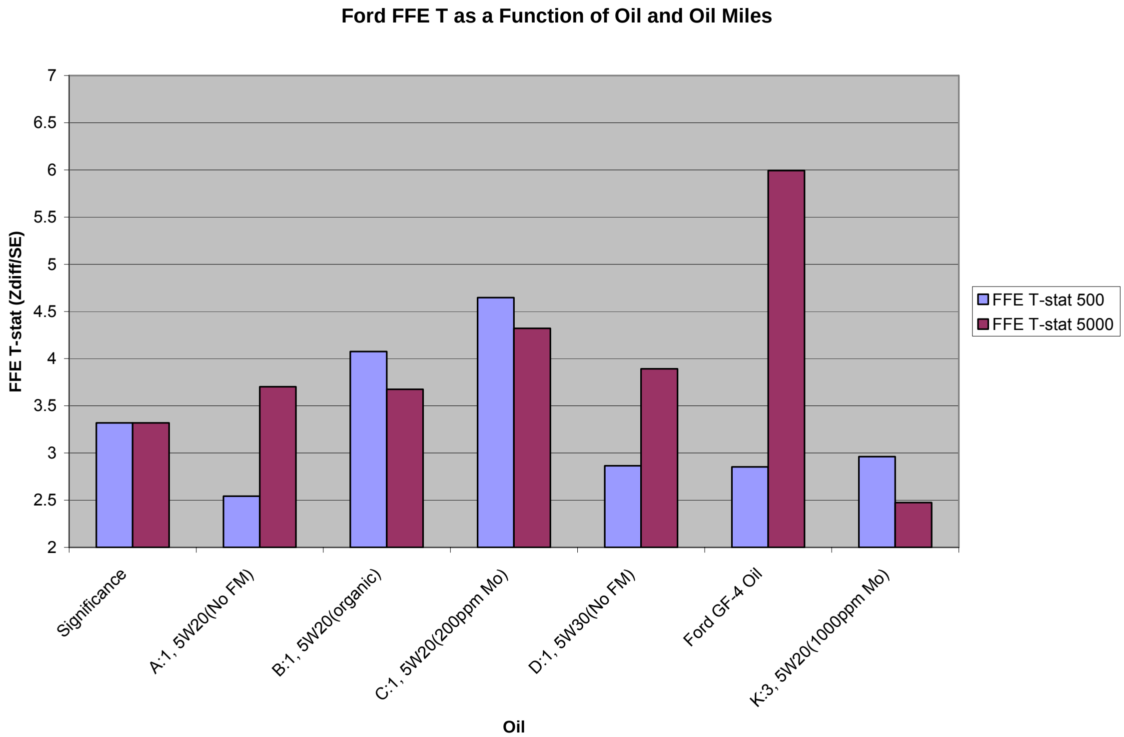


Figure 29. Ford Highway T as a Function of Oil and Oil Miles

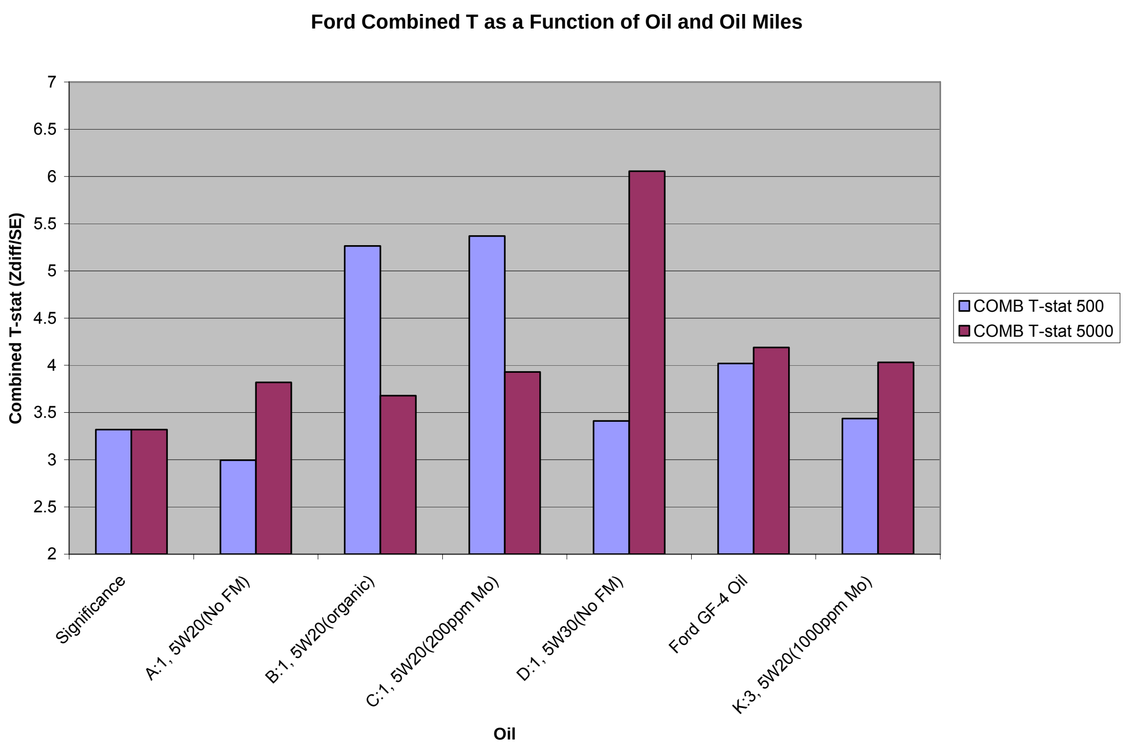


Figure 30. Ford Combined T as a Function of Oil and Oil Miles

Matrix Oil Differences The following bar charts (Figures 31 through 33) depict the estimated Percent Fuel Economy Improvement over Oil Z for each Matrix Oil. As stated earlier, there is no statistical evidence that the oils differ from each other, and there is no statistical evidence of an effect due to friction modifier, viscosity grade, or oil aging. The graphs are presented for observational use only.

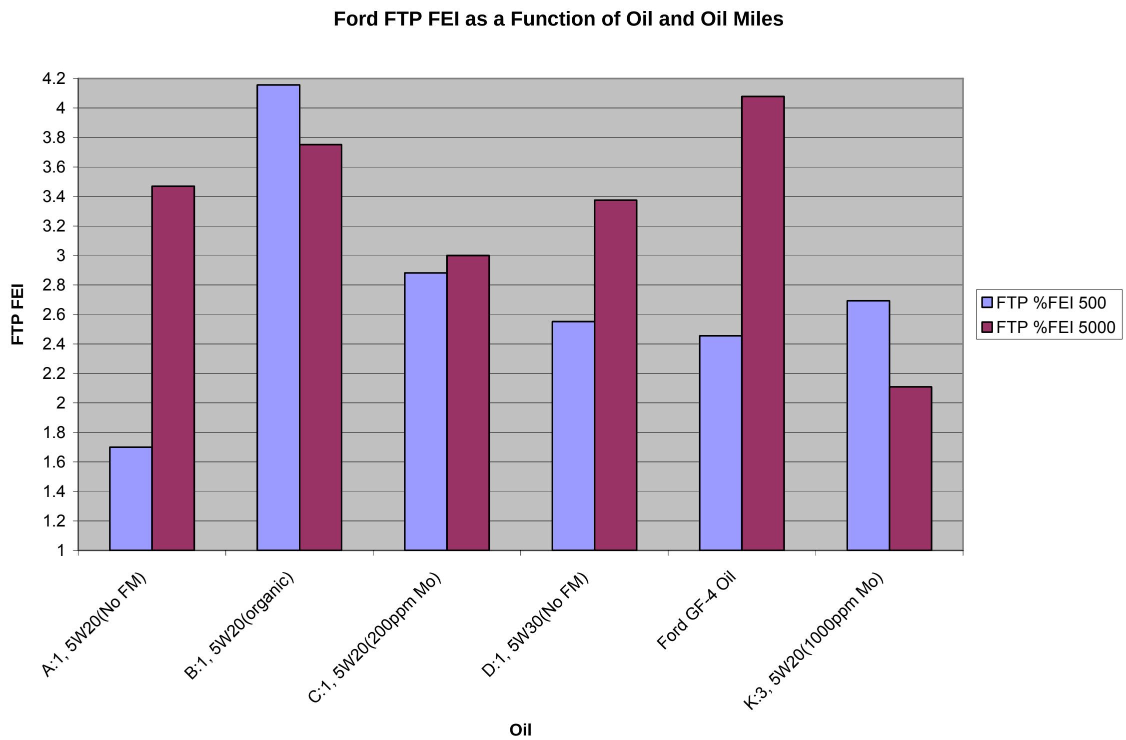


Figure 31. Ford FTP FEI as a Function of Oil and Oil Miles

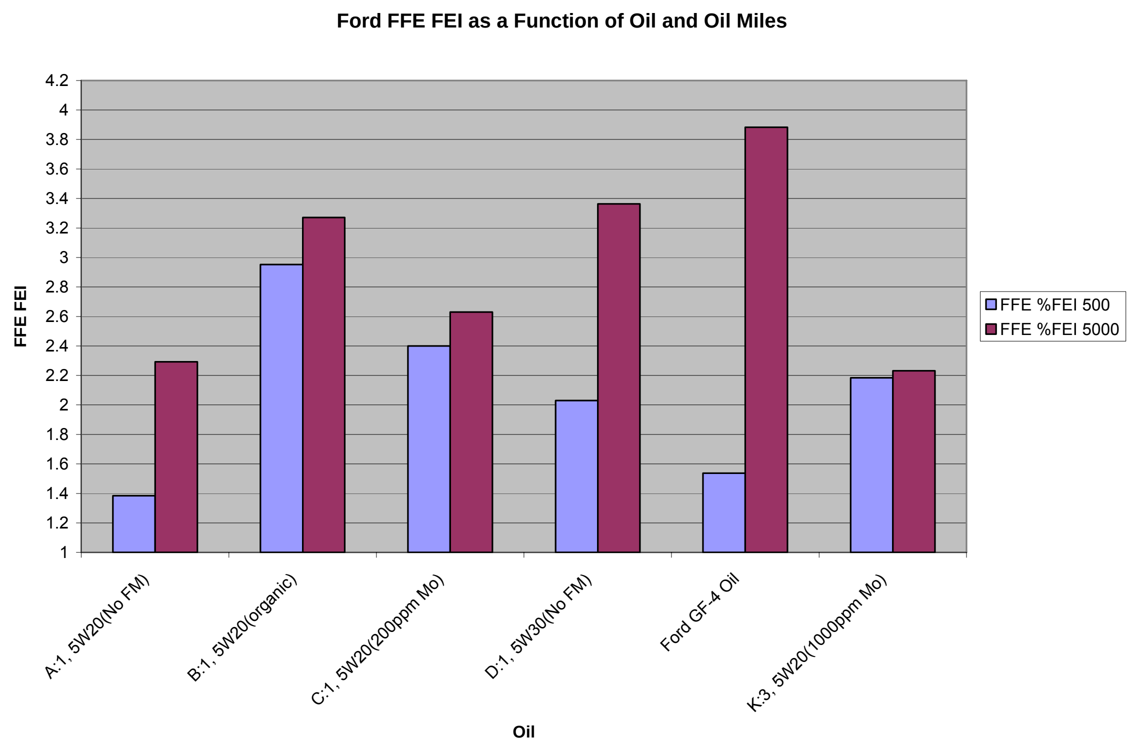


Figure 32. Ford Highway FEI as a Function of Oil and Oil Miles

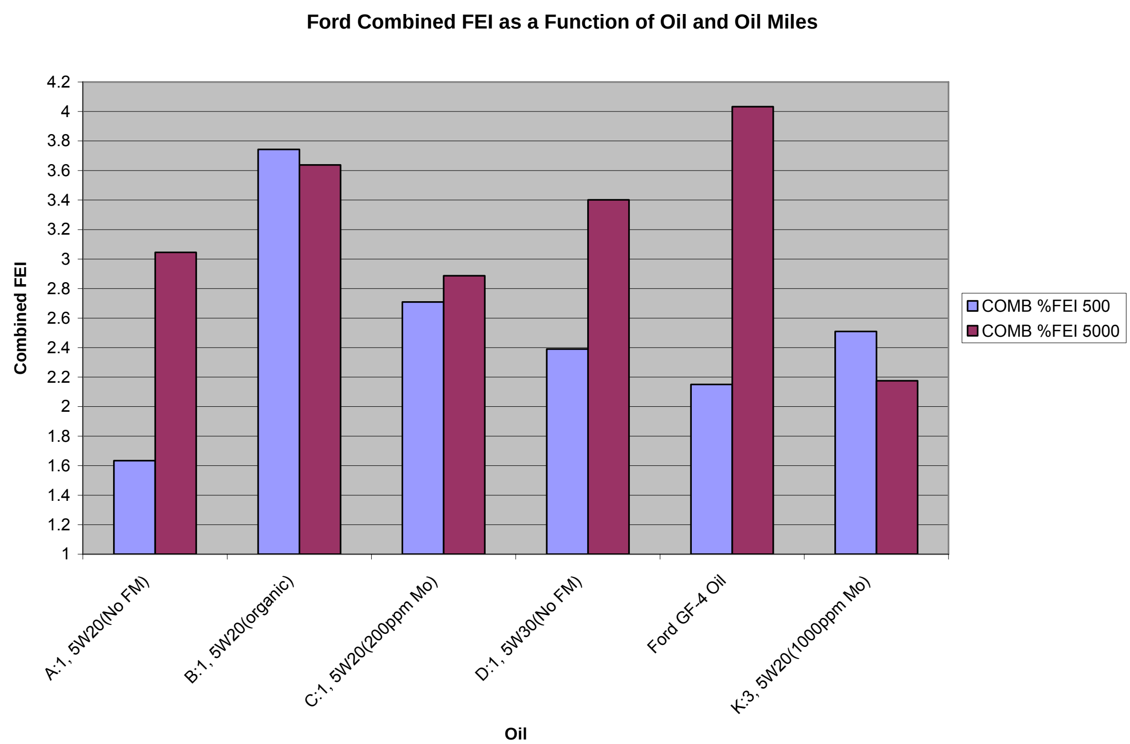


Figure 33. Ford Combined FEI as a Function of Oil and Oil Miles

8 Sequence VID Engine Dyno Set-up

8.1 Test Development Labs Description – Southwest Research Institute

Southwest Research Institute (SwRI) is an independent, nonprofit applied research and development organization. The staff specializes in the creation and transfer of technology in engineering and the physical sciences. The Institute occupies more than 1,200 acres in San Antonio, Texas, and provides nearly 2 million square feet of laboratories, test facilities, workshops and offices. It was founded in 1947. The Fuels and Lubricants Research Division is internationally known for its fuels and lubricants research activities. The Institute helps clients get automotive products to the market and keep them there in response to regulation and competition. A broad range of services is available for product research, product development and product qualification of automotive components and automotive fluids for on-road, off-road, rail, and water-borne transportation systems as well as recreational vehicles and stationary power equipment.

Intertek Automotive Research Intertek Automotive Research (IAR) provides engine and engine related testing, including dynamometer, vehicle, durability, fuels, lubricants, transmission, materials, analytical, and fuel system testing services to the automotive, petroleum and petrochemical industries. IAR is located in San Antonio, Texas, and is one of the largest independent automotive related testing organizations in the world. It was originally founded in 1953.

8.2 Sequence VID Engine Selection and Description

The engine that was selected for the development of the Sequence VID test was the General Motors 3.8L V6, Code LY7, often referred to as the High Feature V6 (HFV6). The LY7 was selected based upon it being a modern-day engine equipped with 4 valves per cylinder, and a variety of advanced engine technology. It was expected that the LY7 would be produced for many years after the introduction of the Sequence VID test to better ensure engine and parts availability for future testing.

The original LY7 calibration that was selected was used in the 2006 Cadillac CTS, and used the E55 engine control module (ECM). Bosch Corporation, the supplier of the E55 ECM, was contracted by OH Technologies (OHT) the “Special Parts Supplier” selected by the Consortium, to develop a special ECM calibration to allow the engine to operate under the conditions selected for the Sequence VID test. However, because of the timing for when a large number of engines could be purchased by OHT, it was necessary to update the engine to the calibration planned for use in the 2008 Cadillac SRX, which uses the E77 ECM. Because of the different ECM, it was necessary for Bosch to develop a special calibration using the E77 ECM. The ECM calibration is covered later in this report.

The 2008 LY7 (Cadillac SRX calibration) is a 3.6L V6. The engine comes equipped with 4 valves per cylinder, and uses variable valve timing to optimize engine operation. The model year engine and vehicle application for the original engine used in the development was a 2006 Cadillac CTS 3.6L High Feature (HF) V6. However, during the early stages of development it was determined by General Motors that it would be necessary to switch to a 2008 Cadillac SRX 3.6L High Feature (HF) V6, to ensure that a supply of this engine would be available for purchase from the GM plant through the end of 2008.

Changes From Stock Conditions Engine Control Module (ECM) - The Contract labs worked with Bosch in the modifications to the vehicle version of the ECM to allow the engine to be run on the dynamometer test stand. As indicated earlier, the original ECM used in the 2006 engine was an E55; with the change to the 2008 engine it was necessary to change the ECM to the E77.

Dyno Engine Harness & Throttle Box – A special Dyno harness was fabricated by OH Technologies with assistance from GM; this is a modified version of the vehicle version which mostly deletes unused connectors. This dyno version of the engine harness also includes a special throttle box/power control unit.

Variable Valve Timing – The 3.6L HF V6 is normally equipped with the ability for the ECM to control valve/camshaft timing in a vehicle application; this feature was disabled in the dyno engine version so it would not interfere with the fuel economy measurements. To do this a special set of camshaft drive gears has been used that will not allow variable valve timing because the oil pressure duty cycle is blocked.

Spark Angle - The 3.6L HF V6 is normally equipped with the ability for the ECM to control spark angle. In this application the spark angle was fixed in the ECM.

Oil Rings – It was determined that to increase the friction and have engines that were reasonably close to each other in this respect, that the oil ring package (rails and expander) should be at the upper tolerance of the original GM specification. OH Technologies obtained oil rings that fell within a proprietary GM specification and ensured that the test engines obtained these rings prior to testing.

Coolant System – Due to the external control on the normal system for vehicle coolant it was recommended by GM that this system be modified for the Dyno engines. To do this a specified restriction plug was installed into the coolant flow passage at the rear of the engine.

8.3 Special Hardware & Engine Assembly Oil Pan Version I & II (displacement block) – The original studies on Aging of the oil showed that with the 6.0 L oil charge it would take approximately 125-150 hrs to correlate to the vehicle data for oil aging so it was decided to lower the oil charge to 5.4 L. Due to the oil pan configuration and the 5.4 L charge OH Technology was requested to engineer a displacement block and therefore modified the original oil pan they supplied so that the engine oil level could be determined using a sight glass mounted on the side of the oil pan. Without the displacement block, there would have been a limited amount of oil in the pan, and it would have been very difficult to determine an accurate engine oil level using the sight glass.

Intake system – A modified version of the vehicle intake air system is used in this test type, and conditioned air is supplied into the normal inlet.

Special Engine/Stand Hardware - A listing of all special hardware for the installation of the engine to a dyno stand and special engine-related hardware is shown in Appendix F.

Engine Assembly - GM provided engines to Intertek and Southwest Research for test development. Following test development, OH Technologies purchased engines that were modified for distribution to the Consortium laboratories. All engines were disassembled for critical parts measurements and reassembled. This included modifications, per a GM supplied Engine Assembly Manual, at Engine Build Workshops. The Workshops were attended by both Intertek / Southwest Research and the Consortium laboratory rebuild personnel.

8.4 Setting Initial Test Conditions Using Buick-3, equipped with the 3.6L HF V6 engine, so as to not interfere with vehicle fuel economy testing, several FTP and Highway tests were run using the baseline oil, Oil Z, where numerous engine and vehicle operating parameters were recorded. These data included oil and coolant temperatures, engine speed, manifold absolute pressure (MAP), fuel consumed, throttle position, percent engine load, spark angle, cam phaser angle for each of four cams, transmission gear, and vehicle speed. An example of the temperatures and vehicle speeds are shown in Figure 3.

8.5 Test Conditions Study and Parameter Selection The goal of the VID test conditions studies and selection was to identify potential VID operating conditions that can be run in steady state and provide the best possible discrimination for viscometric and friction modifying properties of oil without a significant deviation from the conditions under which the FTP data were generated. This was accomplished by reviewing the FTP data from the selected 3.6L HF V6 engine, determining the range of conditions available to run in steady state in the current VID stand configuration, and identifying the combinations of conditions available in the VID stand configuration that would best represent the range of conditions seen in the FTP data.

Data acquired during FTP testing on Buick-3, with a 3.6L HF V6, was provided by GM and reviewed to identify potential test conditions for the VID test. The analysis included modal analysis, K-Means Cluster Analysis, and Principal Components Analysis of 0.1 second data acquired during all four stages of FTP testing; 26,452 data points for each variable with 71 data points missing for the MAP measurement. Historically, engine speed, load (as represented by MAP), and oil/coolant temperature have been identified as the primary variables affecting fuel economy, and the analysis was conducted to identify the ranges and relationships between these parameters to establish potential VID test conditions. See Figures 34 through 43 (Note: In Figures 34 through 53 the terms Phase 1, Phase 2, Phase 3, and Highway Phase have been substituted for Bag 1, Bag 2, Bag 3, and Highway Test, respectively, as the former terms had been used in the FTP test description section of the report). The FTP data review indicated that there was a large range of intake air temperatures during testing and further investigation of potential intake air temperature effects was suggested, Figures 44 and 45. Investigation by GM of the FTP process found that, while the ambient temperature was controlled during testing, the intake air experienced localized heating in the engine compartment. Further investigation was performed at Intertek Automotive Research during the initial VID stand set up using K-Means cluster analysis. K-Means cluster analysis begins by defining the variables to be clustered and the number of clusters to use. In this case the selected variables were engine speed, MAP, and oil temperature. Coolant temperature was not included due to the strong correlation with oil temperature and highly correlated variables would bias the cluster selection. Twelve clusters were selected because a twelve stage matrix was identified as the maximum practical number of stages. After the selection of variables and number of clusters the variables were iteratively grouped to obtain the minimum variability within a cluster and the maximum variability between clusters. The resulted in twelve different groups of conditions (speed, MAP and temperature) generated from the FTP data set that were as independent as possible. The median of each of these groups was calculated to provide an indication of how the groups differed and provide a potential starting point for steady state stage selection. . It is important to note that this is only one possible independent set of conditions; if a different number of clusters were selected, different analysis techniques used, or different variables were selected very different but equally valid conditions may have been identified.

The medians are shown in Figures 42 and 46. The medians provide some sense of how the data is concentrated since the sheer volume of data makes it hard to identify which conditions occur more often than others, and include the influence of the variables that are not on the chart. The medians on the speed and MAP chart take temperature conditions into account and the medians on the temperature chart take speed and MAP into account. This is best illustrated by the two different clusters at the low and mid temperatures on the temperature chart. Two different clusters at very similar temperatures show that these temperatures are occurring independently at different speed and/or MAP conditions.

Since the statistics group used a designed experiment approach to the initial matrix having selected speed, MAP (load), and temperature conditions that bracketed the majority of the data without going outside of the FTP operating conditions. The cluster medians with extreme values did serve as a good confirmation for the conditions that were selected

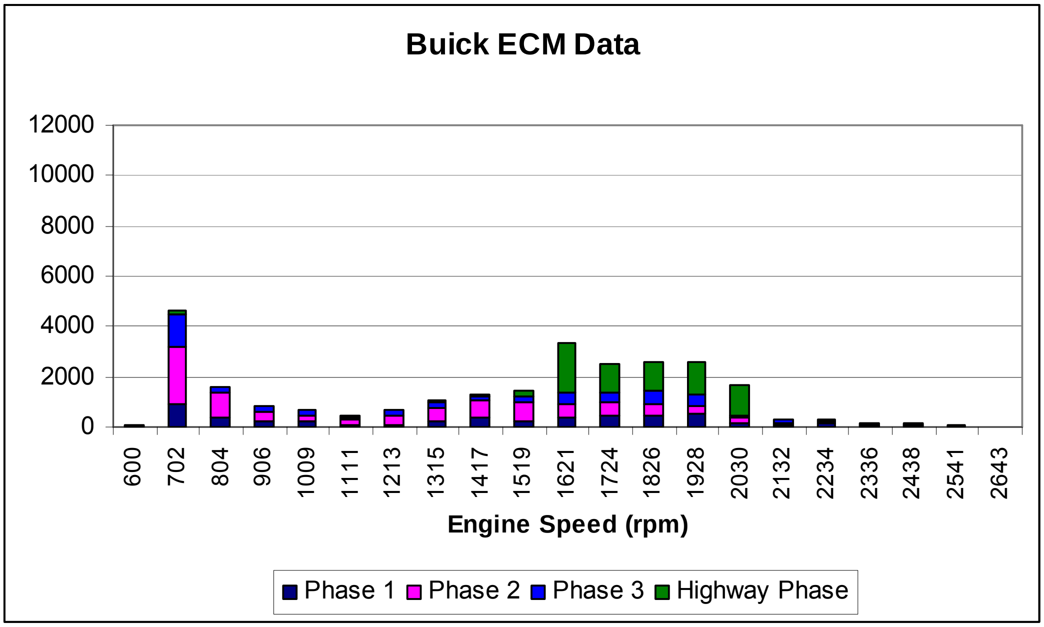


Figure 34. Engine Speed During FTP and HWFET Tests

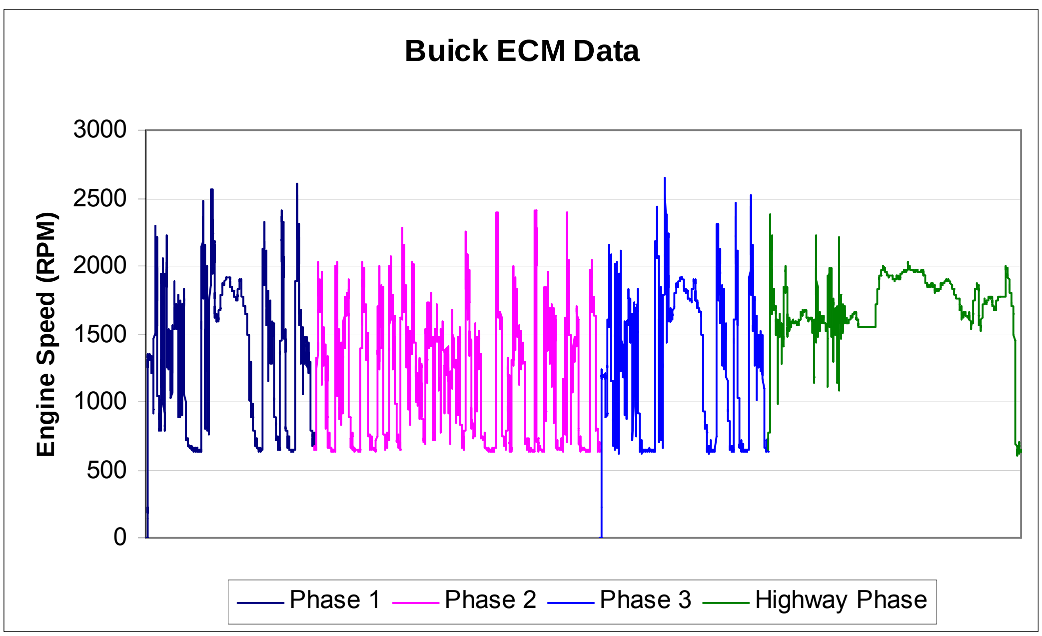


Figure 35. Engine Speed During FTP and HWFET Tests

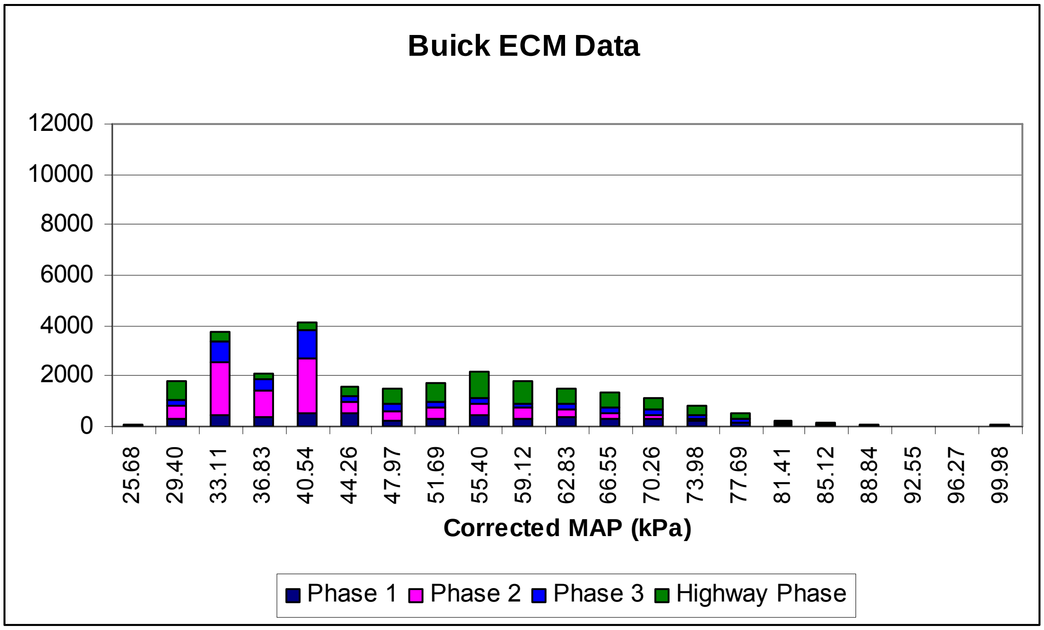


Figure 36. Engine MAP During FTP and HWFET Tests

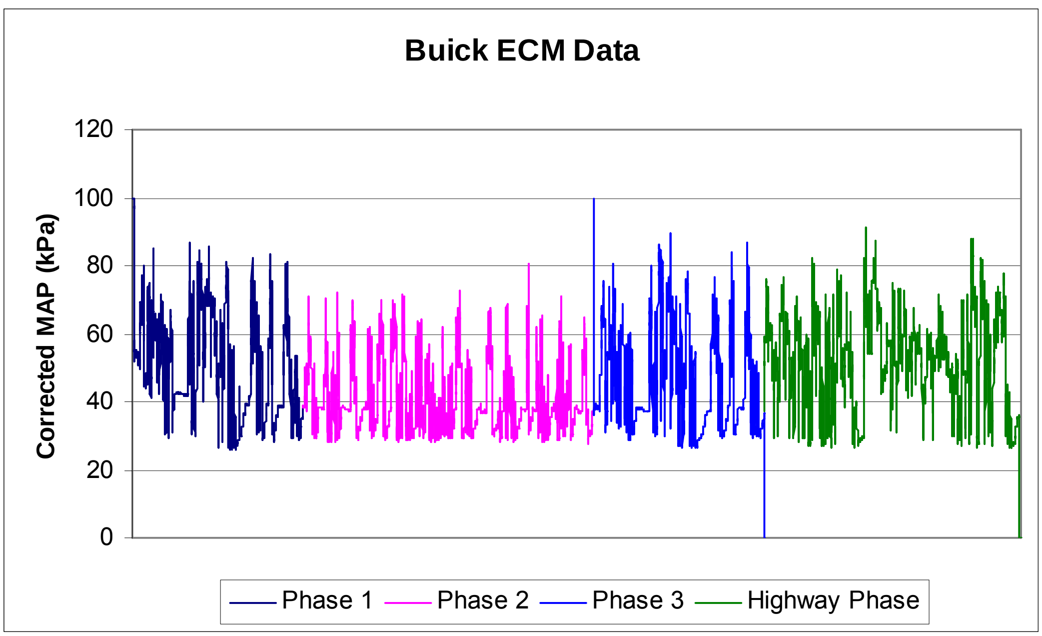


Figure 37. Engine MAP During FTP and HWFET Tests

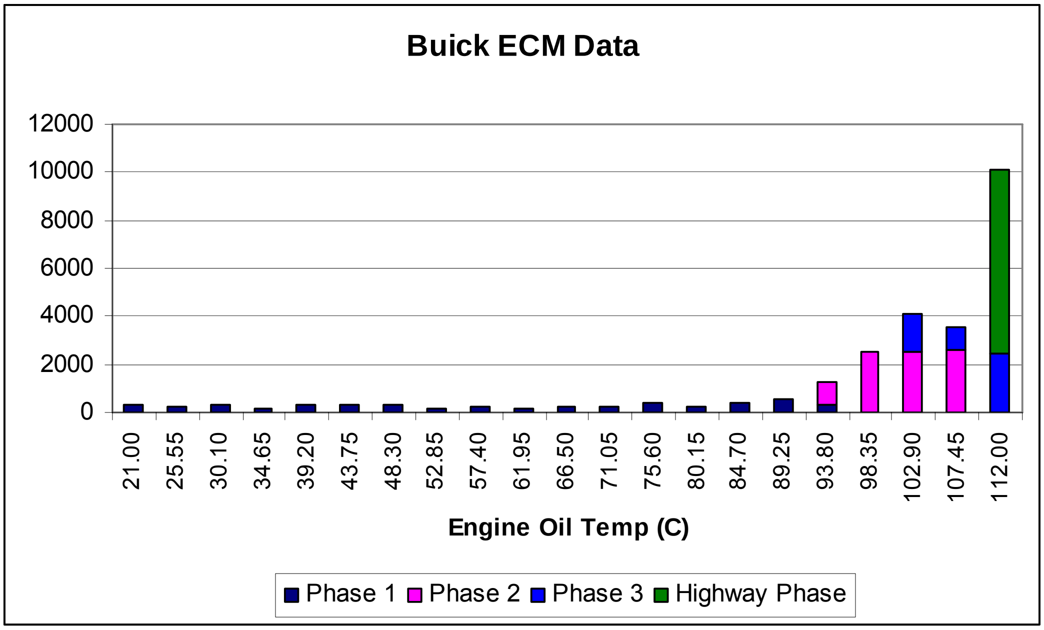


Figure 38. Engine Oil Sump Temperature During FTP and HWFET Tests

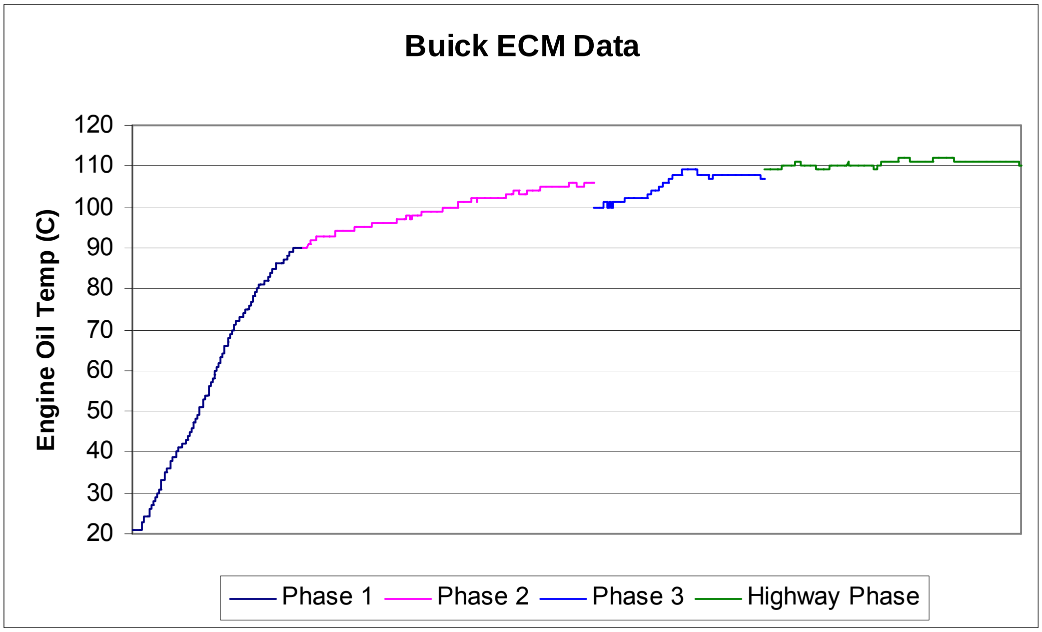


Figure 39. Engine Oil Sump Temperature During FTP and HWFET Tests

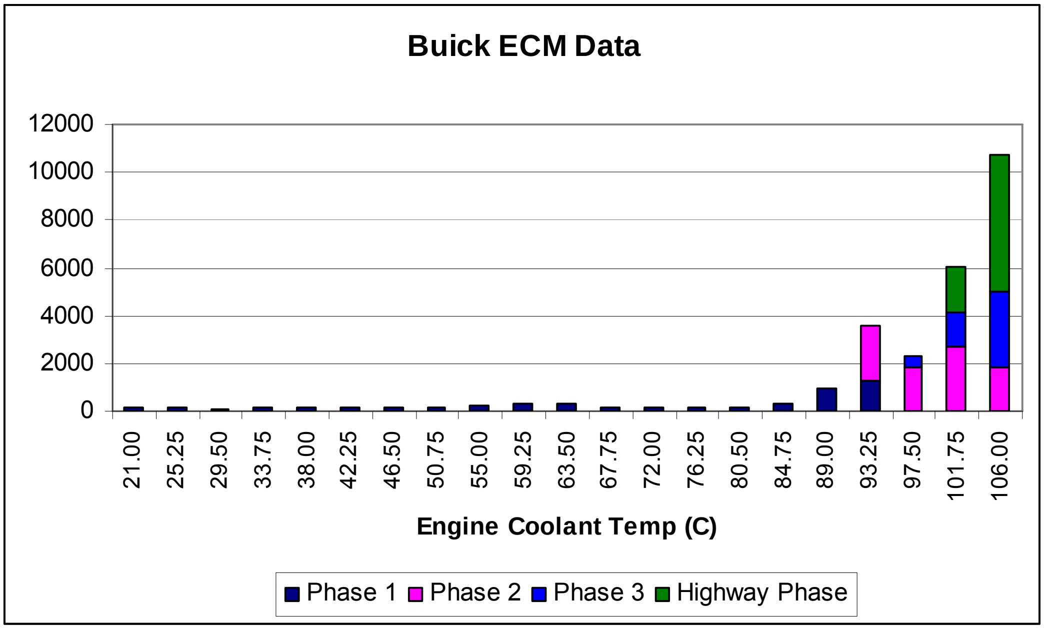


Figure 40. Engine Coolant Temperature During FTP and HWFET Tests

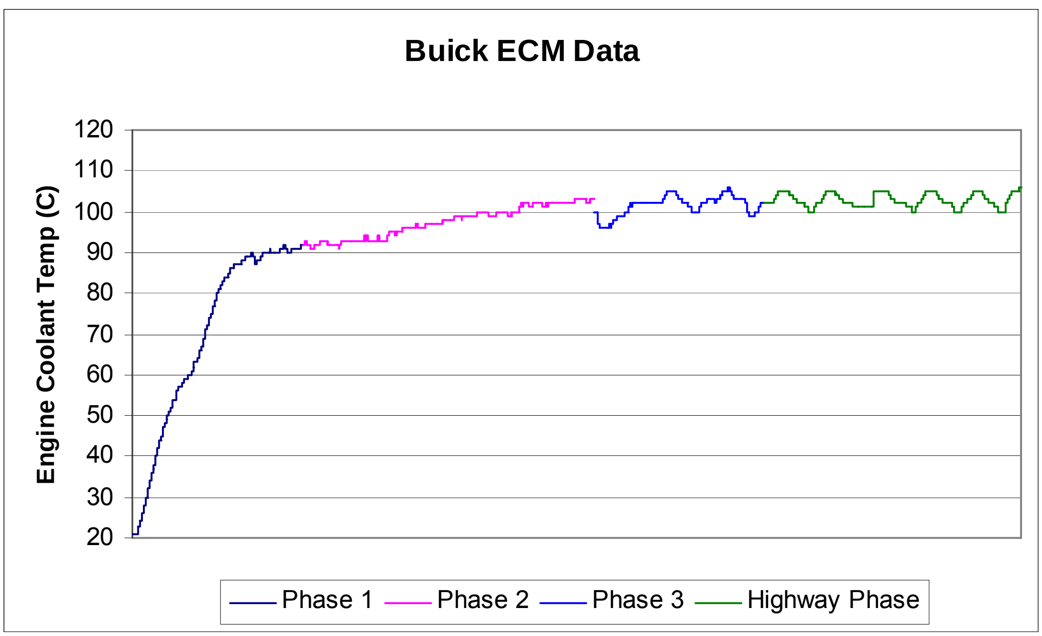


Figure 41. Engine Coolant Temperature During FTP and HWFET Tests

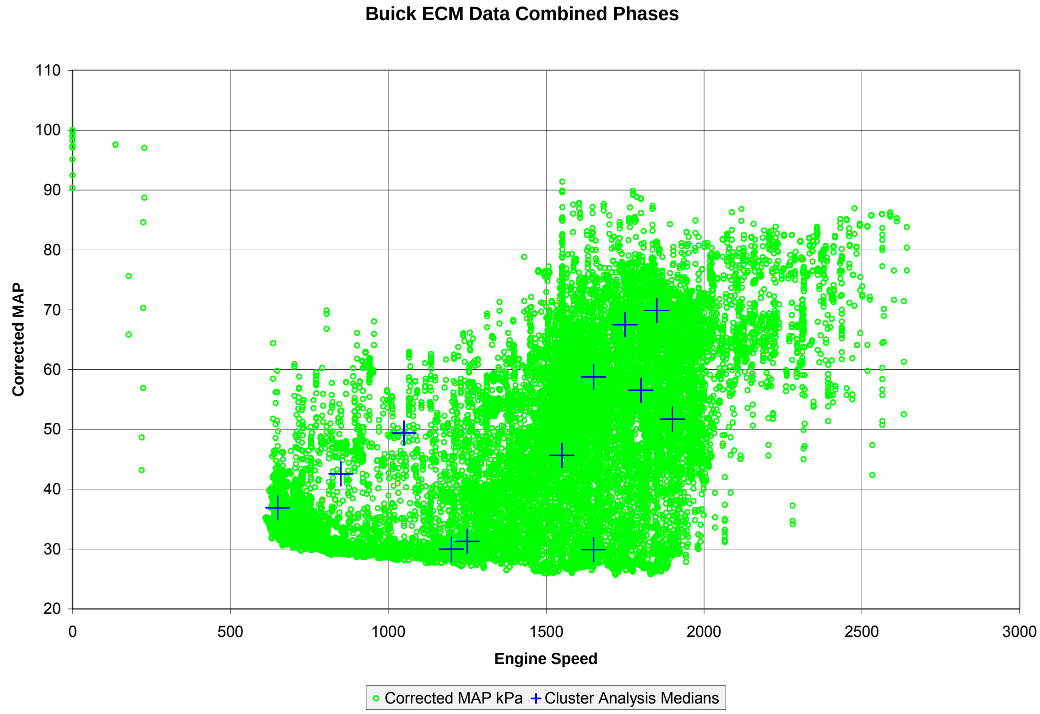


Figure 42. Engine MAP and Speed Scatter Plot with Cluster Analysis Medians During FTP and HWFET Tests

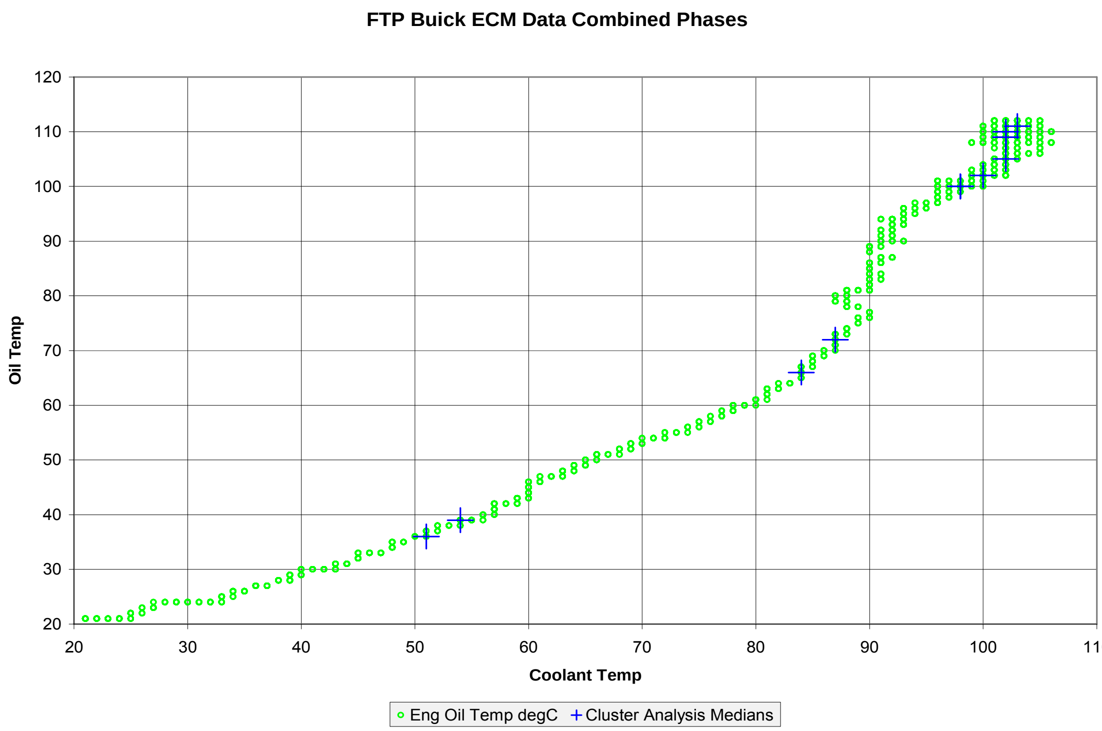


Figure 43. Engine Oil and Coolant Temperature Scatter Plot with Cluster Analysis Medians During FTP and HWFET

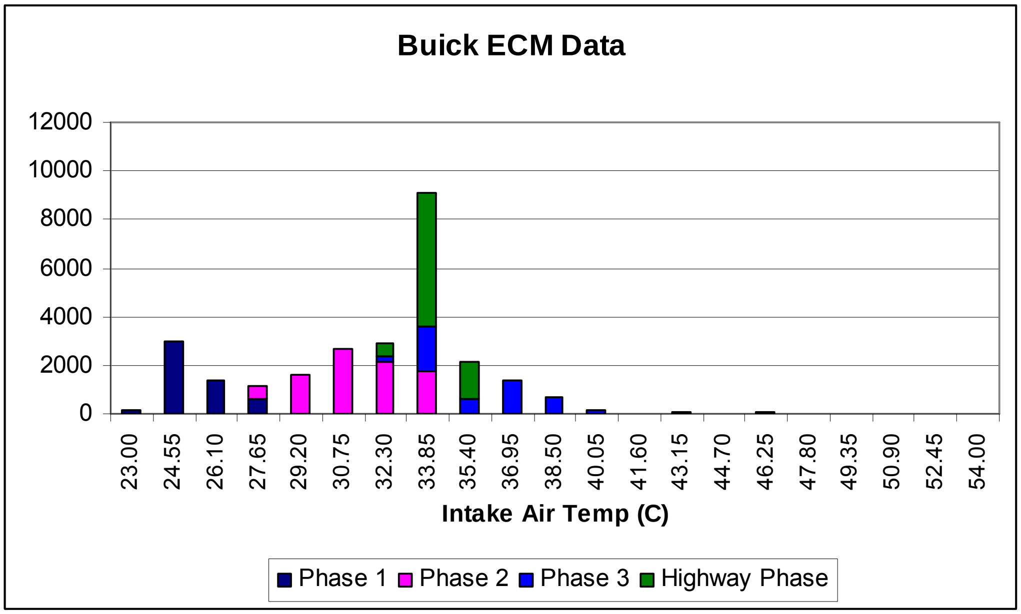


Figure 44. Engine Intake Air Temperature During FTP and HWFET Tests

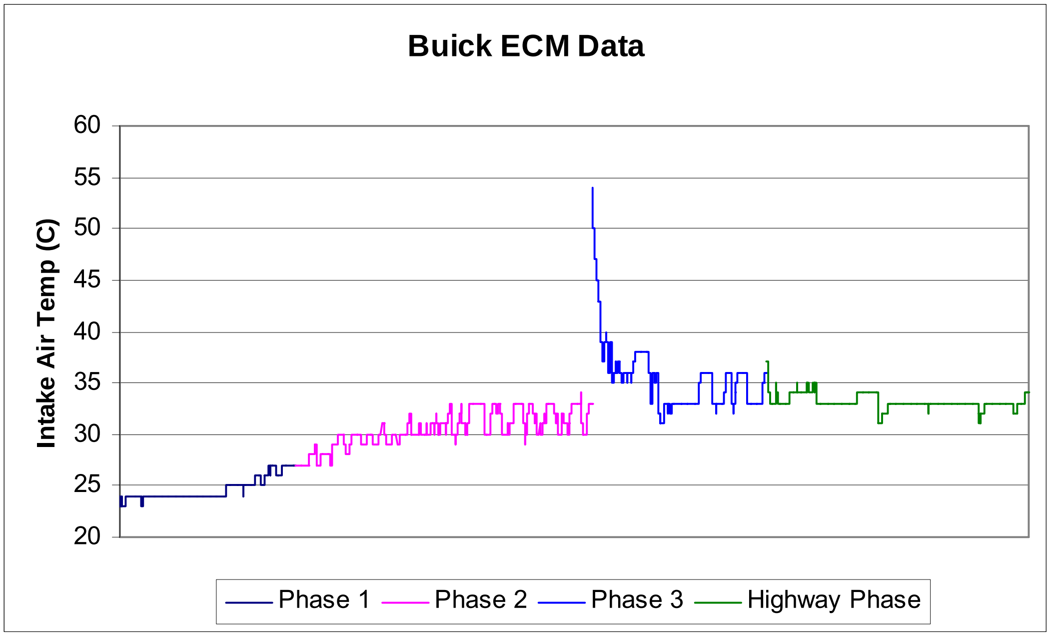


Figure 45. Engine Intake Air Temperature During FTP and HWFET Tests

The initial VID stand set up at Intertek Automotive Research was conducted on a 3.6L HF V6 engine with full variable valve and cam timing using the original ECM and prior to any extensive work to define control loops or set points. The VID stand set up work included a sequence of runs designed to determine the range of speed, load, and oil/coolant temperatures the current stand-engine combination was capable of sustaining, and to evaluate the potential significance of intake air temperature set points. Ultimately 37 runs of one-half to one hour each were conducted with settings of approximately 700, 1500 and 2,200 RPM for speed, 20, 45, 58, and 120 N-m for load, 20% and 80% for oil and coolant temperature control valve positions, and intake air temperatures from 26 to 40°C. Data was acquired as a single snapshot reading at the end of each run sequence. Review of the data found that the VID stand-engine set up was capable of running conditions similar to the majority of FTP testing, Figures 46 and 47, and found that intake air temperature did not require additional consideration as a test variable in the initial VID stage matrix design, Figure 48.

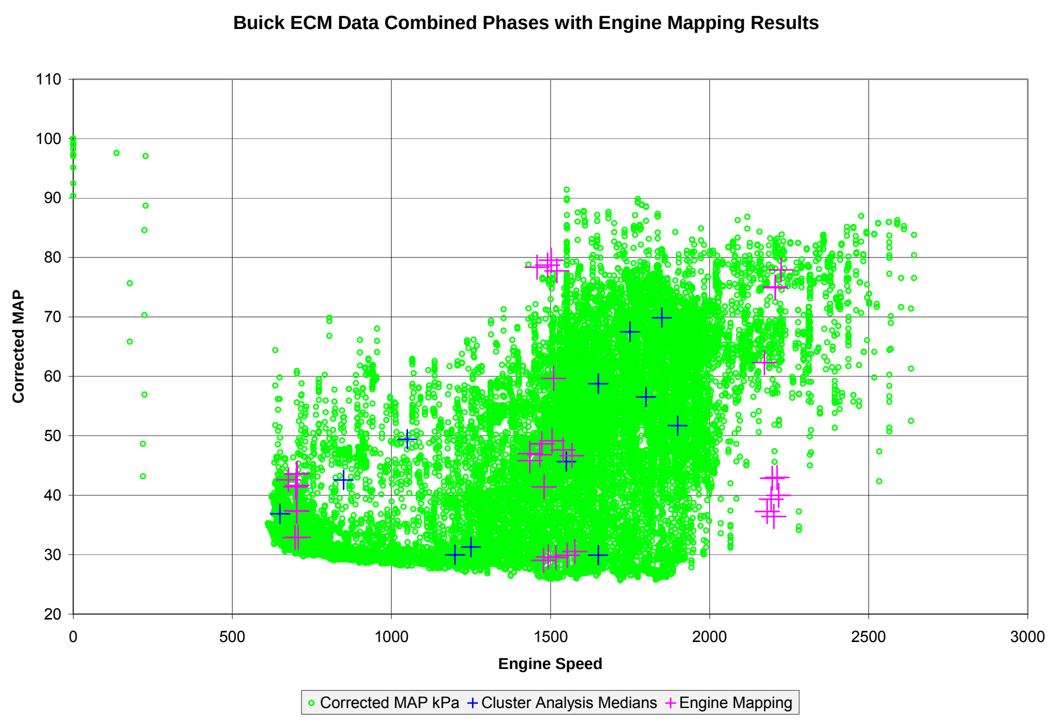


Figure 46. Engine MAP and Speed Scatter Plot with Cluster Analysis Medians During FTP and HWFET Tests and Engine Mapping Points

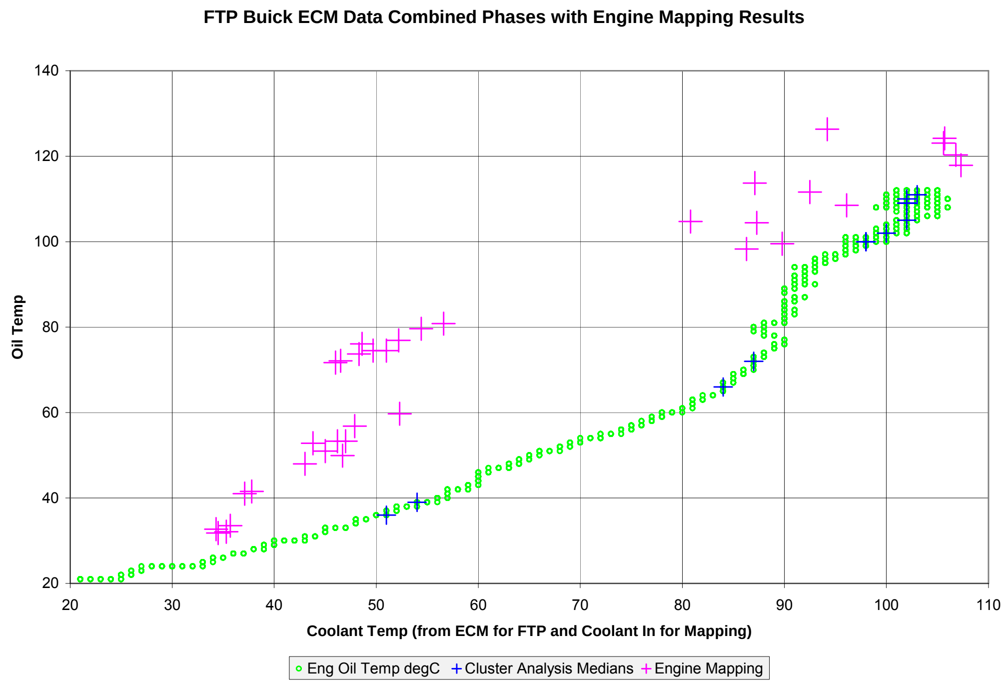


Figure 47. Engine Oil and Coolant Temperatures Scatter Plot with Cluster Analysis Medians During FTP and HWFET Tests and Engine Mapping Points

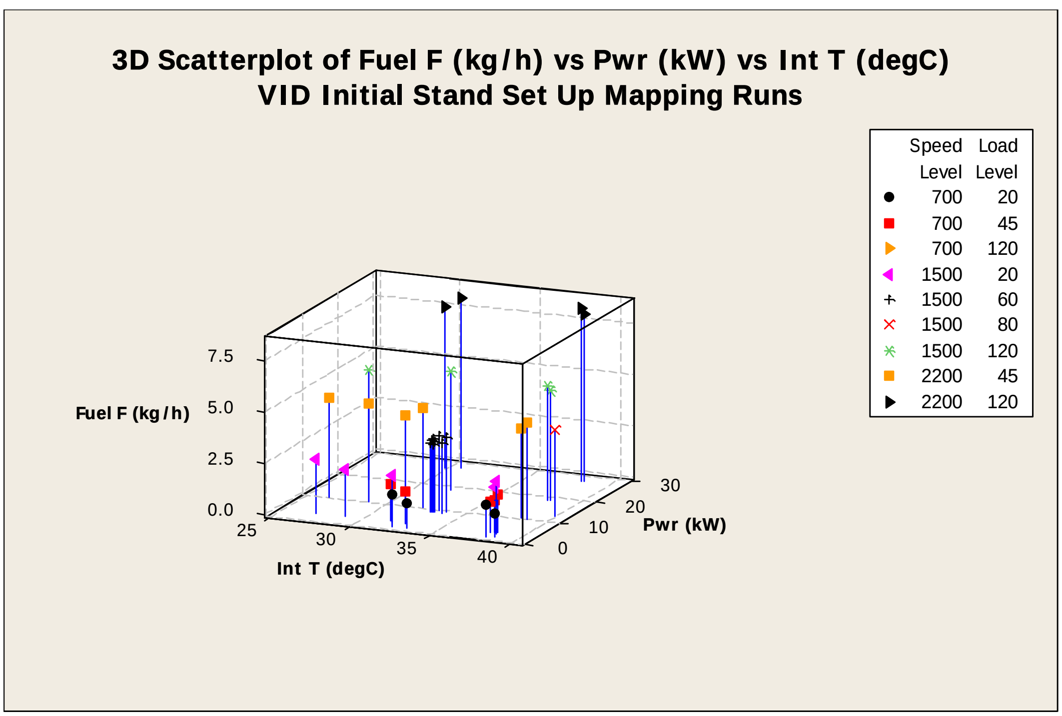


Figure 48. Scatter Plot of Fuel Flow, Power and Intake Temperature

Initial stage selection for the VID test was based on the data reviewed and the known historical effect of speed, load, and oil/coolant temperature on fuel economy. Based on the strong correlation between oil and coolant temperature in the FTP data and the desire to identify stages that provide discrimination a three factor, two level, full factorial experiment with a single center point (nine stages) was initially proposed, Table 13, covering a range of parameters that accounted for the majority of FTP conditions and was within the capabilities of the current VID stand-engine configuration. The nine stages were further refined during initial testing at Intertek Automotive Research and Southwest Research Institute to ensure adequate control while running in steady state and to better align the coolant and oil temperature relationship based on observed differences in the FTP and stand measurement techniques, Table 14. During this period of stage refinement it was determined that cam timing and valve time at engine speeds above idle would be fixed which resulted in considerably lower observed MAP values for the same load conditions in many stages. Review at the Consortium level ultimately resulted in one additional stage being added, and lower intake air temperature set points being selected to define ten stages for the initial VID matrix testing, Table 15, that were representative of the FTP test conditions, Figures 49 and 50.

Table 13. Suggested VID Stage Matrix July, 19, 2006

VID Test Conditions	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9
Speed, rpm	700	700	700	700	1500	2000	2000	2000	2000
Estimated MAP, kPaA	≈ 30	≈ 30	≈ 40	≈ 40	≈ 55	≈ 40	≈ 40	≈ 80	≈ 80
Torque, NM	20.0	20.0	40.0	40.0	70.0	40.0	40.0	110.0	110.0
Power, kw	1.5	1.5	2.9	2.9	11.0	8.4	8.4	23.0	23.0
Oil Temp, °C	35	115	35	115	80	65	115	65	115
Coolant In Temp, °C	49	109	49	109	87	84	109	84	109
Intake Air Temp, °C	33								

Table 14. Suggested VID Stage Matrix August 11, 2006

VID Test Conditions	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9
Speed, rpm	695	695	695	695	1500	2000	2000	2000	2000
Aproximate MAP, kPaA	≈ 33	≈ 34	≈ 38	≈ 41	≈ 44	≈ 34	≈ 34	≈ 54	≈ 56
Torque, NM	20.0	20.0	40.0	40.0	70.0	40.0	40.0	105.0	105.0
Power, kw	1.5	1.5	2.9	2.9	11.0	8.4	8.4	22.0	22.0
Oil Temp, °C	35	115	35	115	80	65	115	65	115
Coolant In Temp, °C	35	109	35	109	80	65	109	65	109
Intake Air Temp, °C	33								
Intake Cam Angle, Deg	0								
Exhaust Cam Angle, Deg	0								
Spark Angle, Deg	Variable				27				

Table 15. Matrix II Stages

VID Test Conditions	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10
Speed, rpm	695	695	695	695	1500	2000	2000	2000	2000	1500
Aproximate MAP, kPaA	≈ 33	≈ 34	≈ 38	≈ 41	≈ 44	≈ 34	≈ 34	≈ 54	≈ 56	≈ 58
Torque, NM	20.0	20.0	40.0	40.0	70.0	40.0	40.0	105.0	105.0	105.0
Power, kw	1.5	1.5	2.9	2.9	11.0	8.4	8.4	22.0	22.0	16.5
Oil Temp, °C	35	115	35	115	80	65	115	65	115	115
Coolant In Temp, °C	35	109	35	109	80	65	109	65	109	109
Intake Air Temp, °C	29									
Intake Cam Angle, Deg	0									
Exhaust Cam Angle, Deg	0									
Spark Angle, Deg	Variable				27					

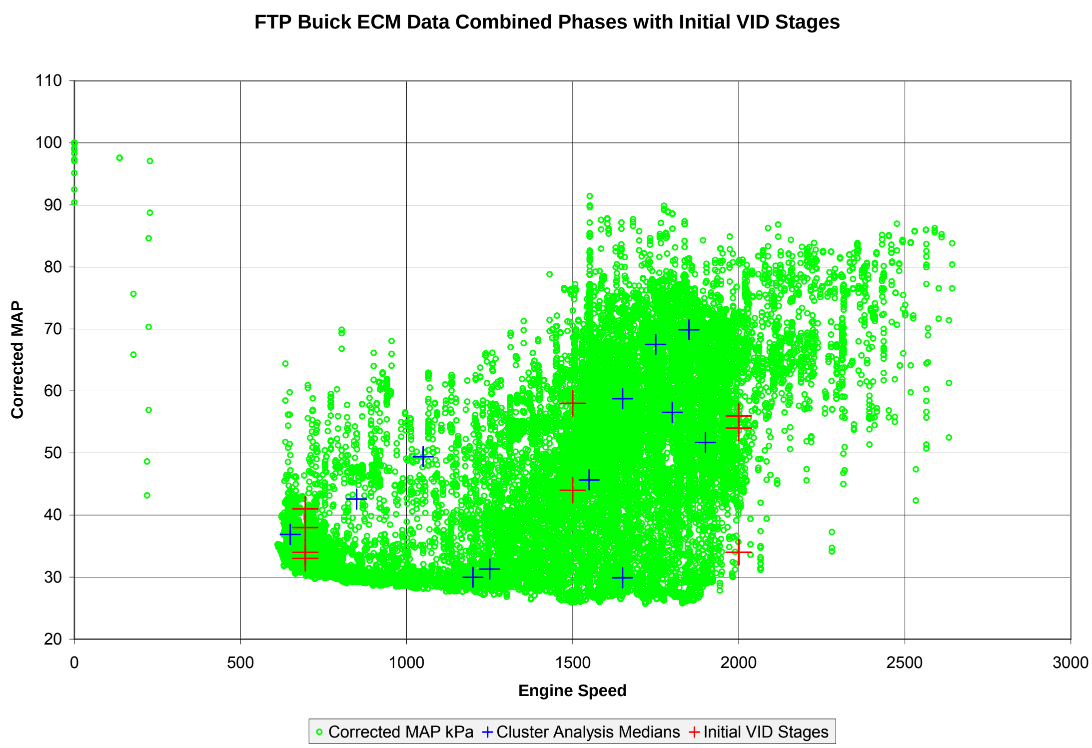


Figure 49 Engine MAP and Speed Scatter Plot with Cluster Analysis Medians During FTP and HWFET Tests and Initial VID

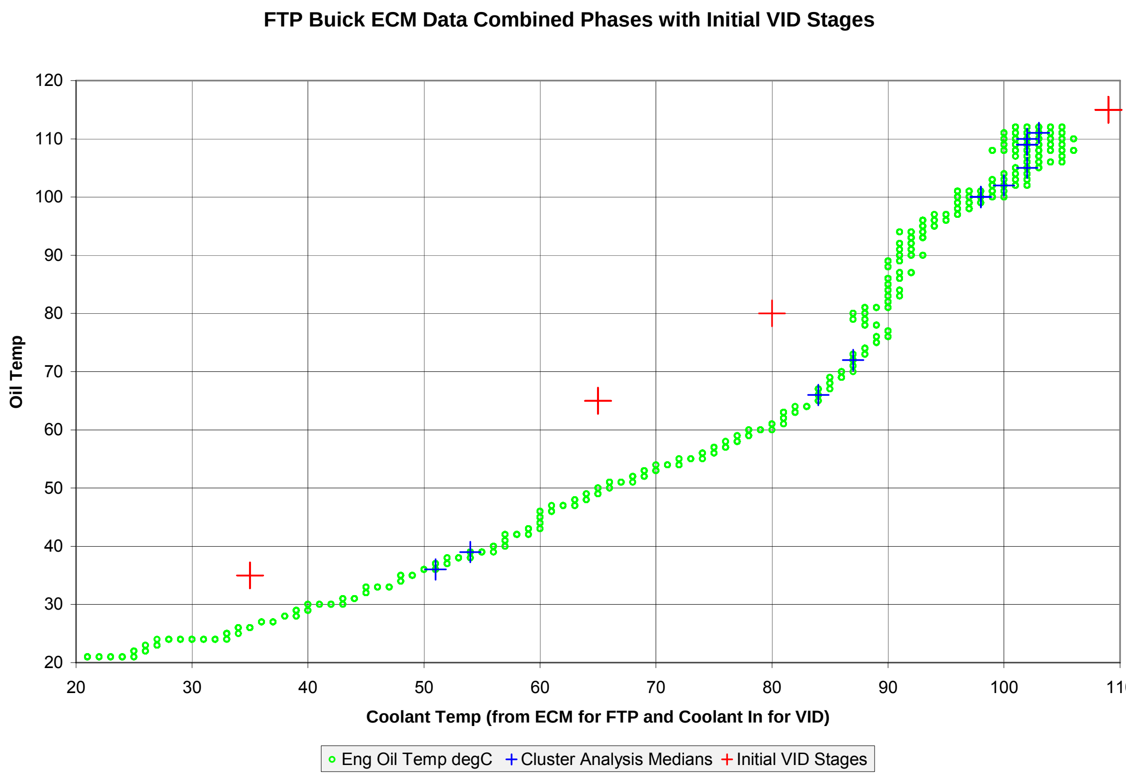


Figure 50. Engine Oil and Coolant Temperatures Scatter Plot with Cluster Analysis Medians During FTP and HWFET Tests and Initial VID

8.6 Fuel Dilution Study and Stage Order Selection The initial VID matrix testing was defined as a matrix of ten stages designed to evaluate the effect of engine speed, load, and temperature on an oil's contribution to fuel economy. Traditionally, the stage order in dynamometer-based fuel economy testing was run with stages ordered hot to cold as cold stages were known to produce more fuel dilution than hot stages, and placing the cold stages at the end of the stage order minimized the overall impact of fuel dilution on the results. There were concerns raised early in VID test development that, due to the large number of initial stages, running hot to cold could result in cumulative fuel dilution effects that might ultimately bias stage selection unfavorably. A three test matrix was designed to evaluate stage order effects on fuel dilution and quantify fuel dilutions in the VID test.

The three test matrix was conducted back to back in the same engine at Southwest Research Institute on baseline oil, with samples taken during the last five minutes of each stage, and with an additional 300 ml of oil charge to reduce potential effects caused by low oil levels due to sampling. All fuel dilution analysis was conducted at Intertek Automotive Research to avoid potential lab effects when comparing the fuel dilution matrix results to results from the FTP testing. The three tests consisted of stages ordered hot to cold, cold to hot, and mixed, Table 16.

Table 16. Fuel Dilution Design Matrix

VID Test Conditions	Stage A	Stage B	Stage C	Stage D	Stage E	Stage F	Stage G	Stage H	Stage I	Stage J
Speed, rpm	695	695	695	695	1500	2000	2000	2000	2000	1500
Torque, NM	20.0	20.0	40.0	40.0	70.0	40.0	40.0	105.0	105.0	105.0
Power, kw	1.5	1.5	2.9	2.9	11.0	8.4	8.4	22.0	22.0	16.5
Oil Temp, °C	35	115	35	115	80	65	115	65	115	115
Coolant In Temp, °C	35	109	35	109	80	65	109	65	109	109
Hot to Cold Run Order	10	2	9	3	6	8	4	7	1	5
Cold to Hot Run Order	1	10	2	9	5	3	6	4	8	7
Mixed Run Order	8	7	3	6	1	5	2	10	9	4

Graphical review of the fuel dilution results from each of the three tests, Figures 51 through 53, found that consecutive cold stages resulted in cumulative fuel dilution effects and that high temperature stages could reduce the amount of fuel dilution present from earlier stages. Based on these results it was determined that a mixed stage order that included the coldest stages later in the test would provide the best opportunity to reduce potential fuel dilution effects during the VID matrix data analysis. A confirmation run with the suggested stage order, Table 17, was conducted at Intertek Automotive Research, Figure 54. Based on the results of the confirmation run the new mixed stage order was accepted for all future VID matrix testing.

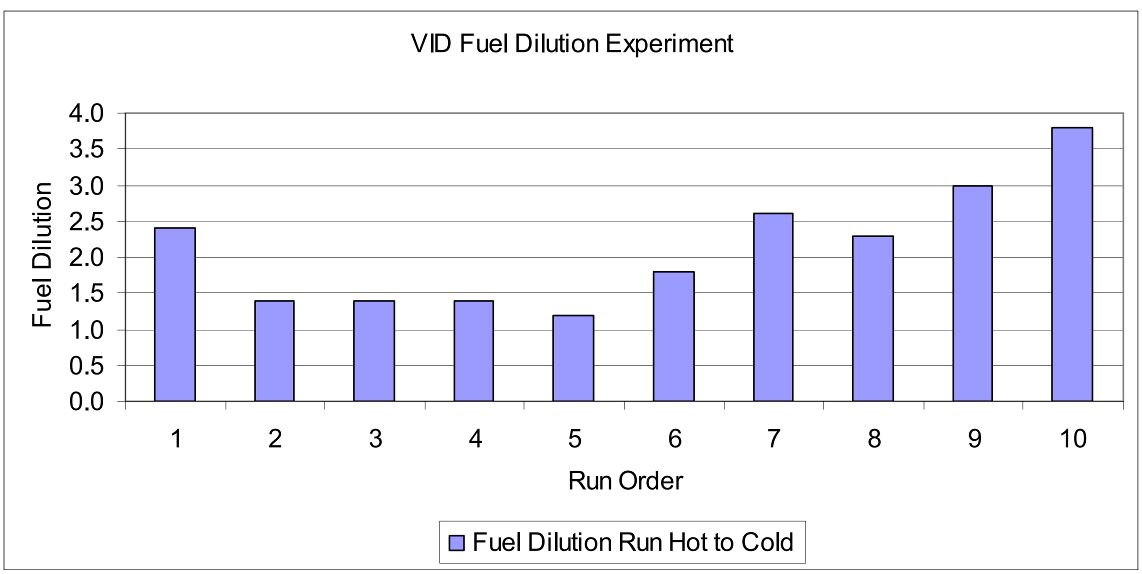


Figure 51. Fuel Dilution – Hot-to-Cold Test Order

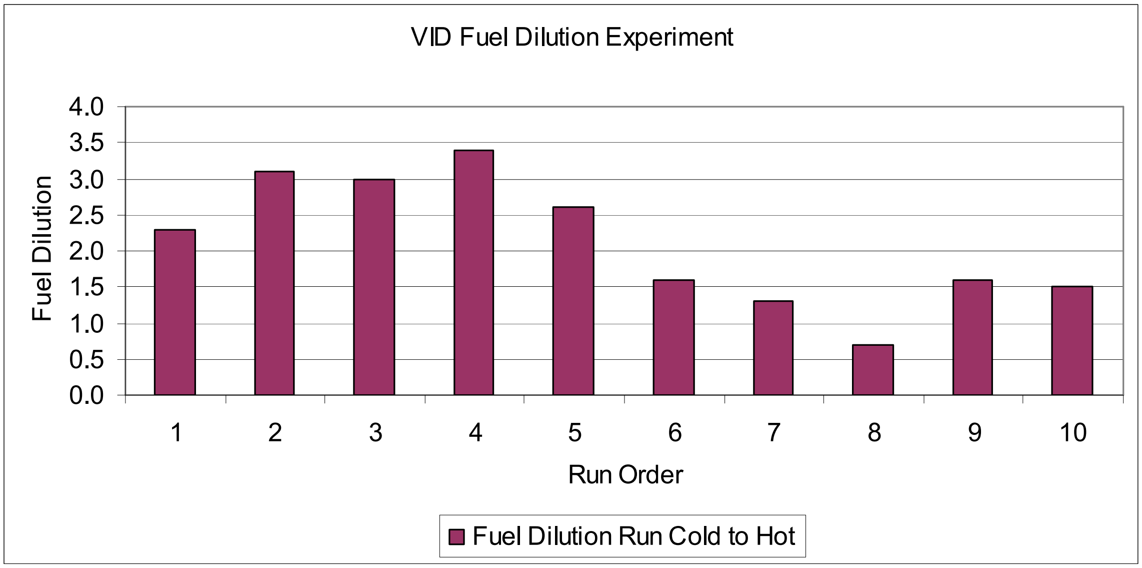


Figure 52. Fuel Dilution – Cold-to-Hot Test Order

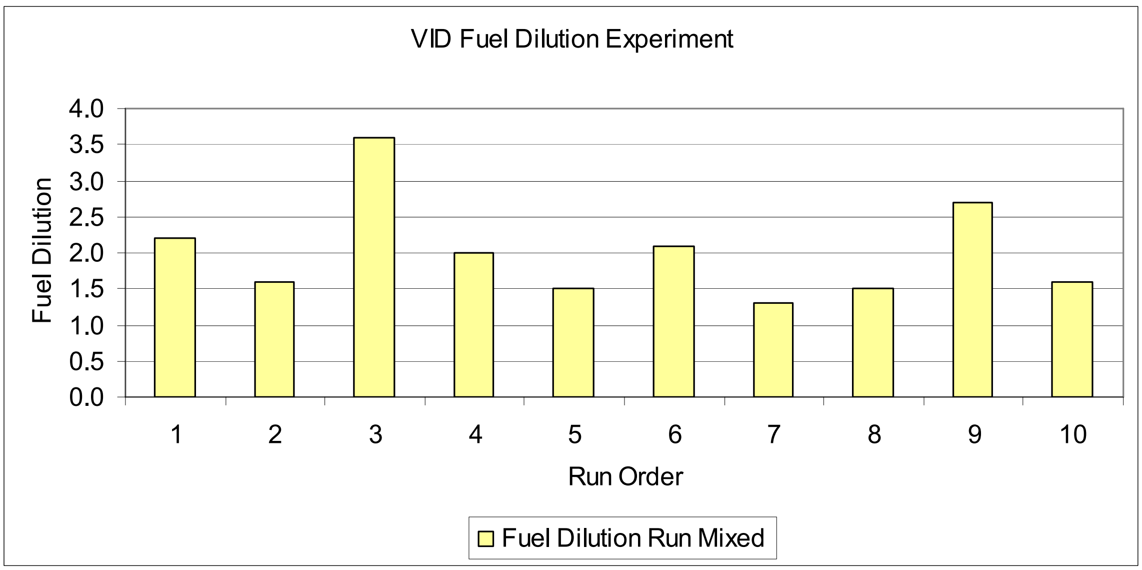


Figure 53. Fuel Dilution – Mixed Temperature Test Order

Table 17. New Mixed Stage Order

VID Test Conditions	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10
Speed, rpm	2000	2000	2000	2000	1500	1500	695	695	695	695
Torque, NM	40.0	40.0	105.0	105.0	105.0	70.0	20.0	20.0	40.0	40.0
Power, kw	8.4	8.4	22.0	22.0	16.5	11.0	1.5	1.5	2.9	2.9
Oil Temp, °C	115	65	115	65	115	80	115	35	115	35
Coolant In Temp, °C	109	65	109	65	109	80	109	35	109	35

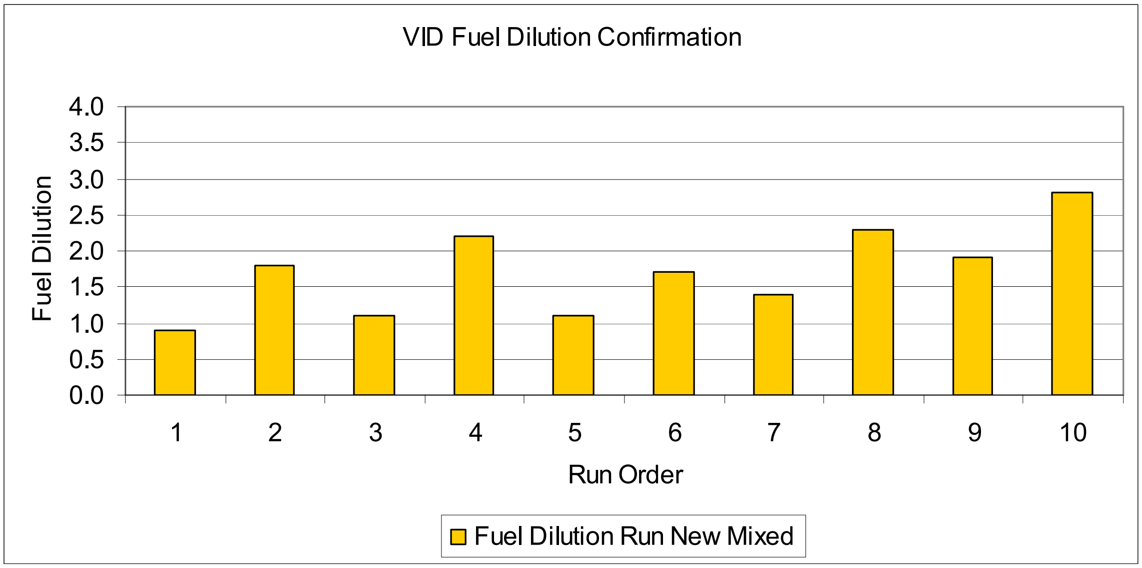


Figure 54. Fuel Dilution – New Mixed Temperature Test Order

8.7 Sense Check Testing When the decision was made to switch from the 2006 LY7 engine to the 2008 LY7 engine there was an expected delay period of one month or more for the new engines to be built and ECM calibration done when testing was not possible using the new engine. It was decided that since the 2006 engines were in place at the test labs that several tests could be run that would give the Consortium members some sense of what results might be expected in the Sequence VID configuration. These "Sense Check" tests used the expected ten stages described earlier and shown in Table 18. The Sense Check tests were run on Oils A, B, D, and E using Oil Z as the baseline oil. The test procedure followed was set up to only compare the test oils under fresh oil conditions; fresh actually meaning after 16 hours of aging, which is equivalent to the amount of oil aging for FEI1 in the Sequence VIB Test. Baseline testing (termed Baseline Before, BLB) was conducted prior to introducing the test oil into the engine. The 16 hours of aging of the test oil was accomplished at 2,000 engine RPM, 110°C oil temperature and 70 Nm engine load. Baseline testing after the test oil (Baseline After, BLA) was also conducted after flushing the engine using Oil F, the high detergent-level flushing oil.

Table 18. Sense Check Test Conditions

Operating Targets										
Stage	1	2	3	4	5	6	7	8	9	10
Speed, rpm	2000	2000	2000	2000	1500	1500	695	695	695	695
Torque, NM	40	40	105	105	105	70	20	20	40	40
Power, kw	8.4	8.4	22	22	16.5	11	1.5	1.5	2.9	2.9
Oil Temp, °C	115	65	115	65	115	80	115	35	115	35
Coolant In Temp, °C	109	65	109	65	109	80	109	35	109	35
Coolant Flow, LPM	60									
Intake Air Temp, °C	27									
Fuel Rail Temp, °C	20									
Fuel Pressure, kPa	400									
Intake Cam Angle, Deg	0									
Exhaust Cam Angle, Deg	0									
Spark Angle, Deg	27						Variable			
Flush Conditions: Speed = 1500, Load = 70 Nm, Coolant Temp = 109 °C, Oil Temp = 115 °C										
Aging Conditions: Speed = 2000, Load = 70 Nm, Coolant Temp = 100 °C, Oil Temp = 110 °C										

The Sense Check series included Oil A (SAE 5W-20 with no friction modifier), Oil B (SAE 5W-20 containing an organic-type friction modifier), Oil D (SAE 5W-30 with no friction modifier) and Oil E (SAE 10W-30 with no friction modifier). The results from these Sense Check tests are contained in Table 19. The percent changes in fuel consumption shown in Table 19 were calculated from the average of the BLB and BLA fuel consumption and the fuel consumption results for the test oil for each of the ten stages. The overall result for the test oil used the average of the BLB and BLA total fuel consumed for all ten stages compared to the total fuel consumed in all ten stages for the test oil.

Table 19 shows that in two stages, 7 and 9, that fuel consumption increased with Oil A compared to the baseline Oil Z. The second test with Oil A showed this effect only in Stage 7, with only a small improvement in Stage 9. In contrast, Oil B (same oil as Oil A, but containing an organic friction modifier) showed a large improvement in fuel consumption in stages 7 and 9, an indication of the effectiveness of friction modification under the conditions of Stages 7 and 9. Oils D and E which are higher viscosity versions of Oil A, show that under the conditions seen in Stages 8 and 10, viscosity can have a large effect on fuel consumption. Based upon the responses of the various oils evaluated in the Sense Check tests members of the Consortium were encouraged that the proposed Sequence VID engine and initial operating conditions would be able to show differences among the oils related to the use of friction modifiers and viscosity grades.

Table 19. Fuel Consumption Improvements in Sense Check Tests

Stage	1	2	3	4	5	6	7	8	9	10	Over-all
Oil A 5W-20	2.25	4.72	1.03	2.60	0.21	2.05	-0.92	4.67	-1.23	5.25	2.04
Oil A 5W-20-rpt	2.69	5.29	1.17	3.01	0.73	2.43	-0.76	6.04	0.12	4.68	2.46
Oil B 5W-20 + Org FM	3.95	5.30	2.11	2.83	1.98	2.83	3.51	6.29	4.22	4.38	3.26
Oil B 5W-20 + Org FM-rpt	3.88	5.16	2.19	3.06	2.23	2.76	3.36	7.32	2.25	6.57	3.38
Oil D 5W-30	2.60	4.31	1.48	2.67	1.04	2.47	0.26	5.78	0.18	4.60	2.40
Oil E 10W-30	1.92	3.18	0.73	1.60	0.75	1.41	0.24	4.16	-0.39	2.93	1.54

Lubrication Regimes in Sense Check Testing In describing lubrication conditions there are three primary lubrication regimes, Boundary, Mixed, and Hydrodynamic. Boundary refers to conditions under which metal-to-metal contact is made between components when the lubricant film is insufficient to keep the metal parts separated and friction between metal components is high because of the metal-to-metal contact. Hydrodynamic refers to conditions where the lubricant film is thick enough to keep the metal components from contacting, however friction levels are influenced by lubricant film thickness and friction increases with increasing film thickness. Mixed refers to the lubrication regime where there is a combination of Boundary and Hydrodynamic conditions. The effect of the parameters of viscosity, speed, and load on friction are graphically shown in the Stribeck Curve, Figure 55.

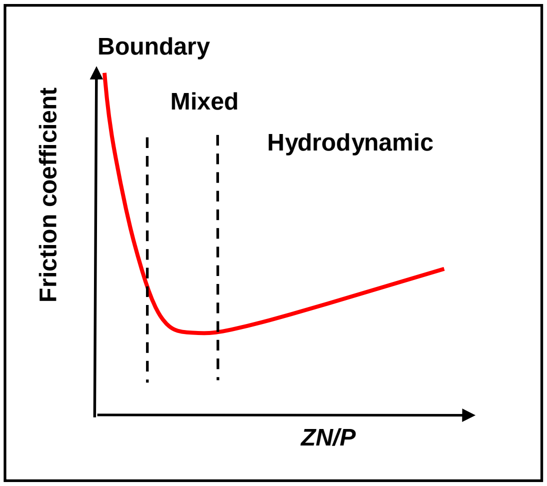


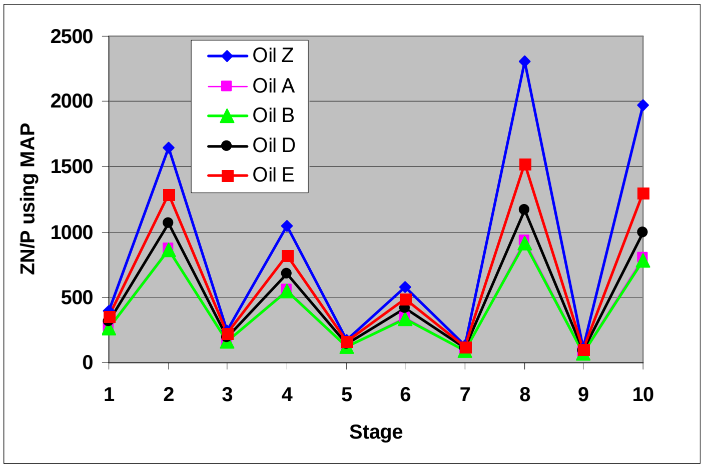
Figure 55. Stribeck Curve showing the Effect of Viscosity (Z), Speed (N) and Load (P) on Friction

In an operating engine different components are operating under different lubrication regimes because of different loads, speeds and temperatures. For example, piston ring-cylinder wall interaction would be a different lubrication regime than the lubrication taking place in a journal bearing. Therefore, using one value of ZN/P to describe all of the different lubrication regimes in an engine at any given time would be misleading. However, calculating the ZN/P values for the different initial stages chosen for the VID test may be useful in determining which of the stages correspond to which lubrication regime. To enable this, using the operating conditions of the engine during the different stages of the Initial operating conditions, a "Pseudo ZN/P" value was calculated for each of the stages. Z, the viscosity value in centipoise, was calculated from the engine oil sump temperature and the known kinematic viscosity at 40 and 100°C. Absolute viscosity was calculated from the density of the oil at the sump temperature. For the speed term, N, engine speed in RPM for each stage was used. The manifold absolute pressure (MAP) in kPa was used as the Load term, P. MAP was used rather than Engine Torque because MAP was recorded during the vehicle testing and engine torque was not. Thus, enable comparisons using ZN/P of the VID stages and vehicle testing required using a load term available for both the VID tests and the vehicle tests. Table 20 shows the terms used to calculate the "pseudo ZN/P" values for the initial ten stages of the Sequence VID used in the Sense Check testing.

Table 20. Values for ZN/P for Oil Z (Baseline Oil) in the initial Ten Stages of VID

Stage	1	2	3	4	5	6	7	8	9	10
Speed, RPM	2000	2000	2000	2000	1500	1500	695	695	695	695
MAP, kPa	34.9	35.5	56.6	55.9	58.1	44.7	35.3	34.7	42.8	40.6
Oil Temp	115	65	115	65	115	80	115	35	115	35
Viscosity at Oil Temp, cSt	8.56	34.6	8.56	34.6	8.56	20.9	8.56	133	8.56	133
Viscosity at Oil Temp, cP	6.88	29.1	6.88	29.1	6.88	17.4	6.88	115	6.88	115
ZN/P	394	1642	243	1043	178	583	136	2304	112	1969

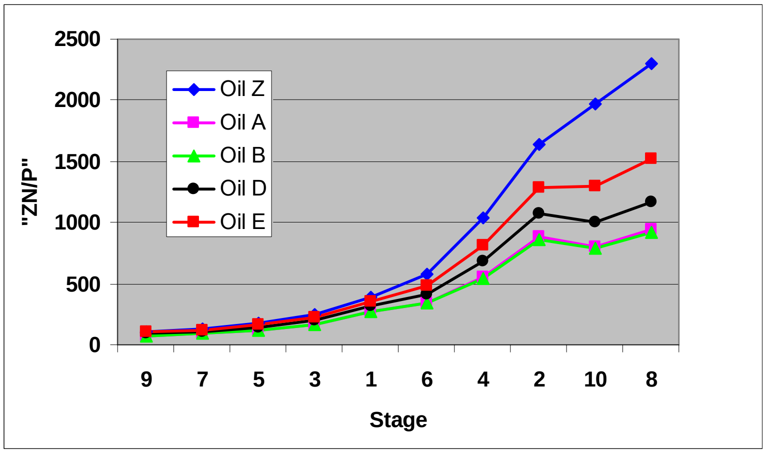
ZN/P values were calculated for the other oils used in the Sense Check testing and these values are plotted in Figure 56 and in Figure 57. The ZN/P values are plotted in ascending numerical order for the ten stages.



Z = Absolute Viscosity at Oil Sump Temperature, cP
N = Engine Speed, RPM
P = Engine Load as Manifold Pressure (MAP), kPa

Figure 56. ZN/P Values for Oils used in Sense Check Tests

Figure 56 shows that for the high temperature stages, the odd-numbered stages, the ZN/P values are lower than those for the lower temperature, even-numbered stages, as would be expected because of the temperature effect on viscosity. For those stages having equal temperatures, e.g., stages 1 and 3, show the effect of load on the ZN/P values. When the ZN/P values are plotted in numerical order the lowest value is for Stage 9 which has the lowest speed and the highest temperature. Stages 7 and 9 are equal in speed and temperature, but stage 9 has a higher load resulting in stage 9 having a lower ZN/P value than stage 7. The lower ZN/P values correspond to more Boundary or Mixed conditions as shown in Figure 57. The high ZN/P values would correspond to the hydrodynamic section of the Stribeck curve. Figure 57 also shows that for the stages with high ZN/P values there is a significant difference among the various oils of different viscosities, however for the stages with low ZN/P values the viscosity effect is not apparent.



Z = Absolute Viscosity at Oil Sump Temperature, cP
N = Engine Speed, RPM
P = Engine Load as Manifold Pressure (MAP), kPa

Figure 57. ZN/P Values for Oils used in Sense Check Tests

The improved fuel economy for the non-friction modified oils (A,D,E) tested in the Sense Check tests, Table 19, are shown in graphical format in Figure 58 as a function of the stages arranged in increasing ZN/P numerical order. The figure shows that the effect of viscosity on fuel consumption is greatest for the high ZN/P stages, 10 and 8, and for the low ZN/P stages, the lowest viscosity oil gave a decrease in fuel economy compared to the Baseline Oil, Z. In Figure 59 the effect of friction modification is shown where two tests on Oil A, a non-friction modified oil, are compared to Oil B, which is a friction-modified version of Oil A. The stages corresponding to more boundary-like or mixed lubrication, stages 9, 7, 5, and maybe 3, show how fuel consumption decreases with the use of a friction modified oil.

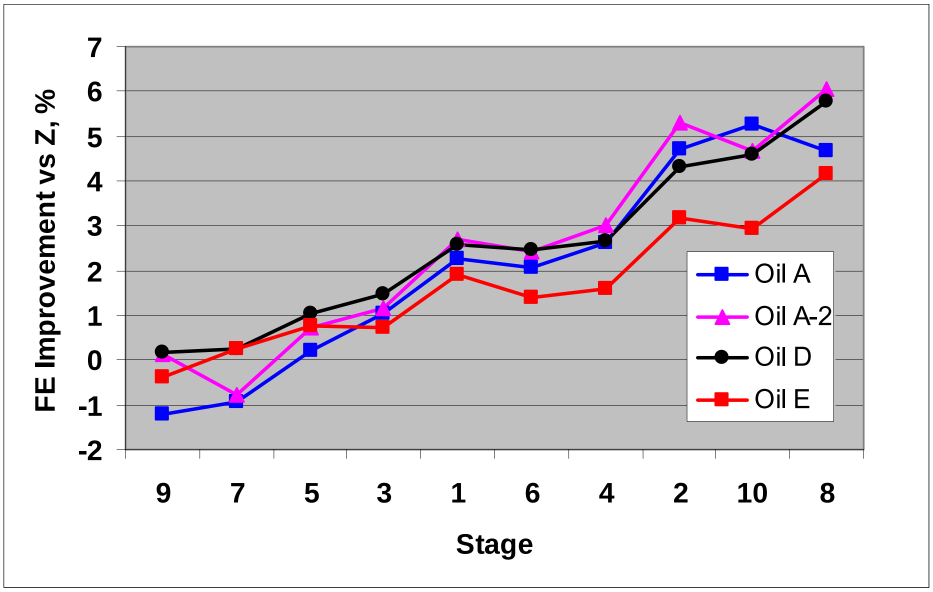


Figure 58. Viscosity Effect in Sequence VID Sense Check Tests

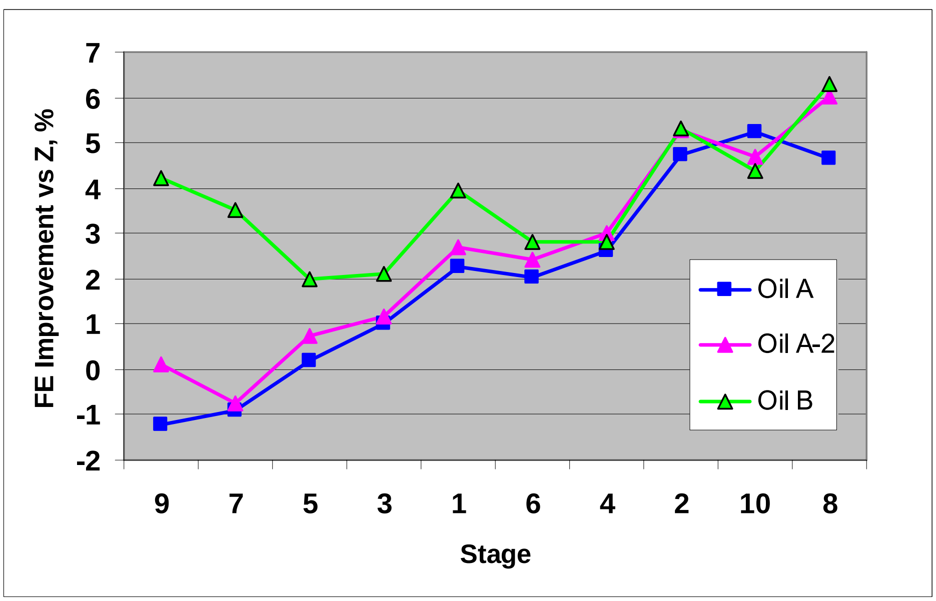


Figure 59. Friction Modifier Effect in Sequence VID Sense Check Tests

ZN/P Values in the FTP and Highway Test To compare how the conditions of the Sequence VID initial stages using ZN/P values compared to the conditions during the FTP and Highway tests, the ZN/P values were calculated from the vehicle data collected during the vehicle tests. The ZN/P values were calculated using the oil viscosity (centipoise), engine speed (RPM), and manifold absolute pressure, MAP (kPa). The oil viscosity in centipoise was calculated from the known kinematic viscosity at 40 and 100°C, the oil sump temperature, the density of the oil and change in density with temperature. Figure 60 shows the ZN/P values calculated during the three portions of the FTP, Cold Start, Stabilized Phase, and Hot Start, and the Highway Test. The ZN/P values are shown for two different oils, the baseline oil, Z, an SAE 20W-30 oil, and Oil A, an SAE 5W-20 oil. Included in Figure 60 is the engine oil sump temperature. Since the engine speed and engine load used in the ZN/P calculations were the same for both oils, any difference in ZN/P values between Oil A and Z is the result of viscosity differences between the two oils. Thus, the difference between the ZN/P values for Oils Z and A should be an indication of how effective a lower viscosity oil like Oil A would be compared to Oil Z, and in what portion of the FTP and Highway test the lower viscosity would be most effective. Based upon the large differences between Oil A and Z during the Cold Start portion, a lower viscosity oil would be most effective under the conditions of the Cold Start portion of the test, whereas the lower viscosity would be less effective at higher temperature portions of the test where there is much less difference in ZN/P values between the oils.

The friction modifier effect seen in Figure 59 is an indication of at what ZN/P level friction modifiers are effective. Since the ZN/P value for stage 3 is about 240, it could be that the conditions during the FTP and Highway testing, where the ZN/P value is 240 or less, would be the conditions where friction modifiers would be most effective. Figure 61 shows the frequency of the ZN/P values over the FTP and Highway tests and a cumulative percent for those values. The two plots show that about forty percent of the FTP and Highway testing has ZN/P values below 240.

As was discussed earlier, during operation the various parts of the engine are operating under a variety of lubrication conditions and to use a single ZN/P value to describe all of the various lubrication conditions is oversimplifying the complexity of engine lubrication. However, using the single ZN/P value is a helpful tool to describe the overall condition the engine is operating under at any given time and may allow easier discussion when describing test results from the Sequence VID test.

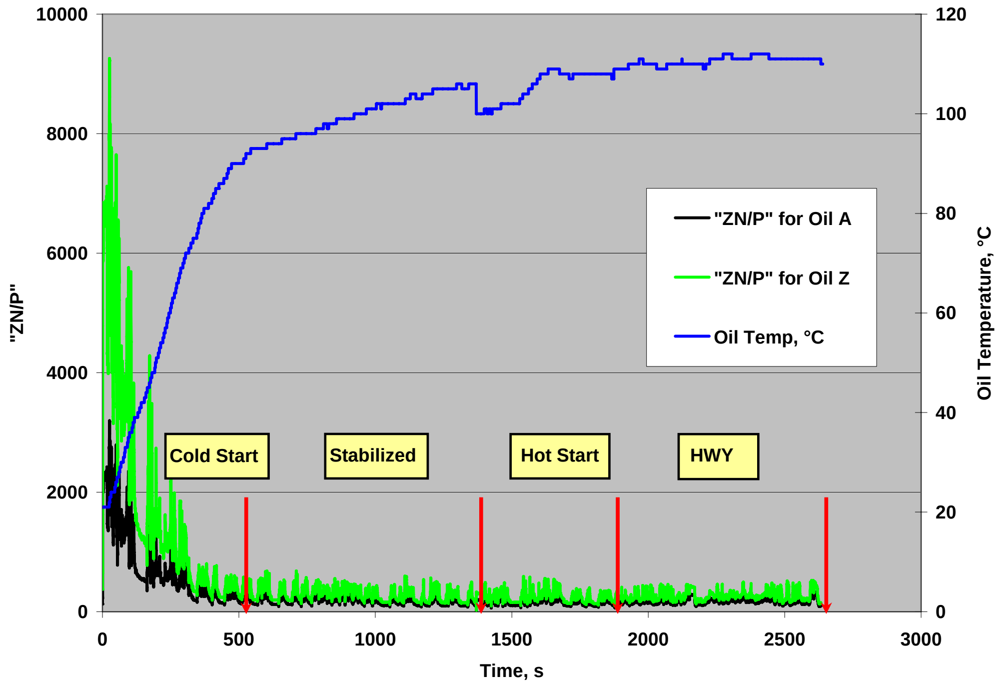


Figure 60. ZN/P Values During FTP and Highway Tests

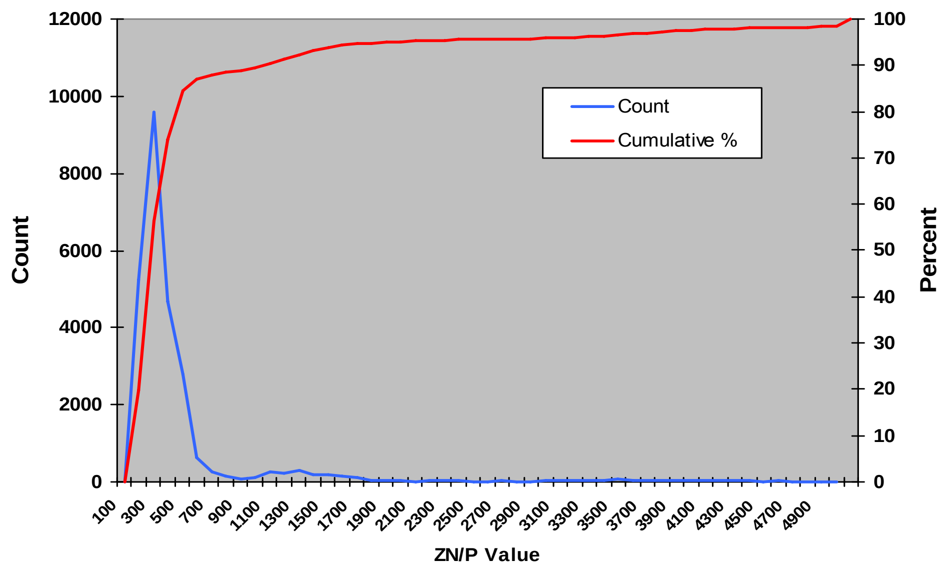


Figure 61. ZN/P Values Frequency and Percent During FTP and Highway Tests

9 Design of Test Matrices

9.1 Stage Gate Review Process At the December 2005 consortium meeting a proposal was made and accepted to use a stage-gate process to manage the project. Advantages cited included improved chance of success, ability to focus efforts on most important outcomes and tasks, ability to identify and evaluate all alternatives at the beginning of the project, ability to identify key decisions and allow stakeholders to provide guidance at critical decision points, reducing the need for rework and overall project timing and budget, and providing a means to stage project investment.

A project process was put in place with the following objectives: provide framework for project management, identify major decisions and deliverables, and provide check points on project progress. Stage 1 included defining project opportunity statement, objectives, scope, and plans. Deliverables were the consortium agreement and initial project plan. This stage completed in 2006. Stage 2 included test scoping and defining alternatives with deliverables of completing FTP testing and analysis and initial engine set-up, shake down, and scoping. Stage 2 completed in June 2007 with agreement to increase test spending and begin the Sequence VID test development process. Stage 3 included the core of the VID development activities. Deliverables included defining the aging conditions and stage selection. Stage 3 completed in May 2008. Stage 4 included the final prove-out of the test procedure and conditions developed in the first 3 Stages, including a demonstration that the test discrimination and test precision were sufficient to proceed with the precision matrix. Deliverables were a final recommendation of a new Sequence VID test to the ILSAC/Oil Committee and this research report. Stage 4 completed in September 2008.

It was decided by the Consortium to structure the development of the Sequence VID test as a series of test matrices. Five matrices were defined and conducted as part of the overall VID development process (although some of the matrices consisted of more than one part). The following sections describe each of the matrices, including their objectives, the results obtained, and an analysis of the results with conclusions drawn and their implications.

9.2 Matrix I – Oil Aging One of the tasks in the VID test development was to determine the appropriate oil aging conditions and the number of hours to run this stage. An initial aging study was done before the Matrix I design of experiment was conducted. The first two experiments were conducted using Oil C in each of the two laboratories with the following conditions:

Aging Experiment 1

Speed: 2000 rpm
Load: 70 Nm
Oil Temperature: 110°C
Coolant Temperature: 100°C

Used oil samples were taken every 25 hours up to 150 hours and tested for DIR Oxidation, Viscosity at 40°C and HFRR. The results from these tests were compared with the used oil results from the GM FTP across vehicles and for the GM FTP Buick Lacrosse alone. This comparison is shown in Figures 62 through 64.

DIR Oxidation – Oil C (GM FTP, Aging Experiment)

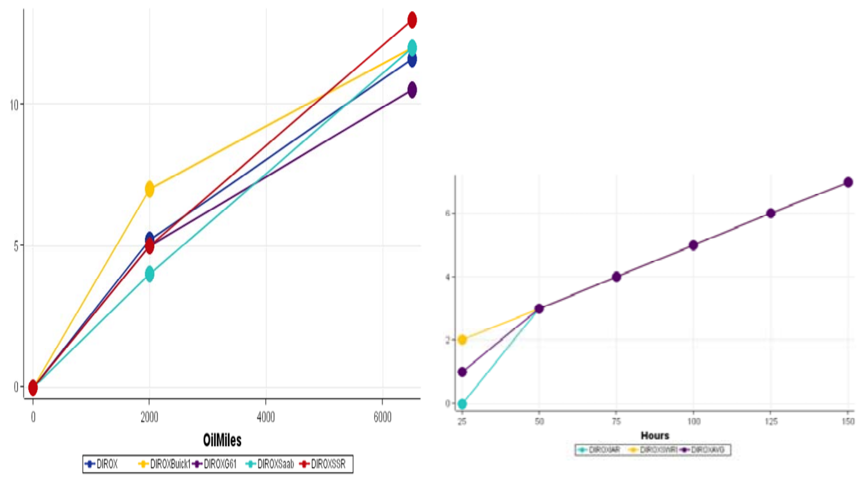


Figure 62. DIR Oxidation for Oil C in GM Vehicle Tests and Oil Aging Experiment

Viscosity @ 40°C – Oil C (GM FTP, Aging Experiment)

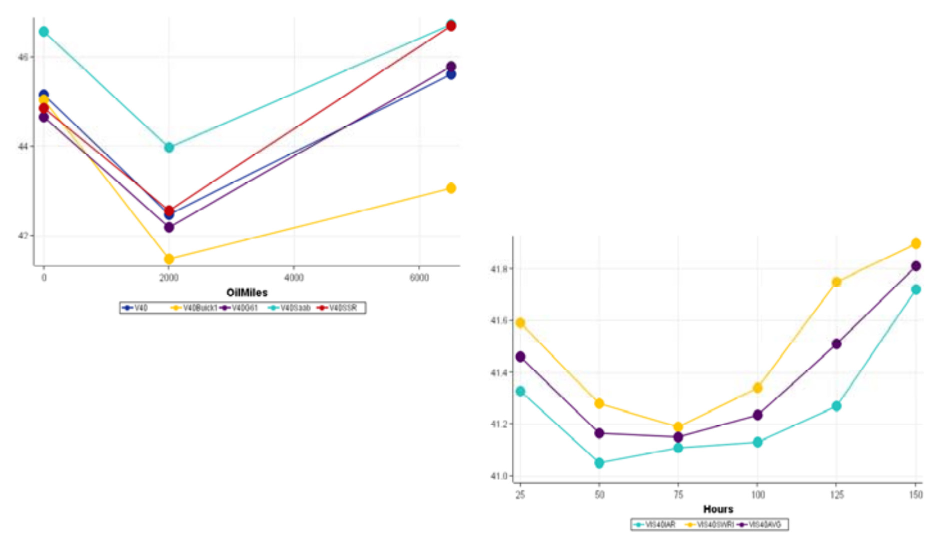


Figure 63. Viscosity at 40°C for Oil C
in GM Vehicle Tests and Oil Aging Experiment

Viscosity @ 100°C – Oil C (GM FTP, Aging Experiment)

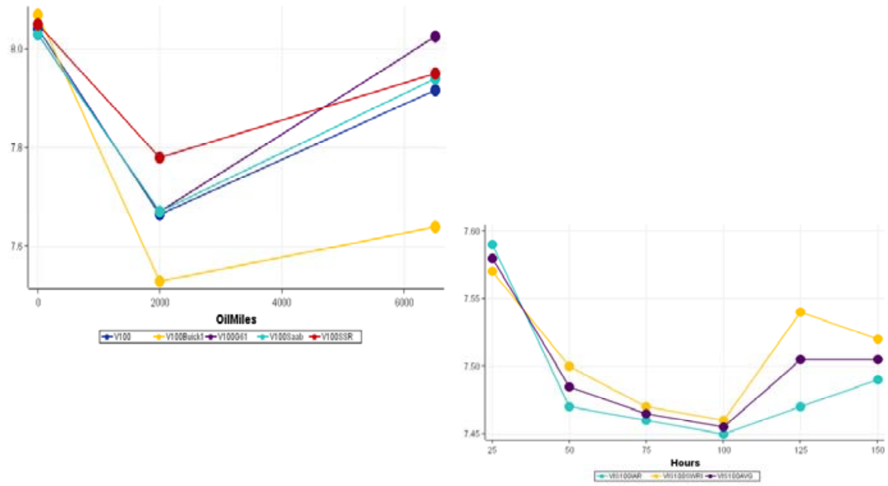


Figure 64. Viscosity at 100°C for Oil C in GM Vehicle Tests and Oil Aging Experiment

In summary, Table 21, below indicates that correlations that exist across all vehicles were not at consistent FTP miles or engine stand hours. The best correlation is with Buick Lacrosse FTP data alone where 150 hours of engine stand aging seems to correlate with 2000 miles for DIR Oxidation, Viscosity and HFRR. It was indicated there was insufficient engine stand aging at 150 hours to correlate with 6500 vehicle miles. Extending engine stand aging past 150 hours was deemed by the Consortium to be an impractical lengthening of the Sequence VID.

Table 21. Used Oil Data from Vehicle and Aging Experiments

Oil C	Oil Miles	GM FTP		VID Hours	Aging Expt
		Across Vehicles	Buick Lacrosse 1		Buick Lacrosse
DIROX	2000	5.2	**7.0**	100	5.0
				150	**7.0**
	6500	11.6	12.0		
Vis40C	2000	42.5	**41.5**	150	**41.81**
	6500	45.6	43.1		
Vis100C	2000	7.7	**7.5**	150	**7.51**
	6500	7.9	7.6		
HFRR140C	2000	0.077	**0.137**	50	0.062
	6500	0.156	0.175	150	**0.139**
HFRR120C	2000	0.113	**0.143**	50	0.084
	6500	0.162	0.175	150	**0.150**

- *Based on FTP data across vehicles:*
  - VID 100 hours seem to correlate with 2000 miles for DIR Oxidation
  - VID 50 hours seem to correlate with 2000 miles and 150 hours with 6500 miles for HFRR
- *Based on Buick Lacrosse FTP data alone, VID 150 hours seem to correlate with 2000 miles for DIR Oxidation, Viscosity and HFRR.*

Per the Procedure, Operation and Hardware Panel (P,O&H Panel) recommendation, an “aging sense check” was conducted on Oil C at SwRI with the 2008 engine at the following conditions to help determine the variables for the aging design of experiment:

Aging Experiment 2

Speed: 2250 rpm
Load: 98 nm
Oil Temperature: 130°C
Coolant Temperature: 110°C

Oil samples were taken at an increment of 25 hours starting at 50 hours up to 200 hours. Table 22, below shows the result of this experiment, and it indicates that more than 100 hours of testing is necessary to correlate with the DIR Oxidation @5.8 averaged across the FTP vehicles. Again, this test length was deemed to be unacceptable by the Consortium members.

Table 22. Used Oil Data from Vehicle Tests and Aging Experiments

Oil C	Oil Miles	All FTP	GM FTP							Ford FTP			VID Hours	Aging Expt 1	Aging Expt 2
		Across Vehicles	Across Vehicles	Buick Lacrosse 1	Buick Lacrosse 2	Pontiac G6 1	Pontiac G6 2	SSR	Saab	Across Vehicles	Fusion 1	F150		Buick Lacrosse	Buick Lacrosse
DIROX 5.8	0	0.0	0.0	0.0		0.0		0.0	0.0	0	0	0	50	3.0	5
	500	2.5								2.5	5	0	75	4.0	7
	2000	**5.3**	**5.0**	**7.0**		**5.0**	**4.0**	**5.0**	**4.0**	**5.5**	**7**	**4**	**100**	**5.0**	9
	5000	13.5								13.5	20	7	**125**	**6.0**	11
	6500	10.9	10.9	12.0	9.0	10.5	9.0	*13.0*	12.0				**150**	**7.0**	13
													175		14
													200		17
DIROX 6.1	0												50		4
	500												75		5
	2000	5.0	5.2	5.0	0.0	6.0	9.0						100		6
	5000												125		8
	6500	13.5	13.5	16.0	6.0	16.0	16.0						150		11
													175		13
													200		17
Vis40C	0	45.1	45.2	45.0		44.7		44.9	46.6	45.1	45.0	45.2	50	41.17	43.7
	500	41.2								41.2	42.2	40.1	75	41.15	44.7
	2000	**41.7**	**42.6**	**41.5**	42.0	**42.2**	**43.2**	**42.6**	**44.0**	**40.8**	**41.3**	**40.3**	**100**	**41.24**	48.0
	5000	42.6								42.6	42.8	42.5	**125**	**41.51**	47.1
	6500	45.2	45.2	43.1	43.2	45.8	45.6	*46.7*	46.7				**150**	**41.81**	48.7
													175		50.4
													200		50.9
Vis100C	0	8.0	8.0	8.1		8.0		8.1	8.0	8.0	8.0	8.1	50	7.49	7.8
	500	7.8								7.8	8.1	7.4	75	7.47	7.9
	2000	**7.56**	**7.7**	**7.5**	**7.6**	**7.7**	**7.8**	**7.8**	**7.7**	**7.4**	**7.5**	**7.4**	**100**	**7.46**	8.0
	5000	7.6								7.6	7.6	7.6	**125**	**7.51**	8.2
	6500	7.9	7.9	7.6	7.7	8.0	8.0	*8.0*	7.9				**150**	**7.51**	8.4
													175		8.5
													200		8.7
HFRR1 40C	0	0.060	0.057	0.057		0.055		0.060	0.056	0.064	0.069	0.059	**50**	**0.062**	
	500	0.058								0.058	0.061	0.055	**75**	**0.101**	
	2000	**0.099**	**0.077**	**0.137**		**0.049**		**0.087**	**0.103**	**0.121**	**0.136**	**0.106**	**100**	**0.117**	
	5000	0.149								0.149	0.145	0.153	**125**	**0.136**	
	6500	0.156	0.156	0.175		0.152		0.170	0.139				**150**	**0.139**	
HFRR1 20C	0	0.062	0.062	0.061		0.061		0.070	0.058	0.062	0.062	0.062	**50**	**0.084**	
	500	0.072								0.072	0.070	0.073	**75**	**0.147**	
	2000	**0.127**	**0.113**	**0.143**		**0.096**		**0.046**	**0.142**	**0.142**	**0.139**	**0.144**	100	0.152	
	5000	0.156								0.156	0.148	0.164	125	0.155	
	6500	0.162	0.162	0.175		0.161		0.162	0.144				150	0.150	

Given the results from the 3-test aging study, the Statistical Group designed an aging experiment with the following assumptions and design:

- *Design of the Matrix*
  - *There are 8 Prioritized Runs for the Matrix*
    - *Consortium May Wish to Terminate Before Completion*
  - *There are 3 Additional Confirmation Runs*
  - *Factors Include Speed, Load, Temperature and Lab*
- *Assumptions*
  - *130°C is an Acceptable High for Aging*
  - *Temperatures Below 120°C will not be Severe Enough*
  - *A Speed of 2250 rpm and a Load of 98 Nm are Minimums given the Constraints on Time and Temperature*
  - *6500 Miles of Aging is Needed*
- *The Matrix Should be Revisited with any Change in the Assumptions*
  - *2000 miles versus 6500 miles Critical*

Table 23. Aging Matrix DOE

Run	Lab	Temperature	Speed	Load
1	SwRI	130	2250	98
2	IAR	120	2500	115
3	SwRI	130	2500	115
4	SwRI	120	2250	115
5	IAR	130	2500	98
6	IAR	130	2250	115
7	SwRI	120	2500	98
8	IAR	120	2250	98

Confirmation Runs

- RUN 1
  - Selected Condition in OTHER Lab Using Oil C
- RUN 2
  - Selected Condition in Lab I Using Oil A
- RUN 3
  - Selected Condition in Lab S Using Oil A

Next Steps

- Consortium Must Discuss Assumptions
  - Must be Realistic
    - 110°C, Low Speed, Low Load Likely Not Good Enough, UNLESS Aging Goal Altered
  - 2000 Miles versus 6500 Miles Must be Decided
    - Matrix would Likely Change if only 2000 Miles
- Statistics Group Redesign if Necessary
- Run the Matrix
  - Labs Should Run Concurrently
- Follow Up with Confirmation Runs

A key concern is the possible need for the bench engine to run at temperatures, speed and load significantly different from FTP conditions to achieve the desired aging with a test length of 100 hours, maximum. It was proposed to reduce the oil fill by 10% as a way to increase aging severity while still running at conditions similar to those used for FTP tests. It was agreed this may be possible by adding a “brick” to replace oil in the engine sump, reducing oil fill, or any other method that would not interfere with engine operation. To determine if reducing oil charge by 10% would have a statistically significant effect on aging, SwRI conducted Matrix Run 8 as indicated except with 10% less oil charge. The result of the experiment is tabulated below in Table 24.

Table 24. Aging Experiment Summary

Aging Experiment	Lab	Aging Conditions				Hours to Average FTP Aging Used Oil Properties at 6,500 Miles					
		Oil Temp, °C	Speed, RPM	Load, Nm	Oil Vol, liters	DIR 5.8	DIR 6.1	kV40	kV100	HFRR at 140°C	HFRR at 120°C
I	SwRI, IAR	110	2000	70	6	>150	0	>150	>150	>150	>150
II	SwRI	130	2250	98	6	125	175	75-100	75-100	-	-
III	SwRI	120	2250	98	5.4	>150	>150	75-100	75-100	125	125

Based on this result, a revised aging matrix was agreed upon. The assumptions and design (Table 25) are as follows:

- Consortium Outlined Matrix Bounds/Goals (8/2/07)
  - Correlation
- Correlate Lab Aging Data at 100 Hours Maximum to All GM Vehicles Field Data at 6.5K (Lab Data to be Recorded Out to 150 Hours)
  - Performance Parameters

- Viscosity at 40°C, Viscosity at 100°C, DIR 5.8 (Oxidation)
- HFRR and DIR 6.1 Dropped
  - Matrix Variables
- Oil Temperature Range from 120°C to 130°C
- Load Range from 98 Nm to 110 Nm
- Oil Charge Fixed at 5.4L; Speed Fixed at 2250rpm
- The Statistical Group has Developed a DOE for VID Aging Based on Bounds/Goals
  - There are 4 Prioritized Runs for the Matrix
  - There are 3 to 4 Additional Confirmation Runs

Confirmation Runs

- CONFIRMATION RUN 1
  - Selected Condition in OTHER Lab Using Oil C
- CONFIRMATION RUN 2
  - Selected Condition in Original Lab Using Oil C
  - Note that this Run is Unnecessary if the Selected Condition is One of the 4 Original Matrix Points
- CONFIRMATION RUN 3
  - Selected Condition in Lab I Using Oil H
- CONFIRMATION RUN 4
  - Selected Condition in Lab S Using Oil H

Table 25. Aging Matrix DOE

Run	Lab	Temperature. °C	Oil	Load, Nm
1	SwRI	120	C	98
2	IAR	130	C	98
3	SwRI	130	C	110
4	IAR	120	C	110
C1	SwRI	TBD	C	TBD
C2	IAR	TBD	C	TBD
C3	SwRI	TBD	H	TBD
C4	IAR	TBD	H	TBD

Next Steps

- The Matrix Must be Revisited with Any Changes to the Consortium Matrix Bounds/Goals

- Statistical Group Redesign if Necessary
- Run the Matrix
  - Labs Should Run Concurrently
- Select Conditions
- Follow Up with Confirmation Runs
  - 3 or 4 Confirmation Runs Dependent Upon the Condition Selection

Results from this 4-run matrix are shown in Figures 65-67.

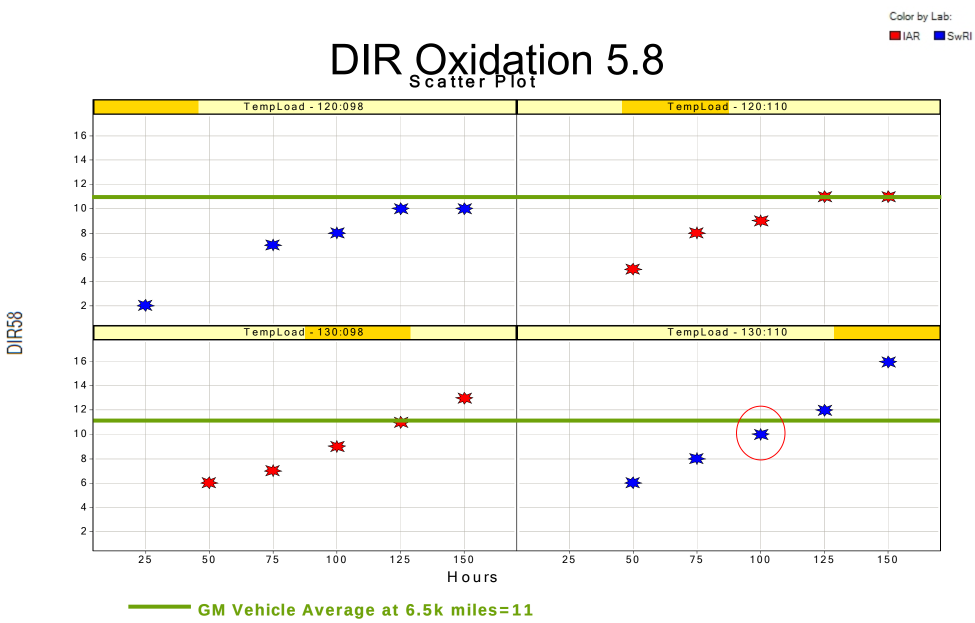


Figure 65. DIR Oxidation Results from 4-run matrix

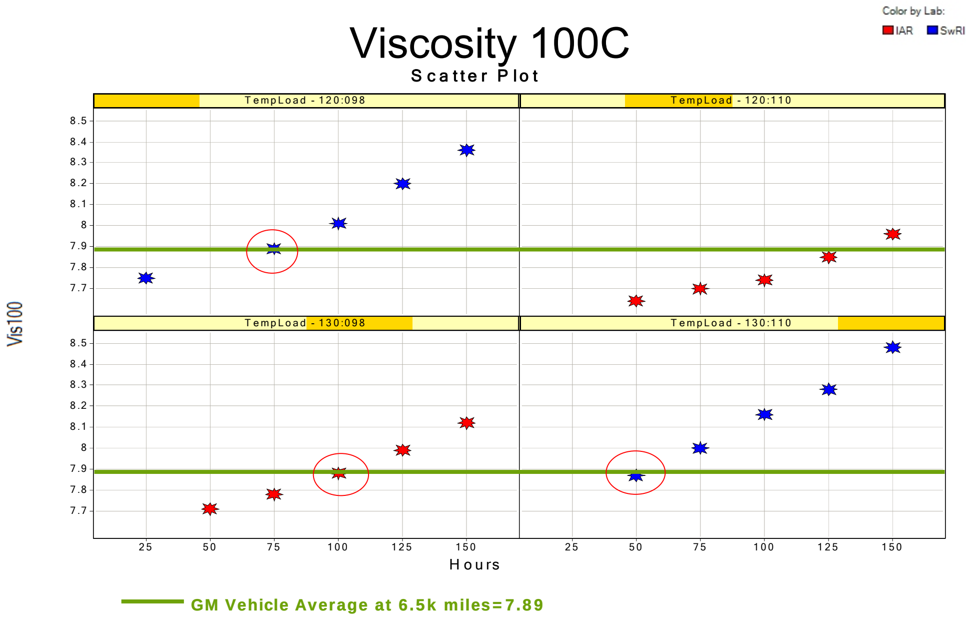


Figure 66. Kinematic Viscosity at 100°C Results from 4-run matrix

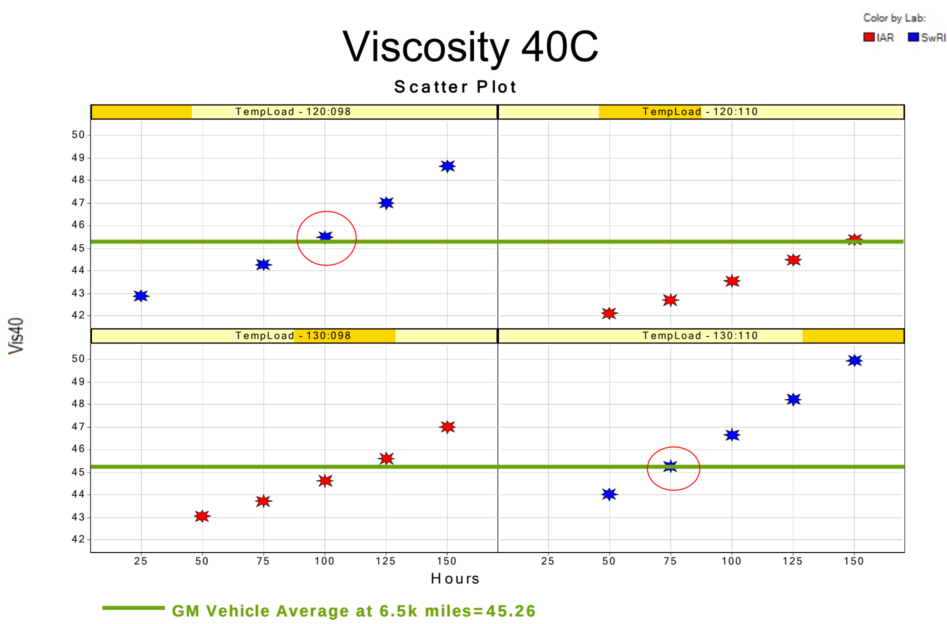


Figure 67. Kinematic Viscosity at 40°C Results from 4-run matrix

The VID Statistical Group reviewed the results from these 4 tests and noted possible differences in results between labs. These differences were attributed to differences in engines, and it was decided that average results should be used to recommend aging conditions. The group believed there were aging differences from engine to engine. To help resolve this issue, it was agreed to run further aging experiments at both Intertek and SwRI with the test conditions of SwRI Test #3 of the recently completed Oil Aging DOE, but with the engines used for the DOE interchanged between the two laboratories. These interchanged engines were installed on the same test stands used for the Oil Aging DOE, and the test length was 100 hours, with oil samples taken at 50, 75 and 100 hours.

As a result of reviewing operational data and stand configurations, coolant flow was suspected as a difference between the laboratories. Coolant flow calibrations indicated the Intertek coolant flow Calibration Table was corrupted. Intertek was running ~ 97 L/min. versus the specified 60 L/min. Intertek repeated the confirmation test with the correct coolant flow. The confirmation run at Intertek indicated that bringing the coolant flow in line with the specification improved correlation with the SwRI results. Analysis of the 4-test aging matrix plus the two confirmation runs is shown in Figures 68 through 72.

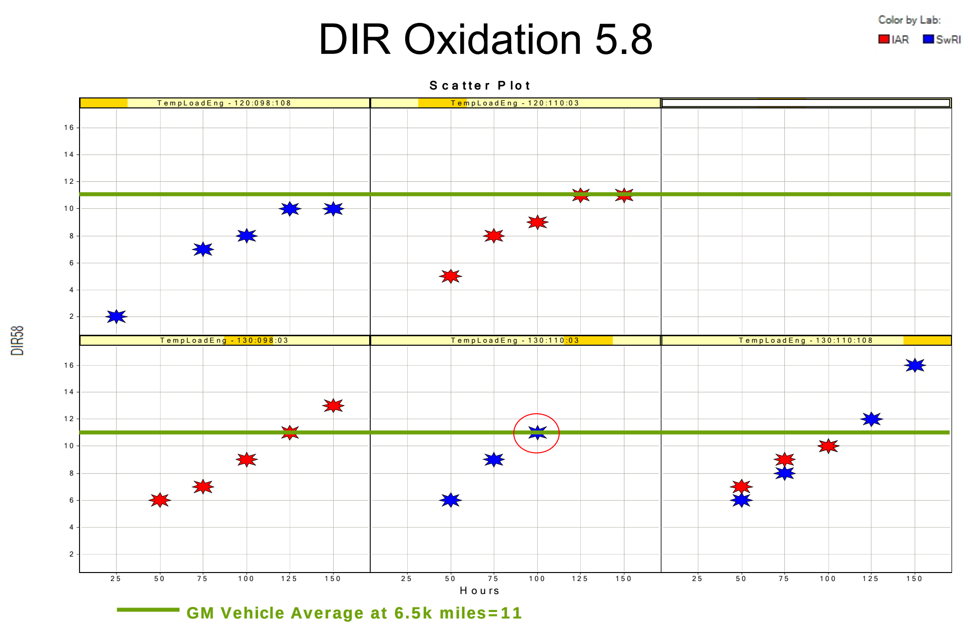


Figure 68. DIR Oxidation Results from 4-run matrix plus confirmation runs

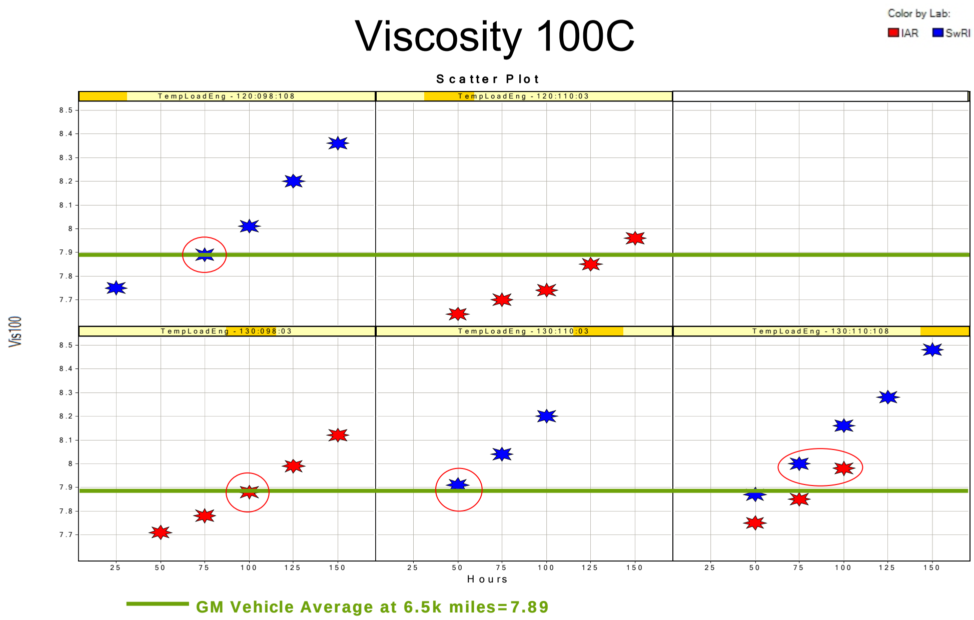


Figure 69. Kinematic Viscosity at 100°C Results from 4-run matrix plus confirmation runs

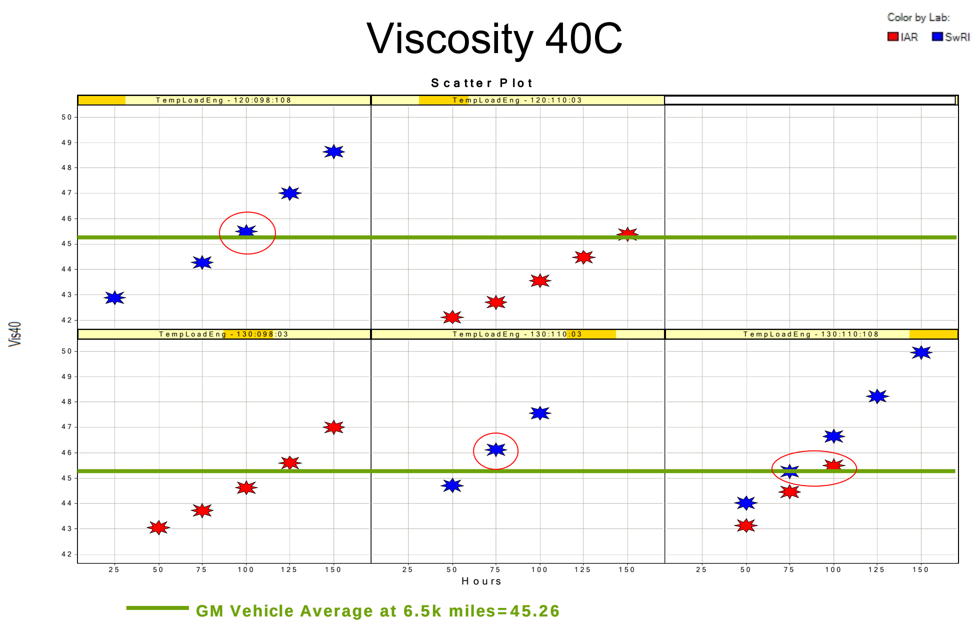


Figure 70. Kinematic Viscosity at 40°C Results from 4-run matrix plus confirmation runs

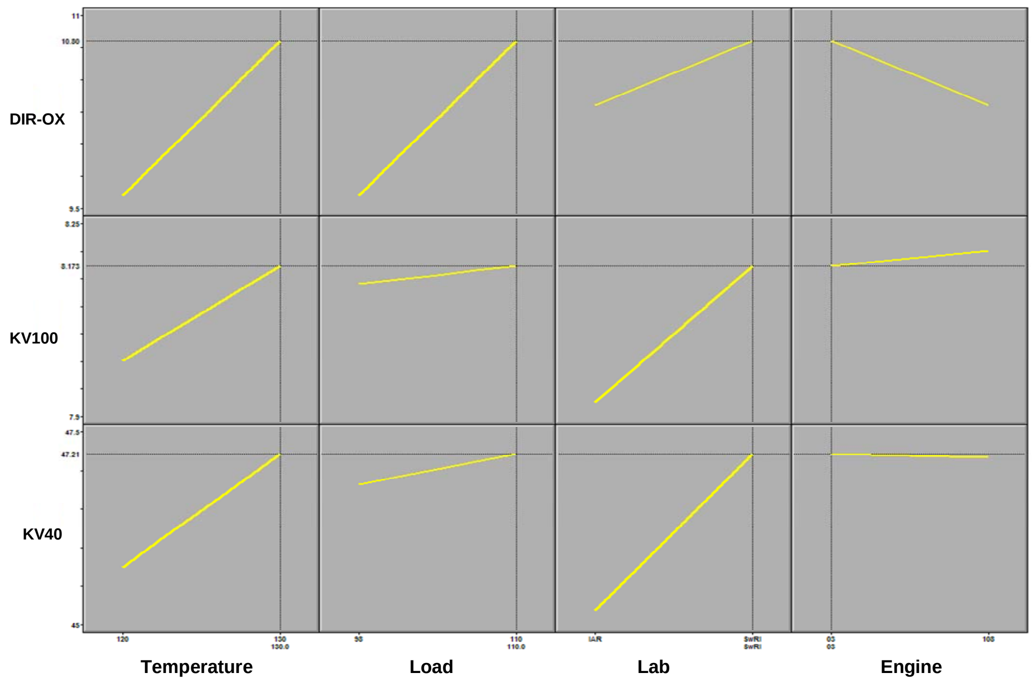


Figure 71. Effect of 100 hours at 130°C and 110 Nm on Oil Properties

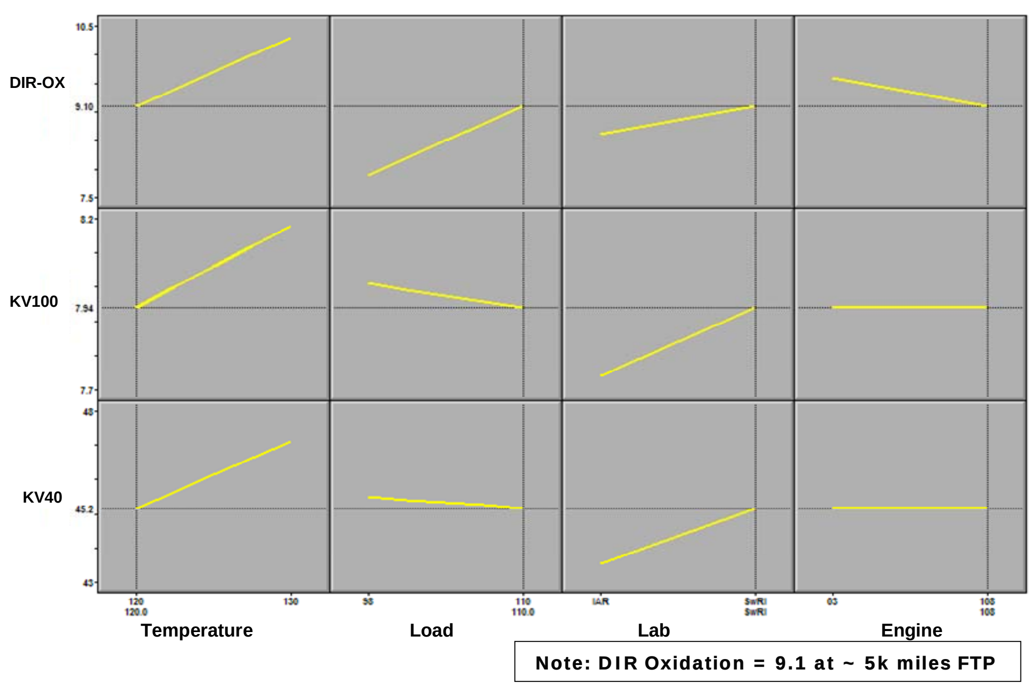


Figure 72. Effect of 100 hours at 120°C and 110 Nm on Oil Properties

Oil Aging Study Conclusions

- DIR Oxidation
  - Higher Temperature and higher Load increase DIR Oxidation

- Viscosity at 100°C and 40°C
  - Lab and Temperature have largest effects on Viscosity
    - SwRI has higher Viscosity than IAR
    - Viscosity increases as temperature increases

- Aging conditions desired: 130°C, 110Nm, 100 hours
  - Oxidation=10.3 < GM average=10.9
  - Vis at 100°C=8.11 > GM average=7.89
  - Vis at 40°C=46.57 > GM average=45.26
  - Oxidation: Ford average=13.5
  - Vis at 100°C: Ford average=7.6
  - Vis at 40°C: Ford average= 42.6

    (at 5000 miles for Ford)

- *Note:* It's possible that Viscosity target can be met at 120°C, 110Nm, 100 hours. Oxidation at this condition will be around 9 which can be correlated to FTP at 5000 miles.

Based on this analysis, the Consortium agreed that the Sequence VID test oil aging conditions will be 120°C oil temperature, 110 Nm load and 2250 rpm for a total test aging time of 100 hours (not including time for actual fuel economy test).

9.3 Matrix II – Check-out of Initial Stages A table of the operating conditions for each of the stages is shown in Table 26.

Table 26. Matrix II Operating Conditions

Operating Targets										
	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10
Speed, rpm	2000	2000	2000	2000	1500	1500	695	695	695	695
Torque, NM	40.0	40.0	105.0	105.0	105.0	70.0	20.0	20.0	40.0	40.0
Power, kw	8.4	8.4	22.0	22.0	16.5	11.0	1.5	1.5	2.9	2.9
Oil Temp, °C	115	65	115	65	115	80	115	35	115	35
Coolant In Temp, °C	109	65	109	65	109	80	109	35	109	35
Coolant Flow, LPM	60									
Intake Air Temp, °C	29									
Fuel Rail Temp, °C	22									
Fuel Pressure, kPa	400									
Intake Cam Angle, Deg	0									
Exhaust Cam Angle, Deg	0									
Spark Angle, Deg	27						Variable			

Flush Conditions: Speed = 1500, Load = 70 Nm, Coolant Temp = 109 ºC, Oil Temp = 115 ºC,

Aging Conditions: Speed = 2250, Load = 110 Nm, Coolant Temp = 110 ºC, Oil Temp = 120 ºC,

Before and after each test oil a baseline oil (oil Z) was run on each of the ten stages. Immediately following the "BaseLine After" (BLA) run, the engine was shut down for stand apparatus calibration. The cycle was likewise repeated for subsequent test oils starting with the "BaseLine Before" (BLB) using the baseline oil, Z.

Matrix Design A matrix was designed to provide data to facilitate a decision to reduce the number of stages. Each of the Supplier 1 and 2 oils (a total of 8 oils in each lab) were included in the 16 run matrix. A new oil from Supplier 1 was added, Oil L (SAE 0W-20), to extend the range of viscosity grades. Extended aging was not included so as to conserve funds for future testing. In one lab, during the second run, it was noted that the first run was invalid. The matrix run order was modified to minimize the amount of retesting required and is shown in Table 27. The matrix design includes portions of the oil run order in one lab being reversed relative to that in the other lab to determine engine aging and carryover effects.

Table 27. Modified Matrix II Oil Run Order

Test Number	IAR	SwRI
1	D	B
2	E	L
3	A	A
4	L	E
5	B	D
6	H	G
7	G	H
8	C	I

Results and Statistical Analysis The results, in terms of % FEI, by stage, for each of the valid runs are shown in Tables 28 and Table 29 for IAR and SwRI, respectively.

Table 28. IAR Matrix II FEI Relative to Oil Z

Oil	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10
D	1.78%	3.22%	0.83%	1.69%	0.45%	1.35%	-0.83%	6.53%	-0.64%	5.81%
E	2.04%	2.37%	0.79%	1.36%	1.00%	1.18%	0.20%	5.33%	0.23%	4.11%
A	1.74%	3.39%	0.65%	1.93%	0.26%	1.73%	-1.07%	7.49%	-1.57%	5.53%
L	1.24%	3.48%	0.79%	1.87%	0.43%	1.16%	-2.19%	7.46%	-1.21%	5.84%
B	2.36%	4.09%	1.36%	2.39%	1.13%	2.26%	1.81%	8.05%	1.47%	6.54%
H	2.00%	3.27%	0.83%	1.84%	0.69%	1.50%	0.50%	5.74%	0.30%	4.16%
G	1.05%	2.71%	0.44%	1.53%	0.70%	1.18%	0.46%	6.72%	-0.83%	5.08%
C	1.77%	4.02%	0.67%	2.07%	0.34%	1.68%	-0.75%	6.79%	-1.64%	5.28%

Table 29. SwRI Matrix II FEI Relative to Oil Z

Oil	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10
B	2.95%	4.37%	1.94%	2.68%	1.70%	2.40%	1.73%	6.51%	2.21%	6.76%
L	1.13%	3.89%	1.02%	2.36%	0.62%	1.72%	-0.44%	6.16%	-1.53%	3.08%
A	1.41%	3.99%	0.77%	2.25%	0.42%	1.46%	-1.80%	5.65%	-2.95%	4.72%
E	1.27%	2.75%	0.58%	1.13%	0.50%	1.11%	-0.17%	3.81%	0.05%	3.20%
D	1.06%	3.21%	0.35%	1.41%	-0.18%	1.02%	-1.03%	4.34%	-1.26%	4.63%
G	1.35%	2.92%	0.72%	1.65%	0.20%	1.29%	0.23%	6.45%	-1.38%	3.82%
H	1.66%	3.02%	1.18%	1.88%	0.90%	1.73%	1.61%	7.27%	0.26%	2.28%
I	2.37%	3.32%	1.26%	2.39%	1.19%	1.97%	2.08%	8.42%	2.49%	5.24%

The following is a summary of the statistical analysis of Matrix II data. Details of the Matrix II analysis follow the summary.

An analysis of the Baseline BSFC data indicates the following:

- BSFCs of Oil Z after FM oils relative to before provides no consistent evidence of FM carryover.

- BSFC variation appears to be strongly impacted by engine torque (inversely related) and/or BSFC (directly related).
- SwRI Baseline Oil BSFCs appear to have experienced a step change increase midway through Matrix II.
- In 8 of the 10 stages, Baseline Oil BSFC variation is higher for IAR than SwRI.

Multiple regression analysis was performed on the results of each stage for all valid tests. The following are conclusions reached based on the analyses.

- FEI (relative to Oil Z) appears to decrease with engine hours (within the range tested).
- FM discrimination is observed in Stages 1, 3, 5, 7, and 9.
- Viscosity Grade discrimination is observed in Stages 2, 4, and 9.

Based on the analysis the Statistical Group recommended the following issues be investigated prior to the following round of testing:

- Lab differences.
- SwRI BSFC step change.
- Engine aging effect (consider re-running the first Matrix II oils in both labs).

Statistical Analysis of Matrix II - Baseline BSFC For each stage, the Baseline BSFCs are plotted in chronological order with the odd test numbers being the before test oil baselines and the even test numbers being the after test oil baselines.

Observations from the plots include the following:

- In general, SwRI BSFCs were higher than those of IAR.
- IAR BSFCs peaked on Run 3 (Before Oil E) and were relatively level starting on Run 5 (Before Oil A).
- SwRI results were a minimum for Runs 4 and 5 and appeared to have a step increase between Runs 9 and 10 (Before and After Oil D).

One of the objectives of this matrix was to determine if there was evidence of FM carryover. For each of the FM test oils, the baselines before and after were compared. In this matrix, two runs with Molybdenum containing oils (Oils C and I) were run. For nine of the 20 stages, the BSFC of the baseline after the test oil was higher than the baseline before. There were four runs on organic FM oils (Oils B and H), for which the baseline after was higher for 21 of the 40 stages. Therefore, there was no consistent indication of FM carryover.

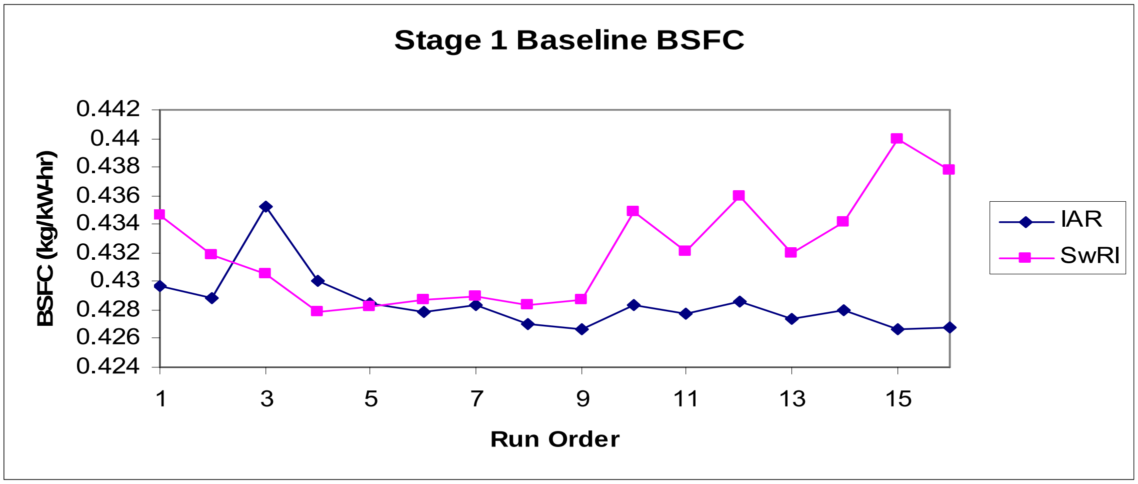


Figure 73. Stage 1 Baseline BSFC Trends

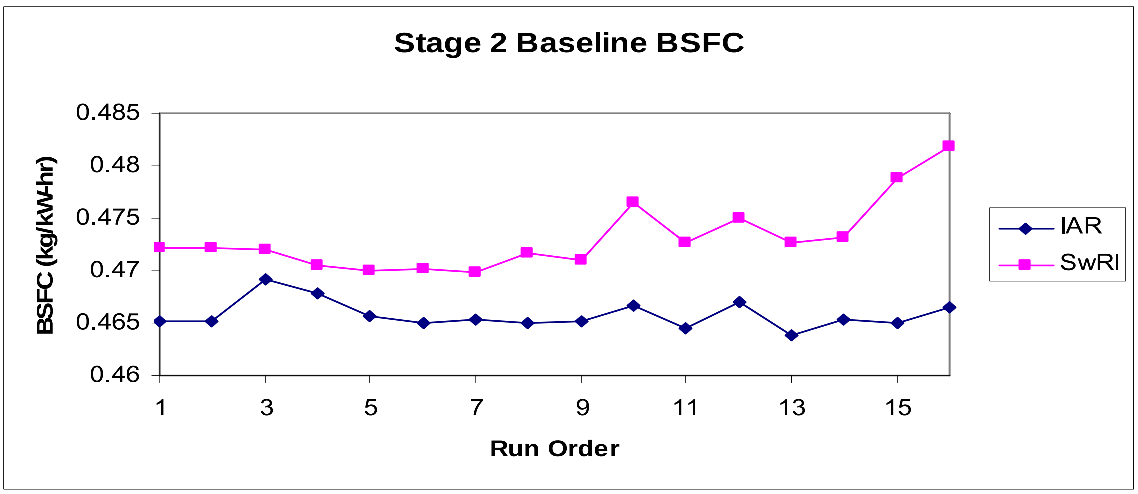


Figure 74. Stage 2 Baseline BSFC Trends

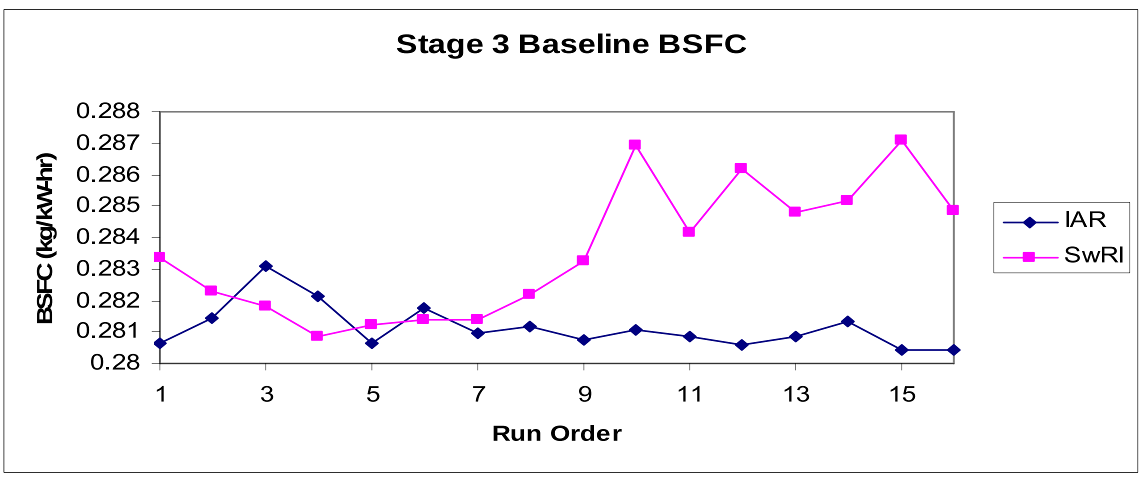


Figure 75. Stage 3 Baseline BSFC Trends

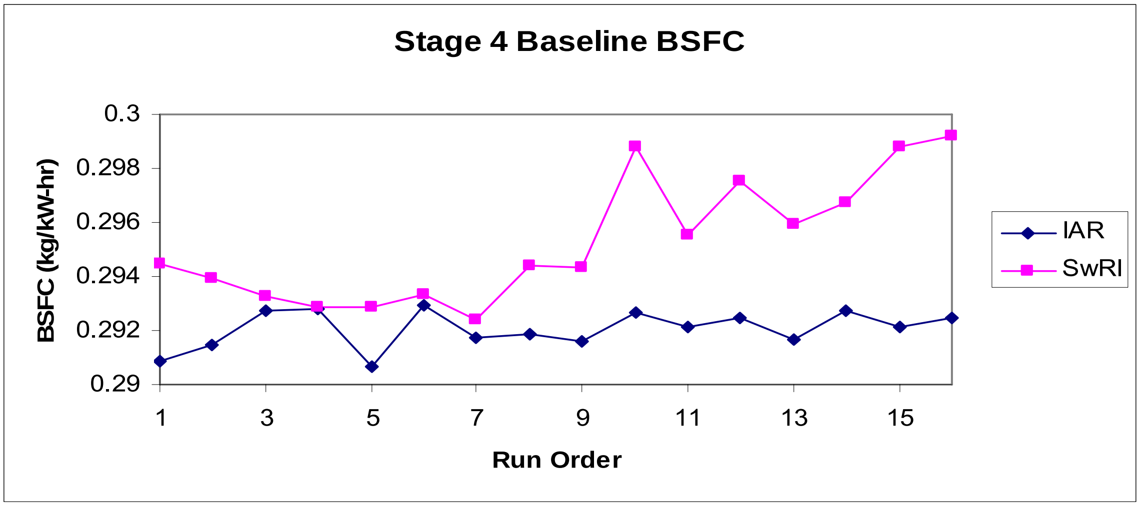


Figure 76. Stage 4 Baseline BSFC Trends

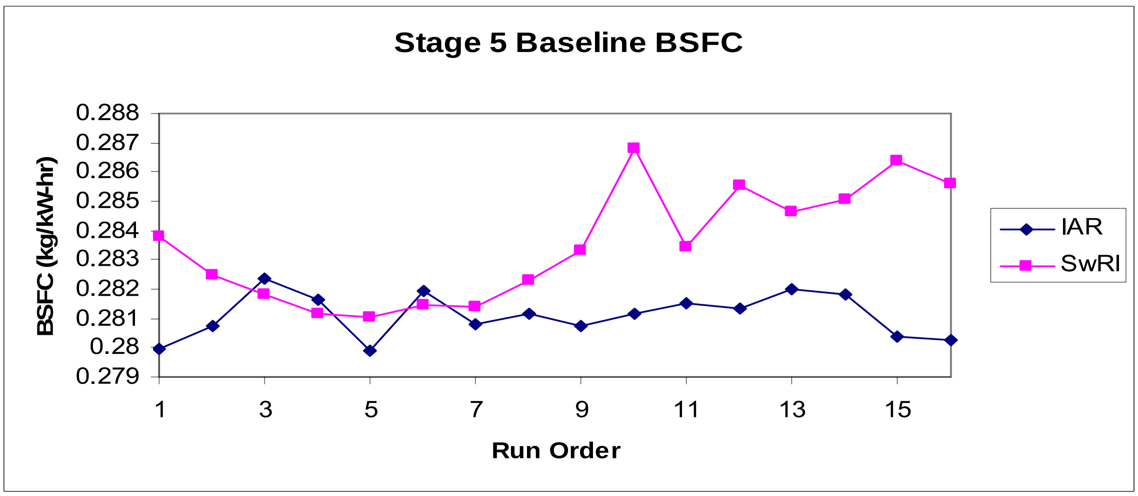


Figure 77. Stage 5 Baseline BSFC Trends

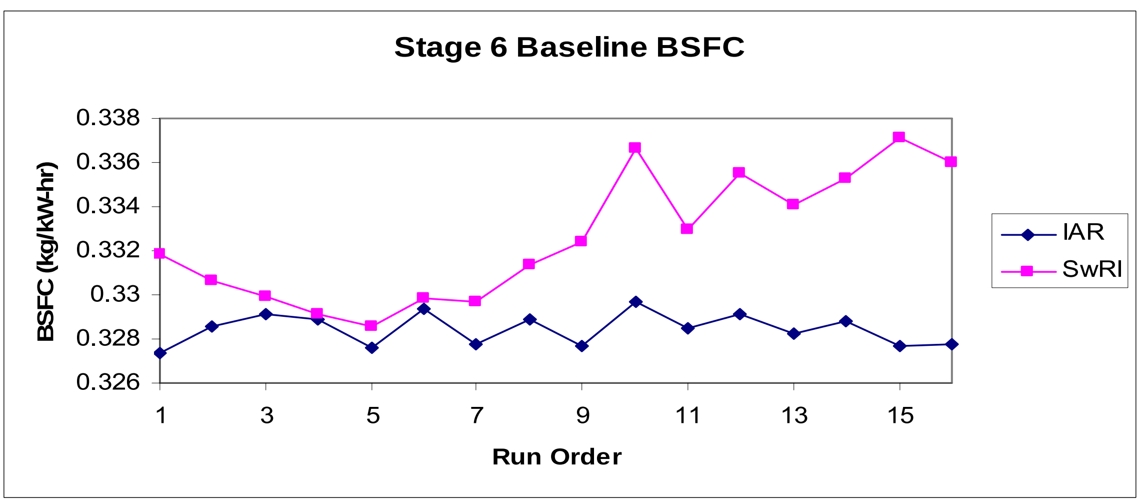


Figure 78. Stage 6 Baseline BSFC Trends

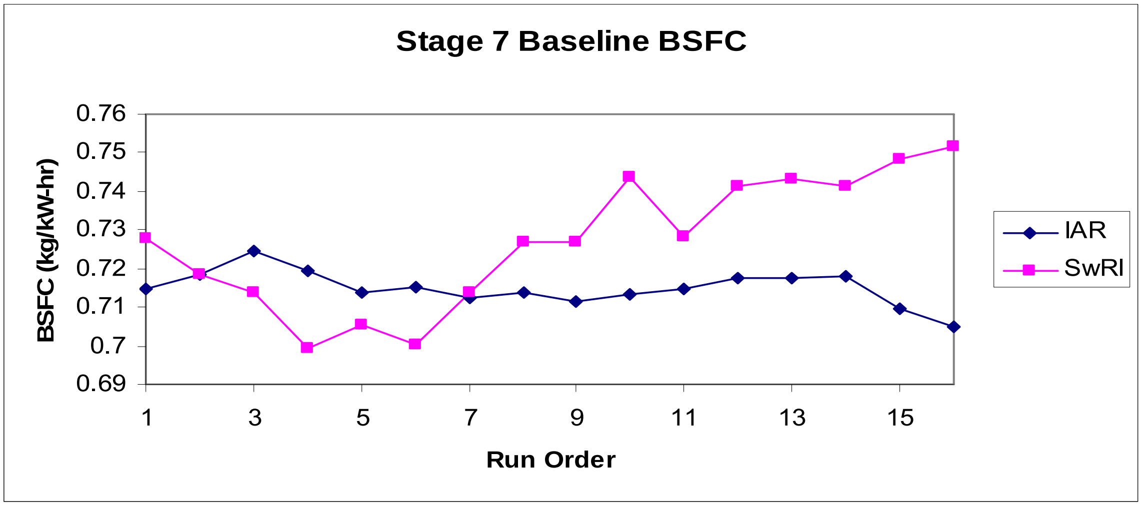


Figure 79. Stage 7 Baseline BSFC Trends

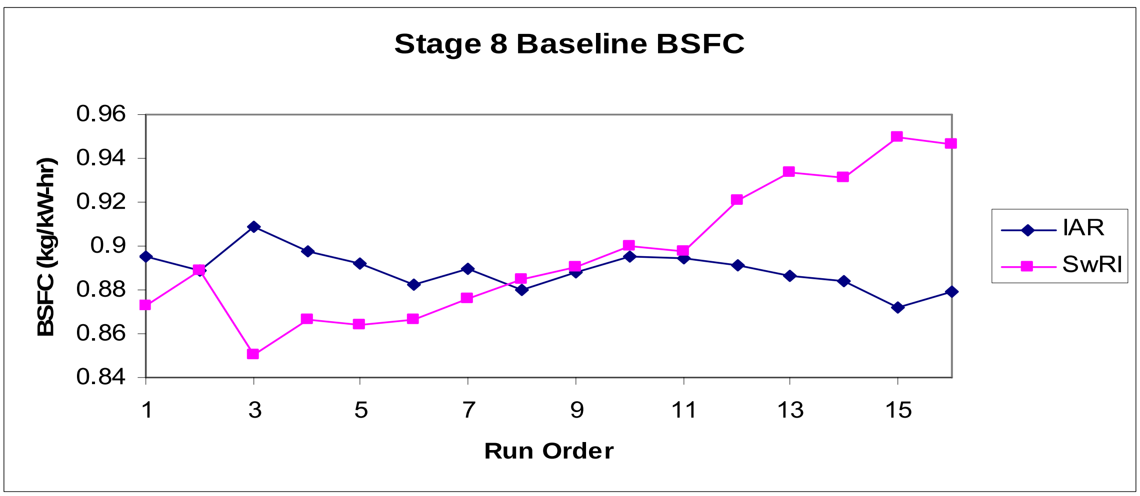


Figure 80. Stage 8 Baseline BSFC Trends

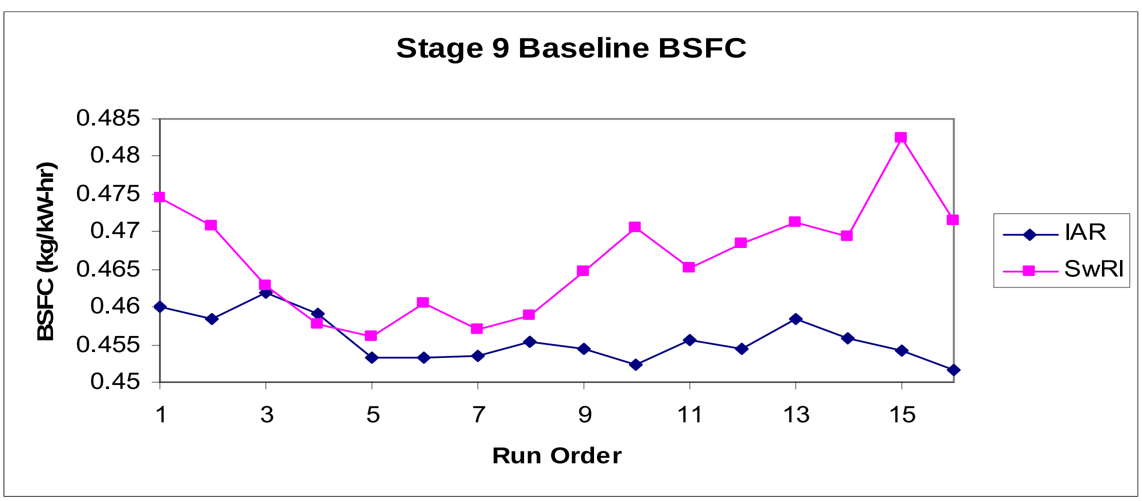


Figure 81. Stage 9 Baseline BSFC Trends

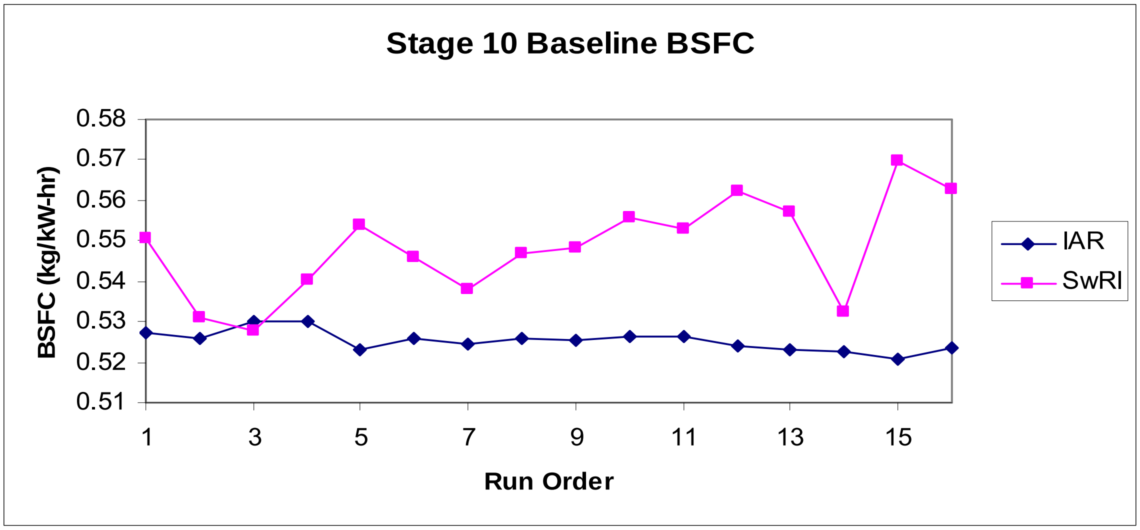


Figure 82. Stage 10 Baseline BSFC Trends

Statistical Analysis of Matrix II - Baseline BSFC Variation For each stage, the within stage Baseline and Test Oil BSFC variation was pooled for each lab. The pooled standard deviations are plotted in Figure 83. The plot indicates that other than Stages 9 and 10, the pooled standard deviation for each stage for IAR is greater than that of SwRI. Note that the variation is inversely related to the mean, that is, the higher the BSFC, the lower the BSFC variation. The plot also indicates that the variations of the test oil BSFC are similar to that of the baseline.

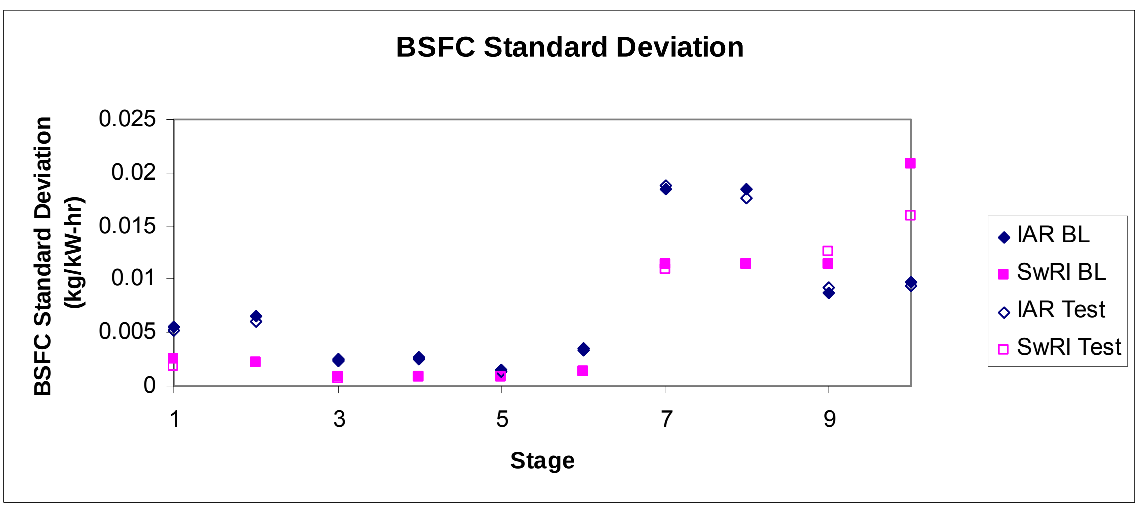


Figure 83. Baseline BSFC Variation

Statistical Analysis of Matrix II - Run Order (Engine Aging) Effect Of the oils tested in both labs (Oils A, B, E, D and L), the contrast in order of Supplier 1 oils is the greatest. For instance, Oil D is tested first at IAR and fifth at SwRI. To determine if there is an order effect we compare the FEIs of the oils tested in both labs relative to their order. This comparison is tabulated in Table 30. These comparisons indicate that the early order oils have higher FEIs in 29 of the 40 stages. This effect is accounted for in the subsequent regression analysis in terms of engine miles.

Table 30. Run Order Effect

Oil	Order Contrast	Stage Count True
A	3 (IAR) > 3 (SwRI)	6
B	1 (SwRI) > 5 (IAR)	8
D	1 (IAR) > 5 (SwRI)	10
E	2 (IAR) > 4 (SwRI)	9
L	2 (SwRI) > 4 (IAR)	6

Statistical Analysis of Matrix II - Regression Analysis For each stage, regression analysis was performed with FEI % as the dependent variable and lab, oil, and engine age (in units of 100 hours) as the independent variables. Table 31 and Figure 84 summarize the analyses. Conclusions based on these analyses follow:

- The Lab coefficient estimates are statistically significant in four of the ten stages, and they are positive in nine of the ten stages, possibly indicating IAR/engine combination has higher FEI than SwRI/engine combination.
- Most stages demonstrate oil discrimination - however, this is not necessarily meaningful as not all contrasts are of interest. For example, comparison of Oils A and H is not meaningful.
- The estimate of the Engine Hours term is negative for all stages (four of them are statistically significant at $\alpha = 0.10$) indicating that FEI decreases with engine life within the range tested.

Table 31. Regression Analyses Summary

Stage	Lab[IAR]		Oil	100 Engine Hours	
	Estimate	p Value	p Value	Estimate	p Value
1	0.39%	0.003	0.002	-0.23%	0.004
2	-0.06%	0.558	0.006	-0.05%	0.472
3	0.13%	0.065	0.004	-0.16%	0.008
4	0.09%	0.196	0.003	-0.11%	0.032
5	0.25%	0.065	0.032	-0.17%	0.053
6	0.08%	0.372	0.019	-0.09%	0.169
7	0.02%	0.943	0.037	-0.09%	0.667
8	0.55%	0.265	0.240	-0.03%	0.906
9	0.37%	0.112	0.002	-0.16%	0.245
10	0.75%	0.060	0.073	-0.11%	0.600

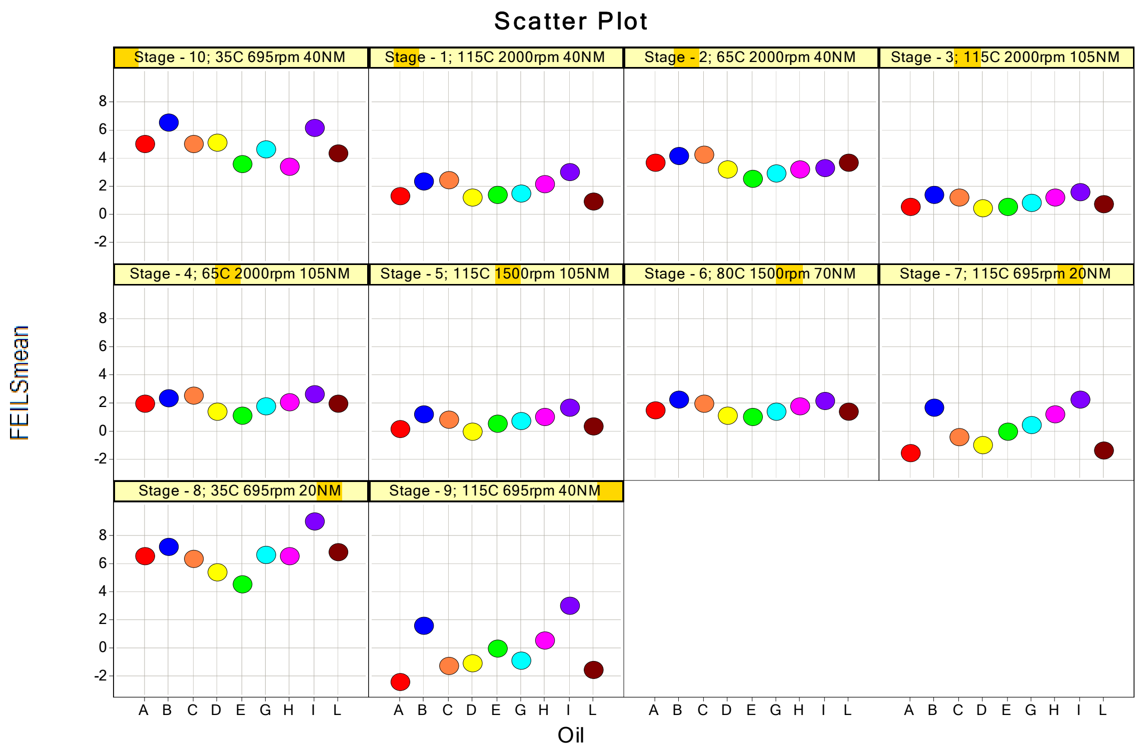


Figure 84. Percent FEI LS Means by Oil and Stage

Statistical Analysis of Matrix II - Oil Discrimination Based on the LS means from the regression analyses, estimations of the oil contrasts of interest were calculated. The t-ratios for each contrast were also calculated to determine statistical significance via the Dunn-Sidak Multiple Comparison test with overall α = 0.10 (individual $\alpha \cong$ 0.01). The t-ratios are tabulated in Table 32 with yellow highlighted cells being statistically significant. (Note that the statistical significance increases with increasing t-ratio.)

Table 32. t-Ratios for Pertinent Comparisons of FEIs

Contrast	Stage									
	1	2	3	4	5	6	7	8	9	10
B - A	6.41	2.55	6.94	3.05	4.27	3.69	4.67	0.71	9.41	2.14
C - A	3.88	1.77	3.06	2.21	1.64	1.45	0.97	0.09	1.51	0.00
D - A	1.03	2.31	0.96	4.03	0.89	2.13	0.73	1.16	3.03	0.13
E - A	0.50	5.47	0.20	6.28	1.71	2.32	2.13	2.04	5.57	2.12
L - A	2.49	0.04	1.51	0.19	0.77	0.78	0.18	0.24	2.06	0.95
E - D	1.53	3.16	0.76	2.25	2.60	0.19	1.40	0.88	2.54	2.24
L - D	1.46	2.28	2.47	4.22	1.66	1.35	0.56	1.40	0.97	1.08
L - E	2.99	5.43	1.70	6.47	0.93	1.54	1.95	2.28	3.51	1.16
H - G	3.99	1.56	3.26	1.96	1.42	1.95	1.04	0.08	3.23	1.76
I - G	7.43	1.62	4.73	5.00	3.10	3.20	1.99	1.88	7.12	1.70

Yellow highlight indicates statistically significant contrast at ℵ= 0.01.

Matrix II Synopsis To facilitate the decision of which stages to exclude (or conversely, which stages to include) in future testing, a matrix was completed with potential decision criteria and corresponding results for each stage. The matrix in stage run order is provided as Table 33 and in order of ZN/P as Table 34. (As indicated earlier, ZN/P is an indication of the relative degree to which the stage is in the boundary versus hydrodynamic regime. ZN/P is calculated as the product of viscosity and speed divided by the manifold pressure. A lower ZN/P indicates the stage is more to the boundary regime side of the spectrum.)

Table 33. Matrix II Synopsis (Stages Ordered by Run Order)

Condition	Stage									
	1	2	3	4	5	6	7	8	9	10
Load (Nm)	40	40	105	105	105	70	20	20	40	40
Speed (rpm)	2000	2000	2000	2000	1500	1500	695	695	695	695
Oil Temperature (ºC)	115	65	115	65	115	80	115	35	115	35
Decision Parameter										
Lab Effect	S		S		S					S
Match to FTP Op. Cond., %	6	1	26	8	12	12	23	3	5	4
Vis Grade Effect	A>E>D>L	**S A>E L>E**	L>A>E>D	**S A>E L>E**	E>L>A>D	A>L>D>E	E>D>L>A	L>A>D>E	**S E>A**	D>A>L>E
OFM1	**S DC**	DC	DC	DC	**S DC**	DC	**S DC**	DC	**S DC**	DC
OFM2	DC	DC	DC	DC	DC	DC	DC	DI	DC	DI
Moly1	DC	DC	DC	DC	DC	DC	DC	DI	DC	DC
Moly2	**S DC**	DC	**S DC**	DC	DC	DC	DC	DC	**S DC**	DC
FEI RMSE (%)	0.16	0.21	0.11	0.13	0.24	0.19	0.68	0.98	0.43	0.7
Boundary/Hydrodynamic (ZN/P)	394	1642	243	1043	178	583	136	2304	112	1969
Ease of Running										
Theoretical Engine Wear										

DC is not statistically significant ($\alpha = 0.1$) but directionally correct.
S DC is statistically significant ($\alpha = 0.1$) and directionally correct.
Red font indicates unfavorable result.

Table 34. Matrix II Synopsis (Stages Ordered by ZN/P)

Condition	Stage									
	9	7	5	3	1	6	4	2	10	8
Load (Nm)	40	20	105	105	40	70	105	40	40	20
Speed (rpm)	695	695	1500	2000	2000	1500	2000	2000	695	695
Oil Temperature (ºC)	115	115	115	115	115	80	65	65	35	35
Decision Parameter										
Lab Effect			S	S	S				S	
Match to FTP Op. Cond., %	5	23	12	26	6	12	8	1	4	3
Vis Grade Effect	**S E>A**	E>D>L>A	E>L>A>D	L>A>E>D	A>E>D>L	A>L>D>E	**S A>E L>E**	**S A>E L>E**	D>A>L>E	L>A>D>E
OFM1	**S DC**	**S DC**	**S DC**	DC	**S DC**	DC	DC	DC	DC	DC
OFM2	DC	DC	DC	DC	DC	DC	DC	DC	DI	DI
Moly1	DC	DC	DC	DC	DC	DC	DC	DC	DC	DI
Moly2	**S DC**	DC	DC	**S DC**	**S DC**	DC	DC	DC	DC	DC
FEI RMSE (%)	0.43	0.68	0.24	0.11	0.16	0.19	0.13	0.21	0.70	0.98
Boundary/Hydrodynamic (ZN/P)	112	136	178	243	394	583	1043	1642	1969	2304
Ease of Running										
Theoretical Engine Wear										

DC is not statistically significant ($\alpha = 0.1$) but directionally correct.
S DC is statistically significant ($\alpha = 0.1$) and directionally correct.
Red font indicates unfavorable result.

9.4 Matrix III – Additional Evaluation of Initial Stages Following the VID Consortium meeting in Phoenix (December, 2007), a number of issues were identified during the review of the Matrix II analysis results. First, the idle (695 - 1500 RPM) test stages exhibited the least amount of discrimination between the different viscosity grades and friction modified test oils. One factor that contributed to the lack of discrimination was based on the regression model's Root Mean Square Error (RSME). In contrast to the non-idle test stages (1 - 6), the RMSE was much larger in the idle test stages (7 - 10). A summary of the Matrix II regression model FEI1 - RMSE for each stage is provided in Table 35.

Table 35. RMSE Summary of Matrix II Data for each of the 10 Test Stages

[redacted]

If the idle stage repeatability could be improved, then the model-based RMSE may also be reduced. A reduction in the RMSE could help to statistically discriminate the effects of viscosity and friction modifier differences in the candidate test oils. In addition to the large RSME for the idle stages, it was noted that some of the Matrix II test runs exhibited some unusual shifts/trends in the BSFCs for the baseline oil Z.

Following the initial analysis of the Matrix II test data, it would have been advantageous (in terms of test cost and time) to reduce number of stages from 10 to a smaller number. However, due to the lack of discrimination at the idle test stages, the concern regarding the test repeatability, and the unknown relationship between the Matrix II and GM fuel economy test data, a consensus could not be reached on which stages could be dropped from the test. As such, it was agreed to perform some additional testing, which included Matrix III, at the IAR and SwRI test laboratories to improve the repeatability of the test. The Statistics Group was also assigned the task of analyzing the correlations between the candidate oil FEI estimates of the Matrix II test stages and GM City, Highway, and Combined fleet data.

ECM-2 - Recalibration to Improve Idle Speed Variability The primary emphasis of the Matrix III test program was to improve the BSFC repeatability of the idle test stages with a different engine controller and a higher (idle) RPM. Based upon an evaluation of the three different engine controllers, the ECM-2 was selected for additional idle stage candidate oil testing. To ensure that the generated data could be compared to the Matrix II results, candidate oils A and B were selected for the Matrix III test program. Following the completion of Matrix III testing at SwRI and IAR, an analysis of the 995 RPM and 695 RPM FEI candidate test data was performed. The analysis suggested the following two points. First, oils A and B lost their separation at 995 RPM as compared to 695 RPM in Stage 9. Second, Oil B had a lower FEI than Oil A in Stage 9 at the SwRI test laboratory. A summary of the average %FEI by test oil, stage, and laboratory is summarized below in Figures 85 and 86.

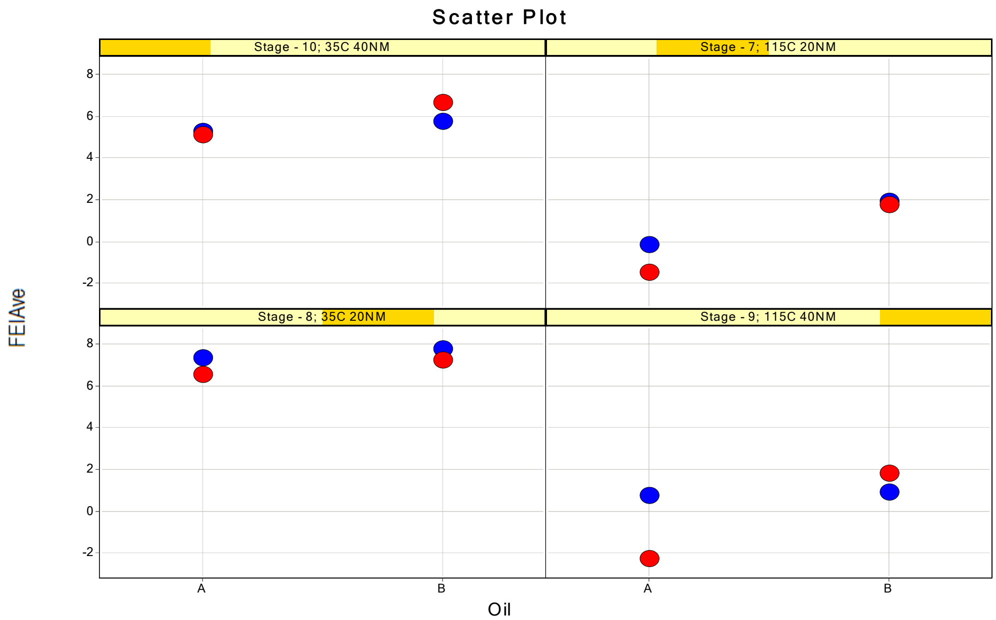


Figure 85. % FEI Average by Stage and Candidate Oil (695rpm 995rpm)

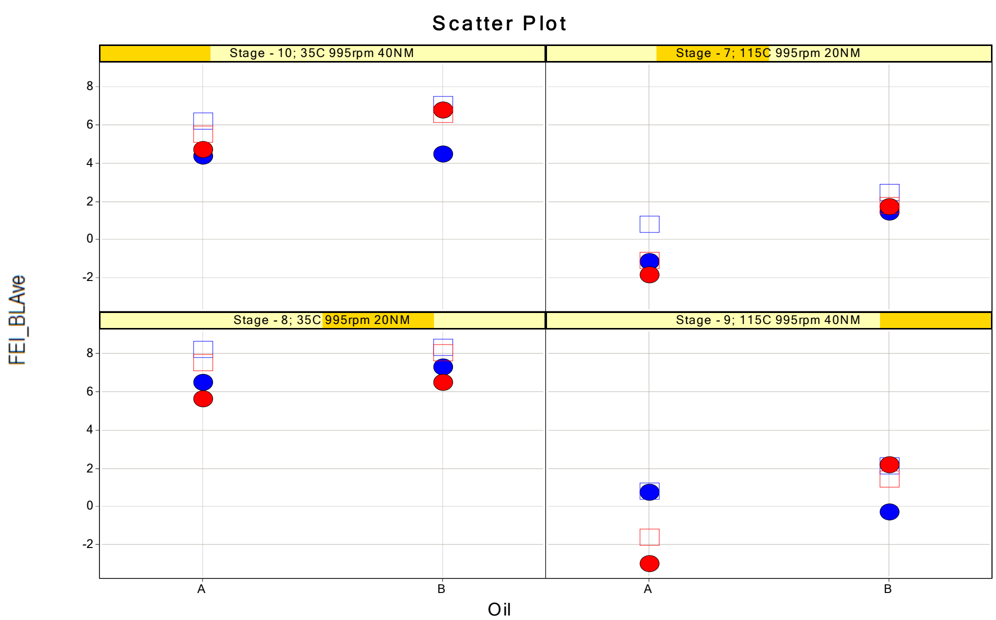


Figure 86. % FEI Average by Stage, Oil, and Lab (695rpm 995rpm IAR SwRI)

An analysis of the standard deviation (STD) of the BSFC (Brake Specific Fuel Consumption) at each stage was also performed. The STD BSFC test data revealed that SwRI had a greater drop in BSFC STD (≈30%) for Stages 9 and 10; and, the separation for Stages 7 and 9 had decreased to approximately zero. A summary of the BSFC STD data by Stage and test laboratory is provided in Figure 87.

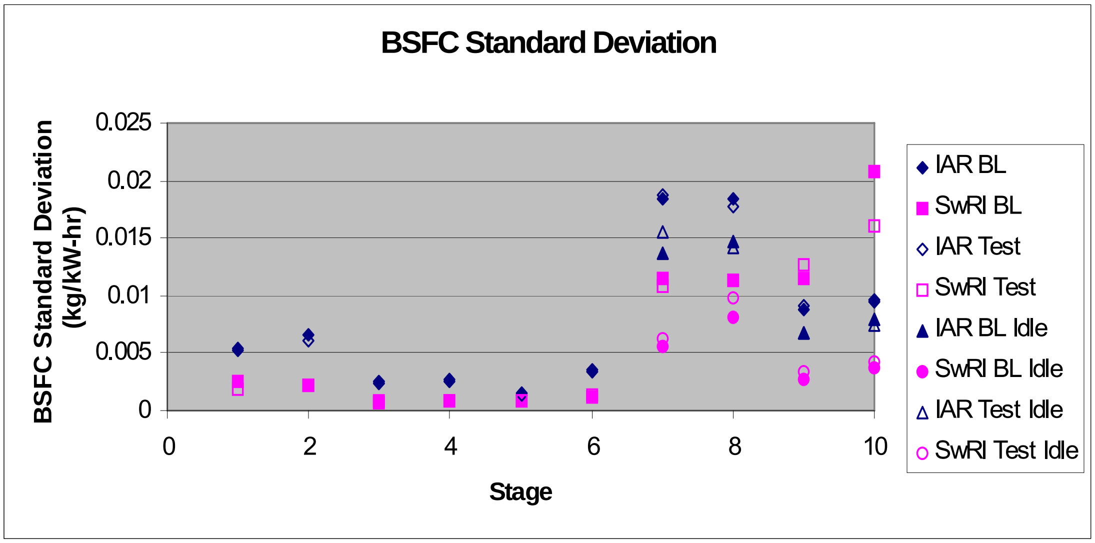


Figure 87. BSFC Standard Deviation Summary by Stage and Laboratory

The raw BSFC data was also used to generate histograms for the two speeds and three different test oils (A, B, and Z) at each lab. The BSFC Histograms, which are summarized in Figures 88 through 91, indicated that the discrimination for stages 7 and 9 had decreased at higher idle speeds. The specific observations of the histogram plots included the following:

- Stage 7 BSFC Histogram - some difference for Oil Z
- Stage 8 BSFC Histogram - no significant difference
- Stage 9 BSFC Histogram - results for SwRI were based on greater amount of data

The overall conclusion of the BSFC histogram plots indicated that an increase in idle speed can improve precision for Stage 8. However, other stages such as Stage 9 may have suffered a loss of response at higher idle speeds.

Based on the analyses of the idle study test data, the ability to make programming changes to the ECM, and a discussion between the consortium members, it was decided that all follow-on matrix tests should use the same ECM calibration (Revision 1 ECM OHT014). Thus, there were no changes to the idle speeds made for any of the test stages.

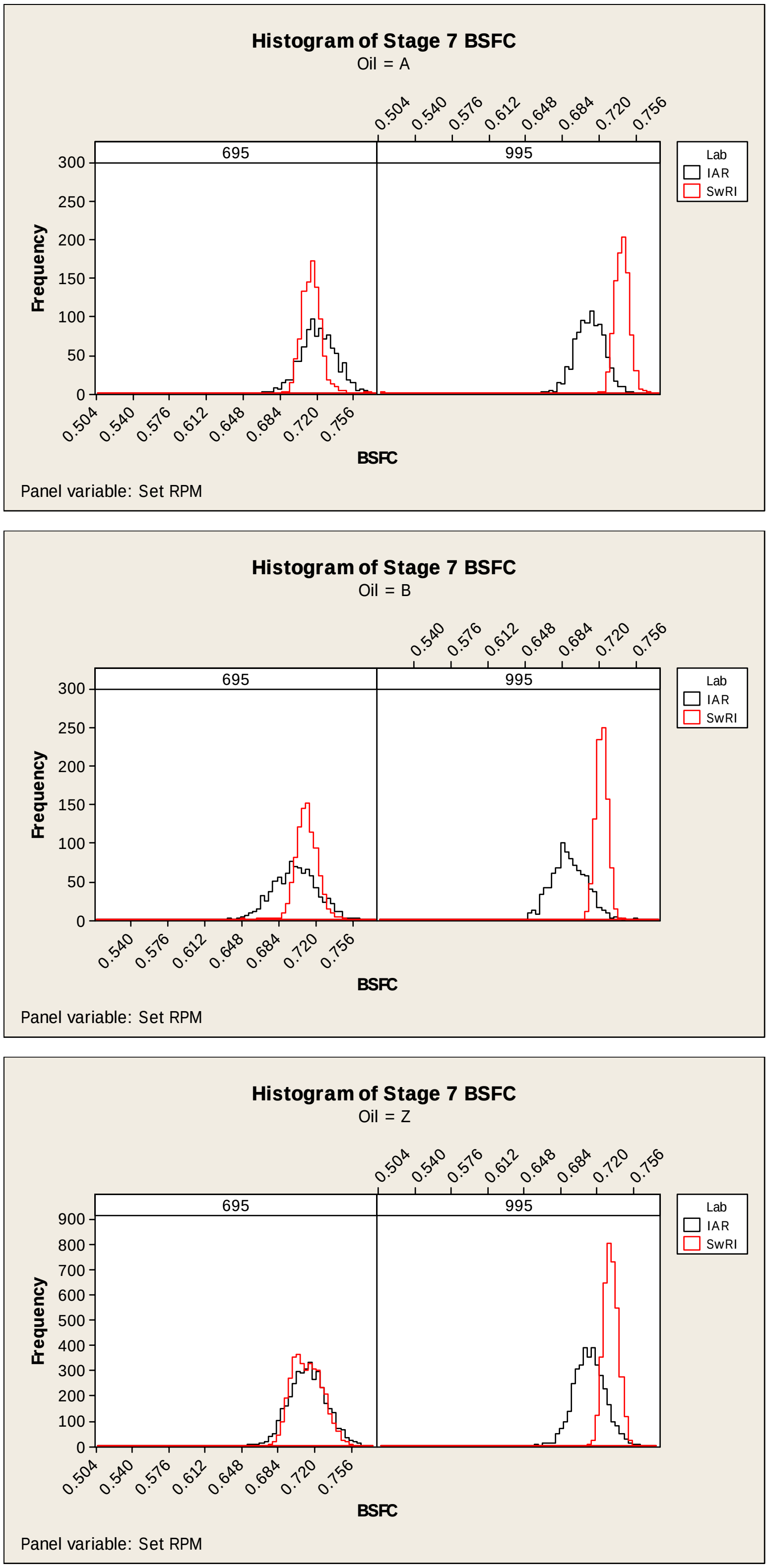


Figure 88. Histogram of Stage 7 BSFC by Lab– Oil A, B, Z

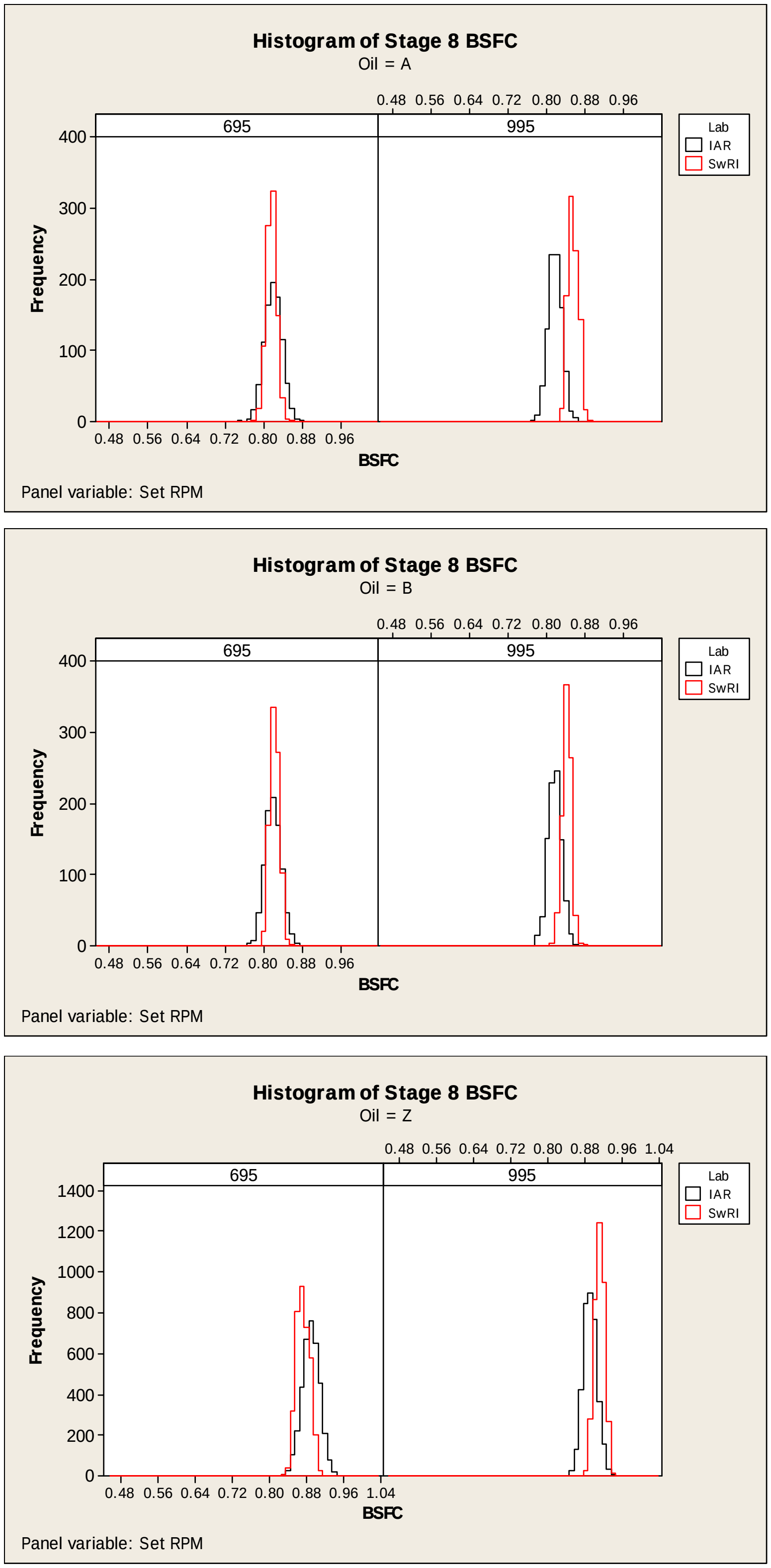


Figure 89. Histogram of Stage 8 BSFC by Lab– Oil A, B, Z

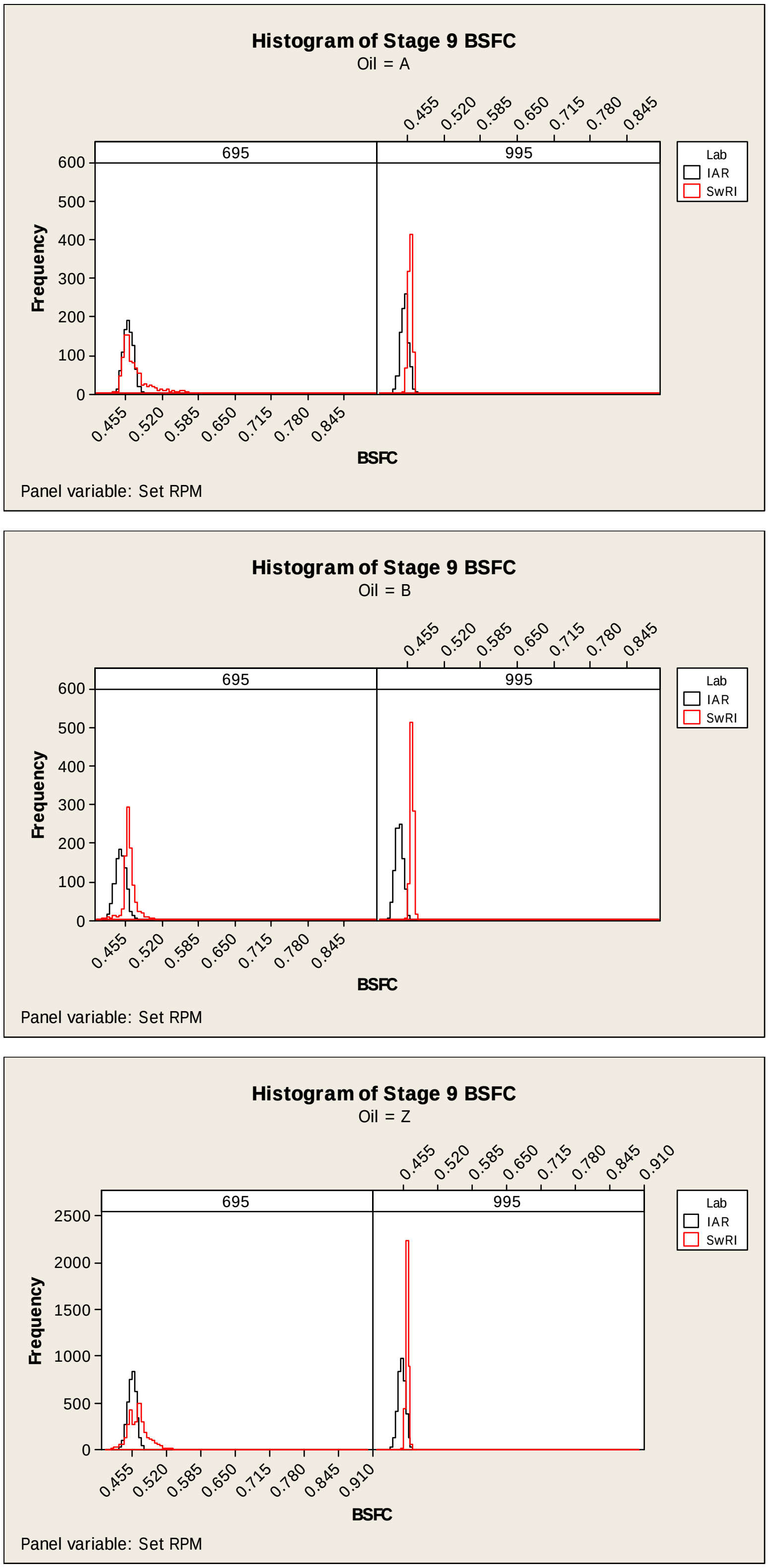


Figure 90. Histogram of Stage 9 BSFC by Lab– Oil A, B, Z

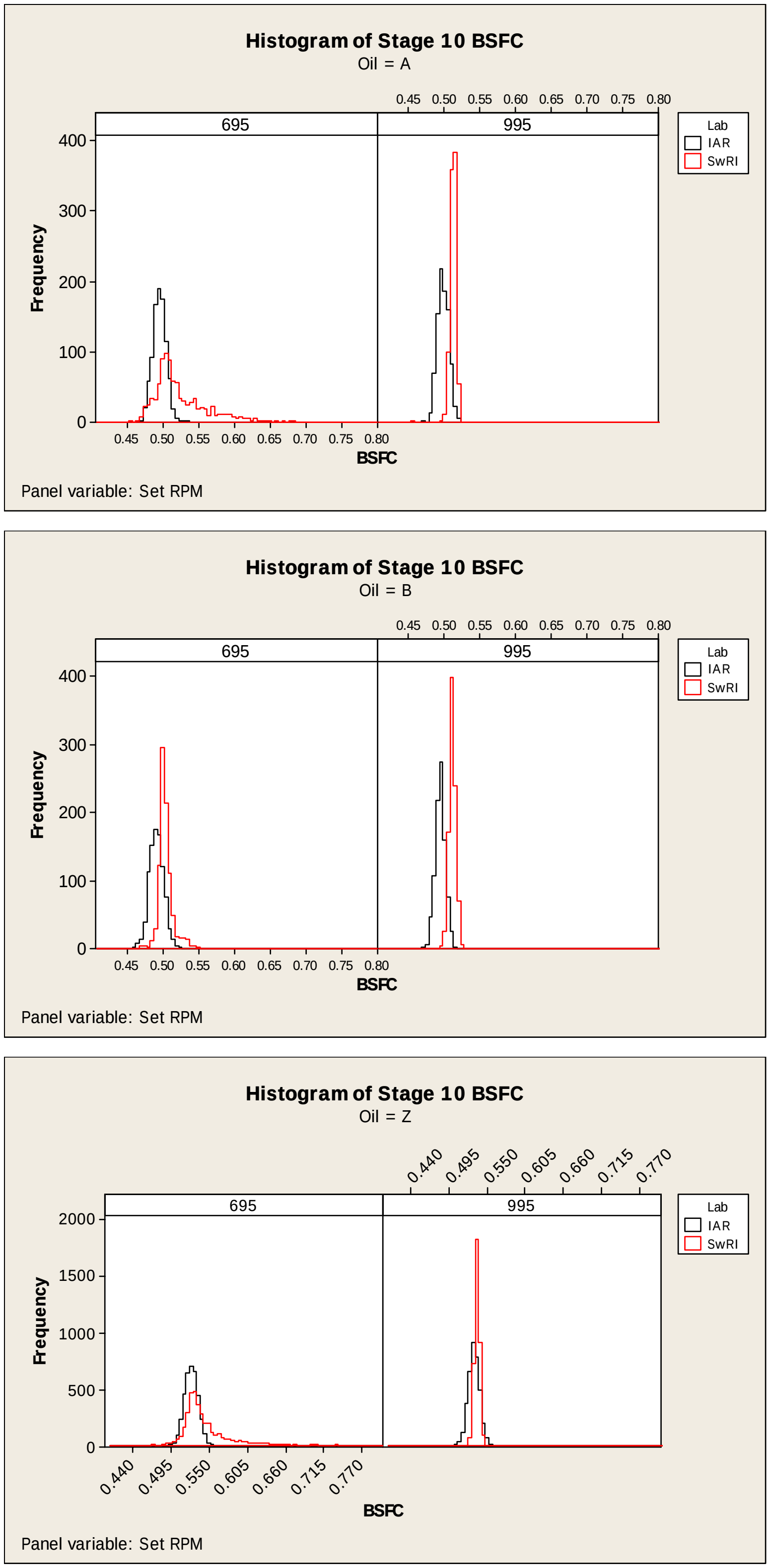


Figure 91. Histogram of Stage 10 BSFC by Lab– Oil A, B, Z

Statistical Analysis - Matrix II Statistical Analysis for Stage Selection The Sequence VID - Matrix II test plan consisted of aging several different candidate test oils at two different test laboratories and then estimating their corresponding fuel economy improvement (FEI1) performance. The aging of the oil was intended to match the used oil properties of the GM vehicle fleet data at 2000 miles. In this study there were nine different candidate test oils {A, B, C, D, E, G, H, I, L}; and, the fuel economy (FEI1) performance of each candidate test oil was evaluated at the 10 uniquely configured test stages summarized in Table 26. The 10 test stages differed by their load, speed, and oil temperature as indicated in Table 26.

As mentioned in an earlier section, one of the goals of the Matrix II test plan was to reduce the number of test stages from 10 to a smaller number. The statistical criteria used for the stage selection was based on correlation and discrimination. A description of both will be provided in the following paragraphs.

Discrimination Analysis The discrimination analysis examined the difference in fuel economy performance between specific viscosity grades and friction modified candidate test oils - for each of the 10 test stages. Thus, it would be advantageous to select the test stages that demonstrate directionally correct and statistically significant viscosity grade and friction modifier effects. With a similar DI package and base oil formulation, a directionally correct viscosity effect implies that an SAE 5W-20 oil will have a greater fuel economy improvement than an SAE 10W-30 oil. In a similar fashion, an organic or molybdenum friction modified oil with a similar DI package, base oil formulation, and viscosity grade is also expected to have higher fuel economy than a non-friction modified oil.

A statistically significant effect is based on the calculated *t*-value (or *t*-ratio) for each of the evaluated contrasts. For the two DI packages, the calculated *t*-value is based on the pair-wise difference between the Least Squares Mean (LSMean) fuel economy estimates (FEI1) for specific pairs of viscosity grade and friction modified candidate test oils, which is then divided by the standardized error. The LSMeans and standardized error are based on a (GLM) regression analysis of the nine candidate oils, two test laboratories, and an engine hour covariate.

Using the regression analysis' LSMean estimates, a multiple comparison analysis was performed to estimate the differences/contrasts between viscosity grades and friction modified - candidate test oils. A contrast is identified as statistically significant if the absolute value of the calculated *t*-value is greater than the critical *t*-value of approximately 4.03. The critical *t*-value is based on the Bonferroni Multiple Comparison procedure with an overall family wise error rate of α = 0.10 for each stage. For the 10 contrasts in each stage, this results in an individual contrast error rate of α = 0.01. A summary of the viscosity and friction modified contrasts of interest and the corresponding *t* values are summarized in Tables 36 and 37.

Table 36. Summary of the Friction Modifier and Viscosity Grade Contrasts of Interest

Candidate Test Oil: Viscosity Grade: Friction Modified: DI Package	A 5W20 None 1	B 5W20 OFM 1	C 5W20 Moly 1	D 5W30 None 1	E 10W30 None 1	L 0W20 None 1	G 5W30 None 2	H 5W30 OFM 2	I 5W30 Moly 2
Contrast 1 - FM	X	X							
Contrast 2 - FM	X		X						
Contrast 3 - Vis	X			X					
Contrast 4 - Vis	X				X				
Contrast 5 - Vis	X					X			
Contrast 6 - Vis				X	X				
Contrast 7 - Vis				X		X			
Contrast 8 - Vis					X	X			
Contrast 9 - FM							X	X	
Contrast 10 - Vis							X		X

(OFM - Organic Friction Modified & Moly - Molybdenum Friction Modified)

Table 37. *t*-Value (*t*-Ratio) Summary for the Contrasts of Interest

t-Ratio for Pertinent Comparisons of Oil FEIs (Engine Hours Term Included)

Contrast	Stage									
	1	2	3	4	5	6	7	8	9	10
B - A	6.41	2.55	6.94	3.05	4.27	3.69	4.67	0.71	9.41	2.14
C - A	3.88	1.77	3.06	2.21	1.64	1.45	0.97	-0.09	1.51	0.00
D - A	-1.03	-2.31	-0.96	-4.03	-0.89	-2.13	0.73	-1.16	3.03	0.13
E - A	0.50	-5.47	-0.20	-6.28	1.71	-2.32	2.13	-2.04	5.57	-2.12
L - A	-2.49	-0.04	1.51	0.19	0.77	-0.78	0.18	0.24	2.06	-0.95
E - D	1.53	-3.16	0.76	-2.25	2.60	-0.19	1.40	-0.88	2.54	-2.24
L - D	-1.46	2.28	2.47	4.22	1.66	1.35	-0.56	1.40	-0.97	-1.08
L - E	-2.99	5.43	1.70	6.47	-0.93	1.54	-1.95	2.28	-3.51	1.16
H - G	3.99	1.56	3.26	1.96	1.42	1.95	1.04	-0.08	3.23	-1.76
I - G	7.43	1.62	4.73	5.00	3.10	3.20	1.99	1.88	7.12	1.70

Yellow highlight indicates statistically significant contrast at α = 0.01.

Correlation Analysis A correlation analysis was also performed on the Matrix II and GM fuel economy test data. The objective was to identify the correlations between each of the 10 VID test stages and the GM FTP fuel economy test data. A positive correlation between the two data sets suggests that the VID may generate fuel economy results that are directionally similar to the GM FTP fuel economy test data. The data used in the analysis is based on the Driver Corrected LSMean (2000 mile) fuel economy estimates and the Matrix II (FEI1) LSMean fuel economy estimates. A summary of the GM and Matrix II test data is provided Table 38.

Table 38. VID Stage and GM Fleet Data %FEI LSMean Summary

[redacted]

A Pearson correlation analysis was performed on each of the test stages. With eight candidate test oils in Matrix II and an α value of 0.10, the critical correlation coefficient value is 0.62. Thus, if the absolute value of the correlation coefficient is equal to or exceeds 0.62, then the correlation is identified as statistically significant. A summary of the correlations between the test stages and fuel economy test data is provided in Table 39.

Table 39. VID Stage and GM FTP Data %FEI Correlation Summary

%FEI Improvement Correlation Summary

Stage	GM FTP FEI-2K	GM FFE FEI - 2K	GM Combined FEI-2k
Stage 1	0.53	0.05	0.49
Stage 2	0.28	-0.16	0.17
Stage 3	0.66	-0.03	0.58
Stage 4	0.45	-0.04	0.39
Stage 5	0.61	0.06	0.58
Stage 6	0.61	0.03	0.55
Stage 7	0.79	0.11	0.73
Stage 8	0.58	0.20	0.59
Stage 9	0.76	0.35	0.79
Stage 10	0.62	0.19	0.57
Highlighted cells indicate a statistically significant correlation at α ≤ 0.10			

Plots were also generated to further examine the relationships between each of the 10 test stages and the GM fuel economy data for each of the candidate test oils. In a number of the plots, the (friction modified) candidate test oil C appears to have an unusual relationship between the GM FTP and Matrix II test data. During a discussion of the plots, it was also noted that the HFRR friction data indicated a similar drop in performance between the new and 2000 mile aged oil samples. Figures 92 through 101 graphically summarize the relationships between the LSMean GM FTP and Matrix II VID %FEI test data.

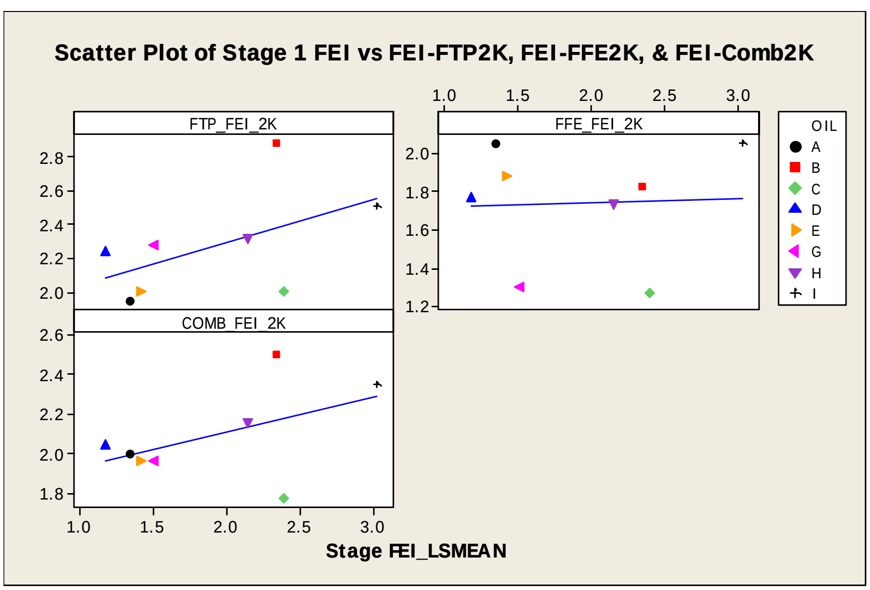


Figure 92. Stage 1 & GM 2000 Mile FTP %FEI LSMean Scatter Plot

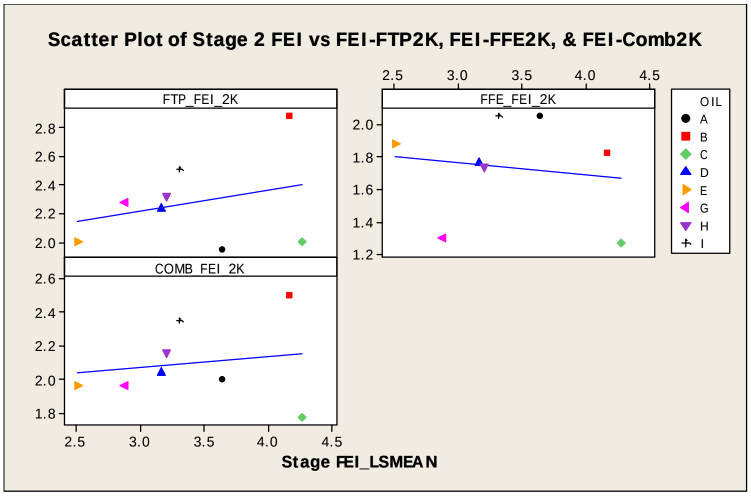


Figure 93. Stage 2 & GM 2000 Mile FTP %FEI LSMean Scatter Plot

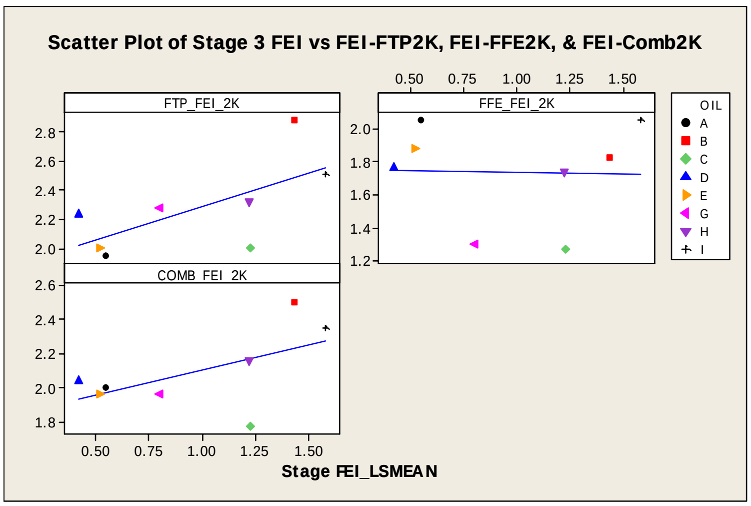


Figure 94. Stage 3 & GM 2000 Mile FTP %FEI LSMean Scatter Plot

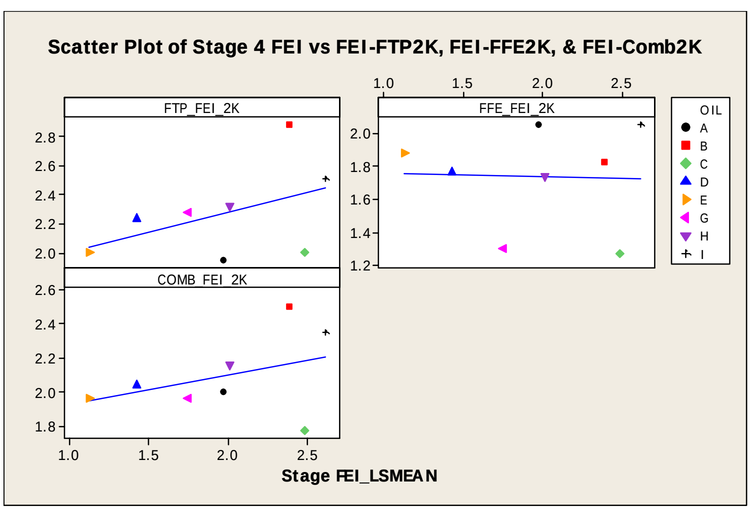


Figure 95. Stage 4 & GM 2000 Mile FTP %FEI LSMean Scatter Plot

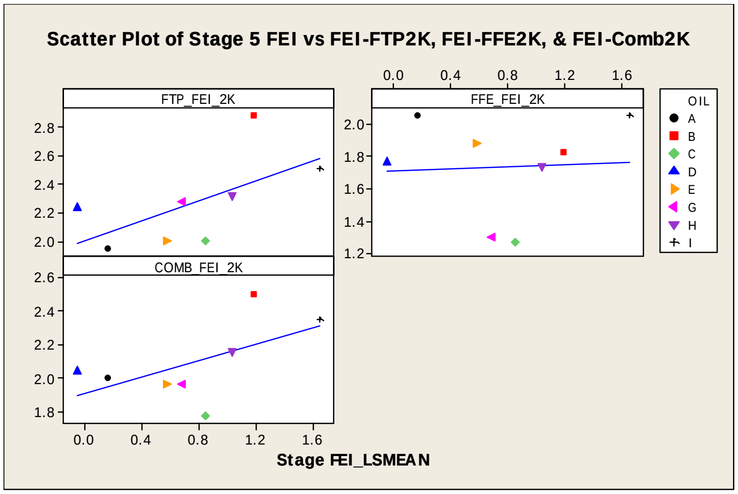


Figure 96. Stage 5 & GM 2000 Mile FTP %FEI LSMean Scatter Plot

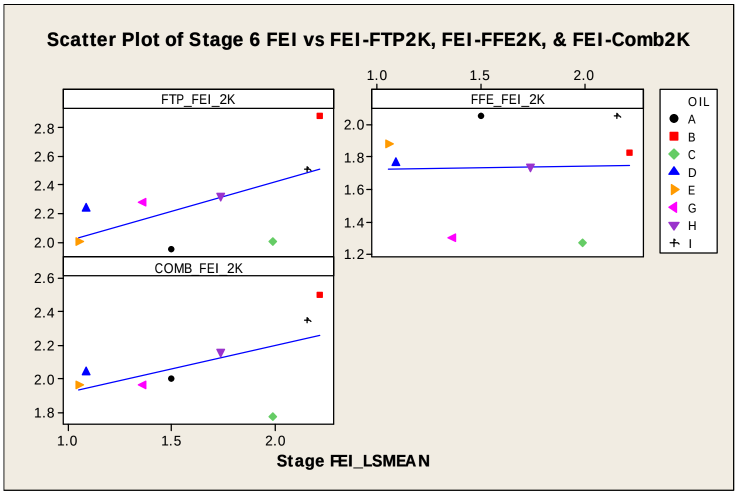


Figure 97. Stage 6 & GM 2000 Mile FTP %FEI LSMean Scatter Plot

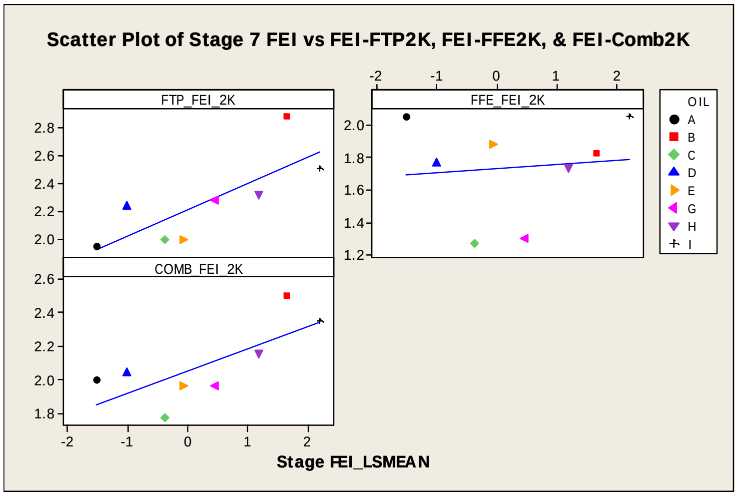


Figure 98. Stage 7 & GM 2000 Mile FTP %FEI LSMean Scatter Plot

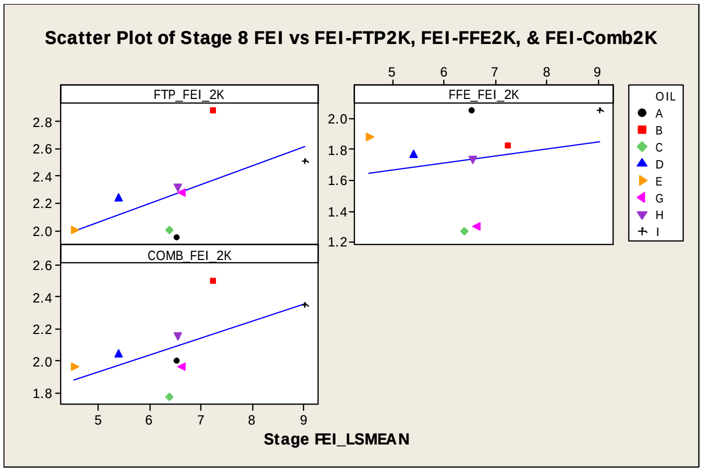


Figure 99. Stage 8 & GM 2000 Mile FTP %FEI LSMean Scatter Plot

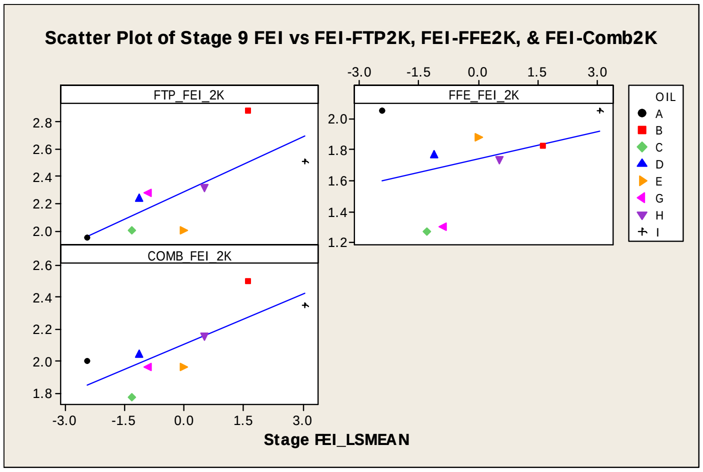


Figure 100. Stage 9 & GM 2000 Mile FTP %FEI LSMean Scatter Plot

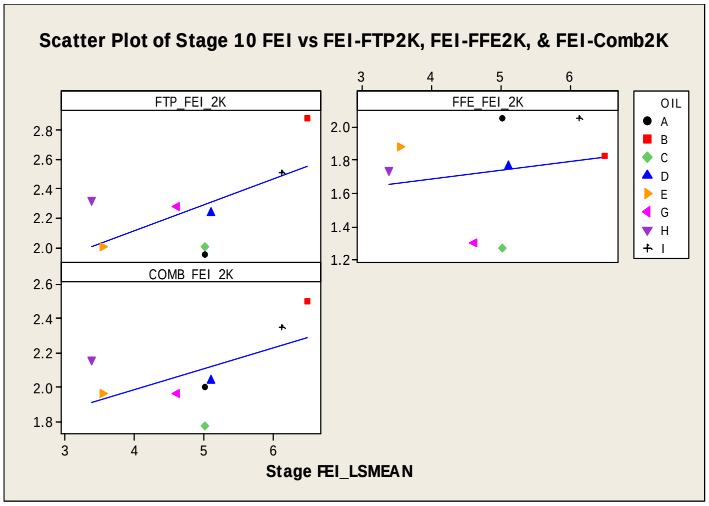


Figure 101. Stage 10 & GM 2000 Mile FTP %FEI LSMean Scatter Plot

Stage Reduction from ten to six   The Consortium members reviewed the GM FTP and Matrix II fuel economy discrimination and correlation analysis results to identify the stages that should be eliminated. Based on a discussion of the analysis results, a consensus was reached to drop stages 1, 2, 6, and 10. The rationale for eliminating these stages from the VID test program is summarized below:

- Stage 6 should be eliminated due to the lack of discrimination for any of the candidate test oils.

- Provided that Stage 3 is retained, Stage 1 should be eliminated. Both Stages 1 and 3 have similar discrimination; however, Stage 3 correlates better with the GM FTP test data.

- Provided that Stage 8 is retained, Stage 10 should be eliminated. Both Stages 8 and 10 had similar correlations to the GM FTP test data; and; neither of the stages provided statistical discrimination between the candidate test oils. Nonetheless, there was some agreement among the consortium members that Stage 8 had more favorable properties than Stage 10.

- Provided that Stage 4 is retained, Stage 2 should be eliminated. The discrimination and correlation for Stage 4 is better than Stage 2.

The retained stages for follow-on testing in Matrix IV included 3, 4, 5, 7, 8, and 9. These stages corresponded to 3 high-load and high-speed and 3 low-load and low-speed conditions. Table 40 summarizes the discrimination and correlation information for all 10 stages.

Table 40. Stage Selection – Statistical Analysis Summary

[redacted]

9.5 Matrix IV – Fresh and Aged Oil Evaluations The main purpose of Matrix IV was to run the test with the reduced number of stages and with extended aging. The objectives of the matrix were to:

- Determine effect of aging on oil response
- Determine effect of aging on variability
- Determine engine aging effect

Figure 102 shows the Matrix IV design:

Final Matrix IV: 5-Oil Matrix – 12 runs

- Stages (3,4,5,7,8,9) – in current order
- Oil (A, B, E, G, I)
- Lab (IAR, SwRI)
- Repeat 1st oil in each lab for engine aging effect
- Error dof = 6
- ~6 weeks to run

RunOrder	IAR	SwRI
1	I	A
2	G	B
3	E	E
4	B	G
5	A	I
6	I	A

Figure 102. Final Design for Matrix IV

There were 12 tests in this matrix, 6 tests in each laboratory. Two invalid runs on Oil A were reported at IAR. Statistical analysis was performed on the dataset with valid runs only and on the dataset with valid runs plus valid stages of invalid runs. Both datasets resulted in the same conclusions.

Looking at the baseline fuel consumed for all tests, SwRI had higher fuel consumed than IAR for all stages except for Stage 8 as shown in Figure 103. Though this was true for the baseline fuel consumed, the fuel economy improvement data did not show this consistent difference between labs in all stages. The chart below indicates that there was a Phase 1 FEI statistical difference between laboratories at stage 7 and a Phase 2 FEI statistical difference at stage 8. See Figure 104.

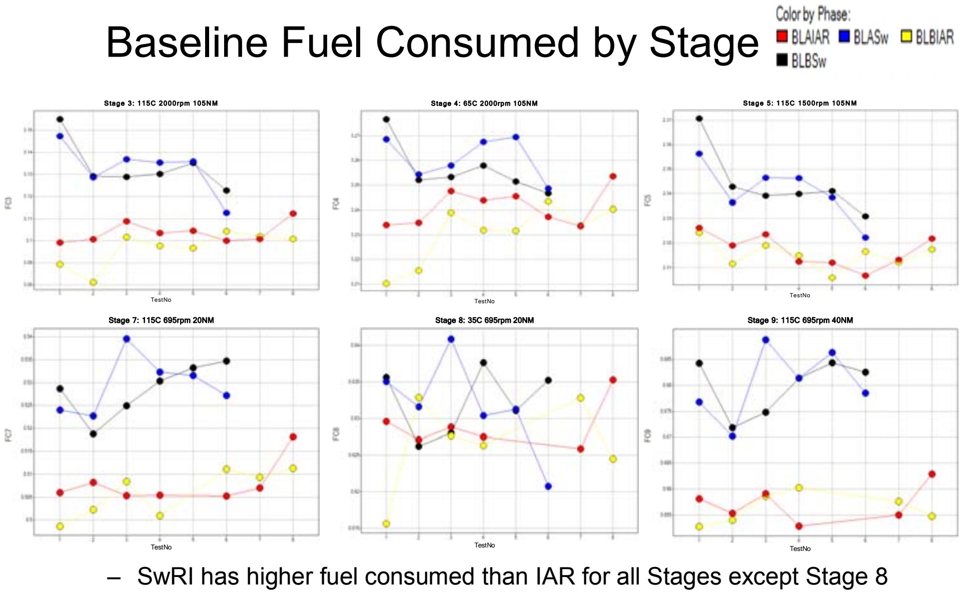


Figure 103. Baseline Fuel Consumed by Stage

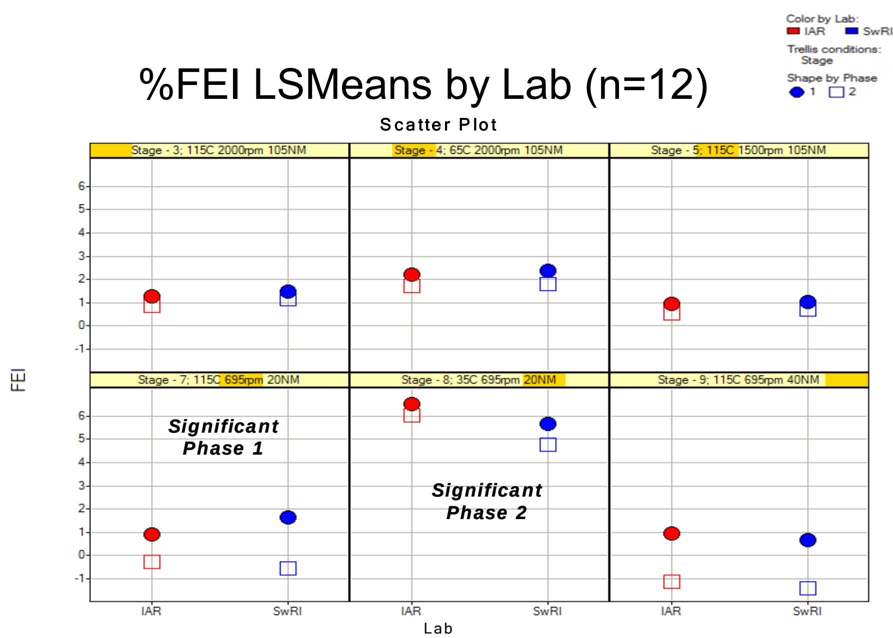


Figure 104. Percent FEI Least Square Means by Lab

Figure 105 shows the Least Square (LS) Means by oil in each of the 6 stages using data on 12 valid runs only. Based on the statistical analysis,

- Phase 1 O-FM (B > A) response is statistically significant in stages 7 and 9, directionally correct for all stages except stage 5
- Phase 1 Moly (I > G) response is statistically significant in stage 9, directionally correct for all stages except stage 8
- Phase 1 Viscosity Grade (A > E) response is statistically significant in stage 4, all stages except stages 7 & 9 favor lower viscosity
- No significant Phase 2 O-FM and Moly responses
- Significant Phase 2 Viscosity Grade response in stage 4

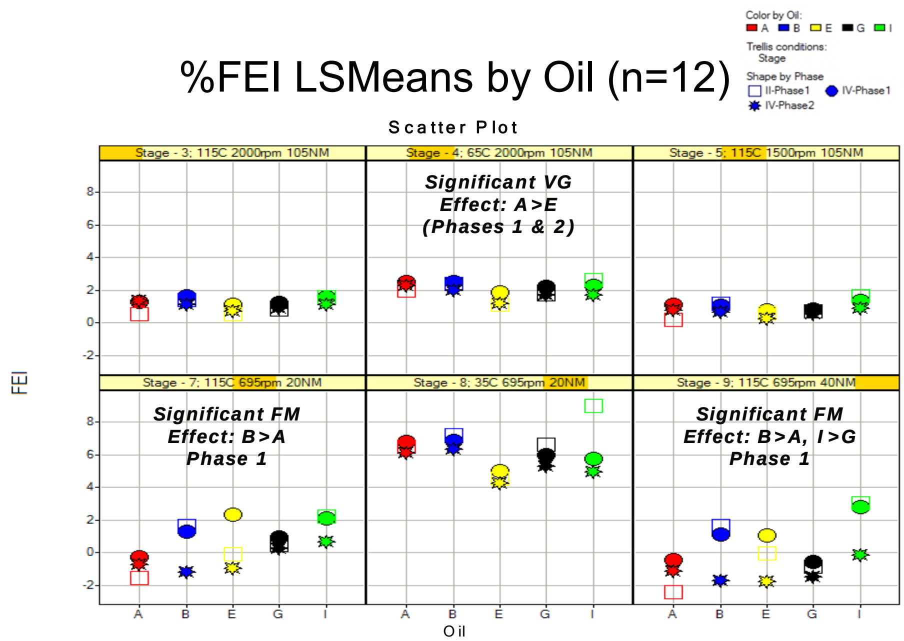


Figure 105. Percent FEI Least Square Means by Oil

VID used oil analysis results on DIR Oxidation and Nitration, Viscosity at 100°C and 40°C and HFRR were analyzed to determine whether VID aging matches that of FTP aging. The following correlation plots, Figures 106 through 108, show that VID aging matches FTP aging for viscosity and HFRR. Little to no correlation can be seen with DIR Oxidation and Nitration.

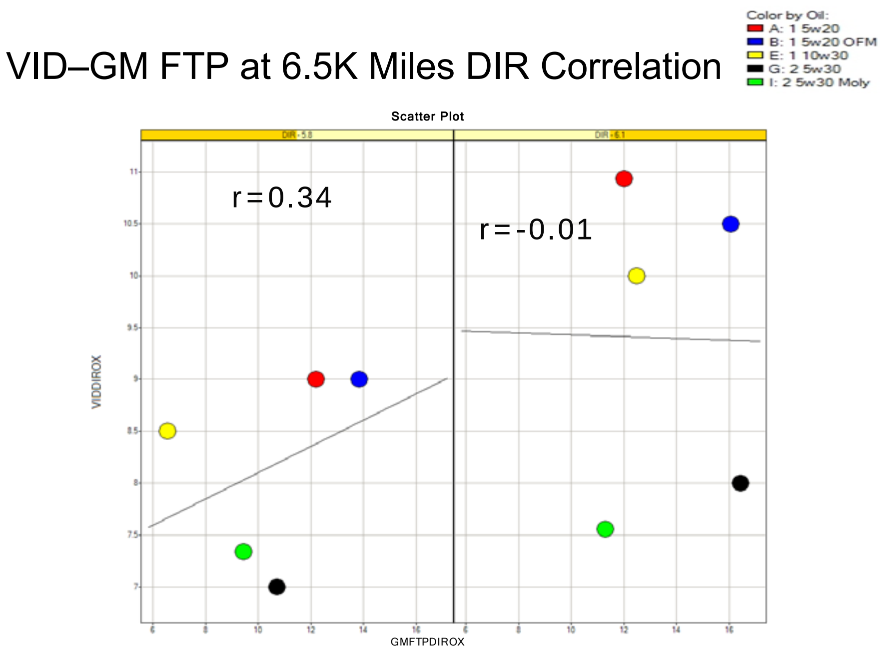


Figure 106. Correlation of DIR, GM FTP at 6,500 Miles and VID Used Oil

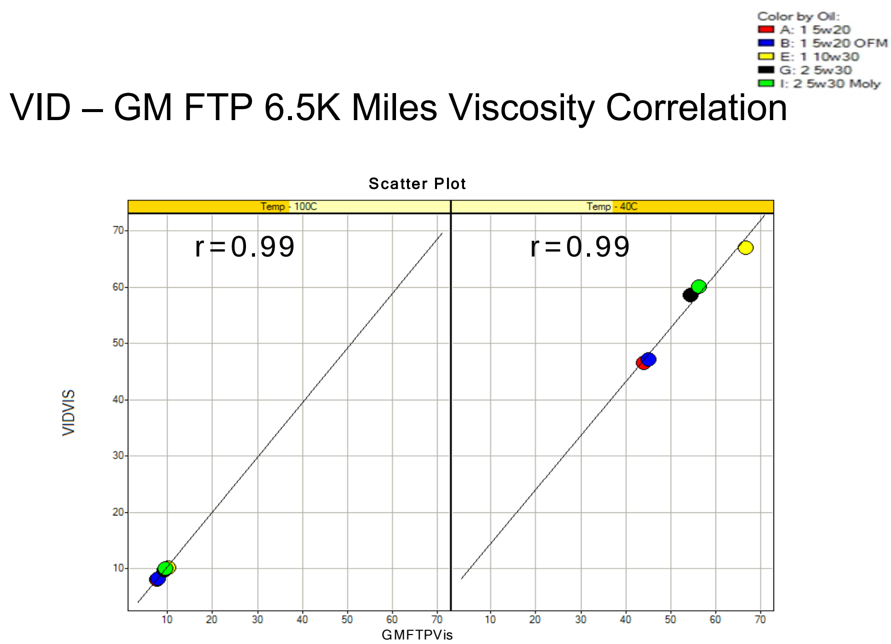


Figure 107. Correlation of Viscosity, GM FTP at 6,500 Miles and VID Used Oil

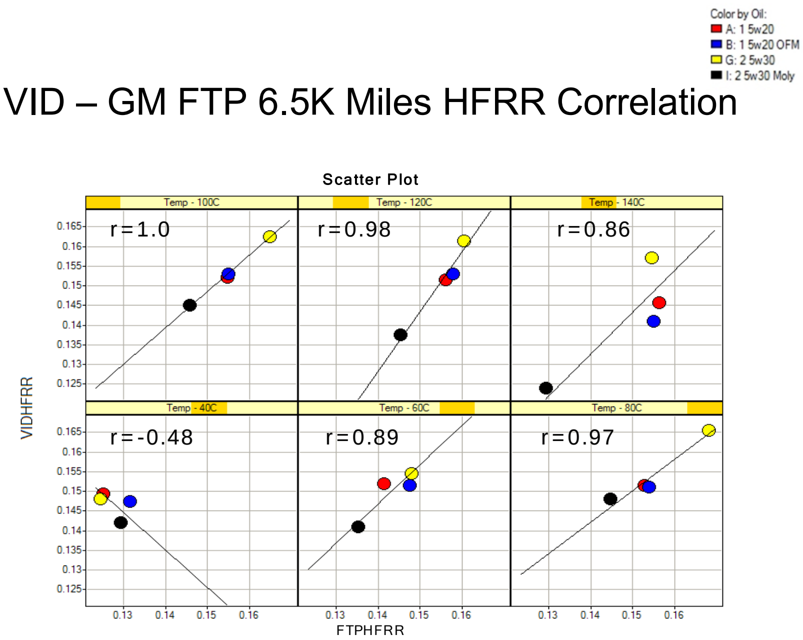


Figure 108. Correlation of HFRR Friction, GM FTP at 6,500 Miles and VID Used Oil

9.6 Matrix IV-A - ECM-Revision 3 and Dual Throttle Evaluation Two approaches were evaluated to determine whether improvements in test variability could be obtained. The first change was a revision to the ECM (engine control module) and the second was the use of a Dual Throttle mechanism. The revision to the ECM was to change from a variable spark timing at idle conditions (stock condition) to a fixed spark timing at idle. In normal operation control of the engine, the ECM uses variable spark timing at idle to control idle speed. However, under the conditions of the VID Test, variable spark timing at idle seemed to be causing more variability in engine operation, and caused spark timing to vary from 8 to 13 degrees before top dead center (BTDC). Additionally, since the fixed spark timing could eliminate control of engine speed at idle conditions, a second throttle controller was used to enable good engine speed control. Revision-3 of the ECM set the spark timing at 10 degrees BTDC.

Lubrizol Dual Throttle With modern engines such as the LY7 engine used in the VID test, more and more advanced controls are added each year in an effort to make them more powerful, have better emissions, and return better fuel economy. The irony is that those very controls are its Achilles heel in transforming it into a precision system for measuring fuel efficiency. In the testing world, simpler is better since fewer variables are left to chance. Sophisticated technologies such as variable valve timing, active intake manifold tuning, and drive by wire throttle systems can affect engine operation in obvious ways, but also in ways that are not readily evident. Early on with the VID program, the variable valvetrain and intake manifold system were addressed by effectively disabling them, but the limitations of the DBW (drive by wire) throttle were not fully appreciated until the review of results from Matrix IV. Idle control, in particular, was unacceptable.

The rationale for DBW is that for the OEM it simplifies the engine system by removing the need to have separate cruise control, traction control, and idle speed control systems. All these can be done collectively by electronically controlling the throttle angle via the engine's ECM. A sensor at the foot pedal sends a signal to the ECM which then decides how far to open or close the throttle based on various other sensor inputs. A sensor at the throttle plate sends a signal back to the ECM to validate that the correct position has been achieved and adjustments are made as necessary (closed-loop feedback control). The resolution of this control is fairly small and unperceivable to the passenger car operator. However, during very finely controlled steady state operation such as on a Sequence VID test, this degree of control can correspond to an rpm variation of more than ±30rpm, which is substantially higher than previous generations of the test. Further, this lack of precise control manifests itself in variations in fuel flow and torque – both key parameters when calculating fuel efficiency.

To overcome the limitations of the original equipment (OE) throttle system, it was necessary to replace the "digital" DBW system with a more familiar cable-actuated "analog" system. This would allow the test stand to precisely control throttle position with very high resolution. The challenge was to satisfy the engine ECM's requirement for sensor feedback – if the ECM detected (electronically) the absence of either the throttle actuator motor or the throttle position sensor, it would surely revert to a failure mode and limit proper engine operation. The solution was to remove the OE throttle from the engine, but leave its connectors plugged in, and install a second throttle body with a provision for cable actuation. The latter unit would do all the "real" work of controlling airflow to the engine, while the "dummy" throttle body would simply respond to the ECM's commands for throttle position and provide the correct position feedback signal to satisfy failure detection. So that both throttles acted in concert, the control signal was split to both the real and dummy throttles.

By implementing this "Lubrizol Dual Throttle" or DT system, the degree of control at part throttle conditions was significantly improved and was on par with previous generation tests. The amount of variation in rpm, fuel flow, and torque was decreased by nearly a factor of two, with no check engine light (engine fault). The issue became how to deal with idle speed control; that is, closed throttle speed regulation.

Traditionally, this is done with the throttle tightly closed. An air passage bypasses the throttle plate and a valve in between controls the air flow, and thus the engine rpm. With DBW, the throttle is adjusted to a coarse position that is nearly closed, and then the fine speed adjustment is done by varying spark timing. Engine speed will be highest for a given throttle angle when spark timing is at its optimum setting since combustion efficiency is maximized and most of the fuel energy is going into pushing on the piston, and not out the exhaust port. Therefore, for idle speed control, spark timing is retarded to a setting somewhat less than optimum, and if engine speed needs a slight increase, spark timing is increased (nearer to optimum), and vice versa. The result is that even at fixed throttle conditions, spark timing continuously varies between about 6 and 20º. Although the Sequence VID test as it was currently configured at the time averages stage data for 30 minutes, the average spark timing for a given stage may end up anywhere between 8 and 13 degrees. This is quite significant since a difference of even 1 degree results in a fuel use change of 1.3% (determined experimentally). This realization drove the requirement to fix spark timing at the idle stages (<750rpm) to a value of 10º BTDC. This was accomplished by reflashing the ECM. A schematic of the Dual Throttle is shown in Figure 109, and a photograph of the prototype Dual Throttle mechanism is shown in Figure 110.

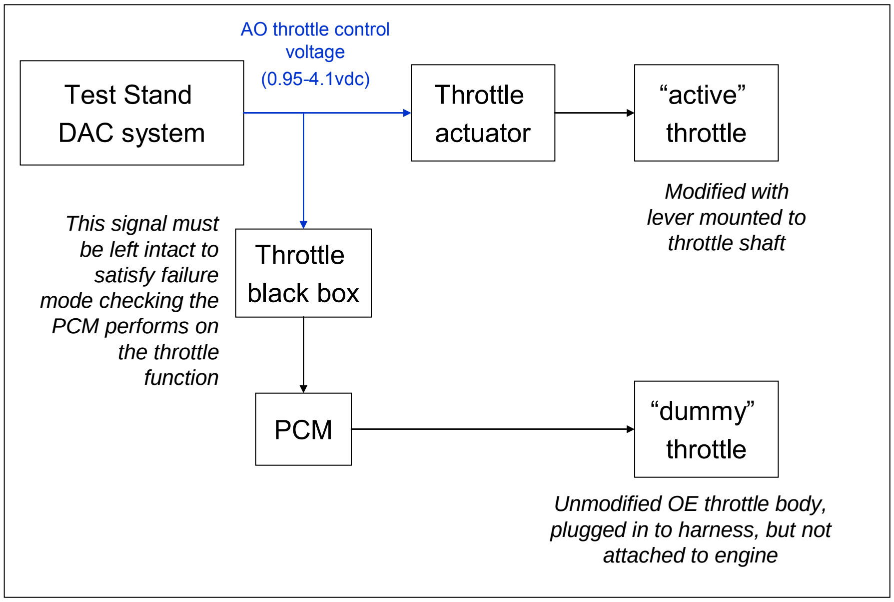


Figure 109. Dual Throttle Operation Schematic

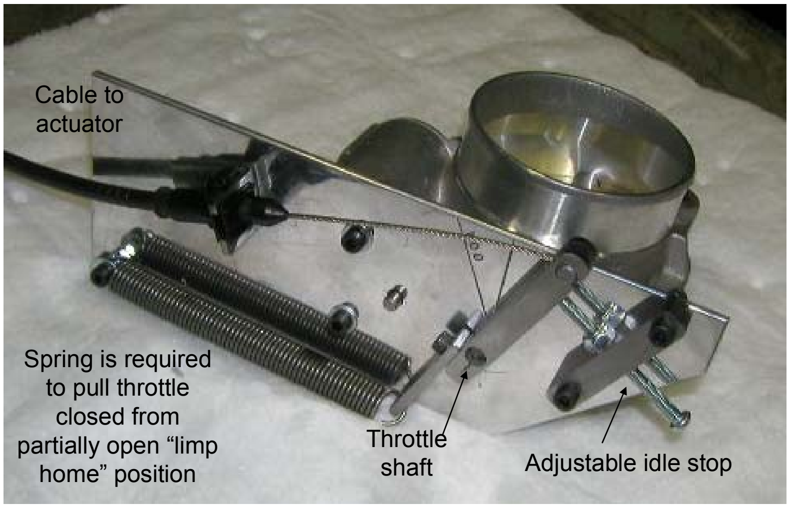


Figure 110. Prototype Dual Throttle Mechanism

In order to improve the variability of the test, a plan to run Matrix IV follow-up experiments was agreed upon. The main objective of these follow-up experiments (referred to as

Matrix IV-A) was to evaluate whether the ECM revision 3 and this Dual Throttle design and/or running of multiple baselines will improve variability. These follow-up experiments were divided into 3 steps as outlined below:

Step 1. Run double baseline with all 6 stages (3,4,5,7,8,9) using ECM-3 Dual Throttle 4X
BL BL Flush BL BL Flush BL BL Flush BL BL

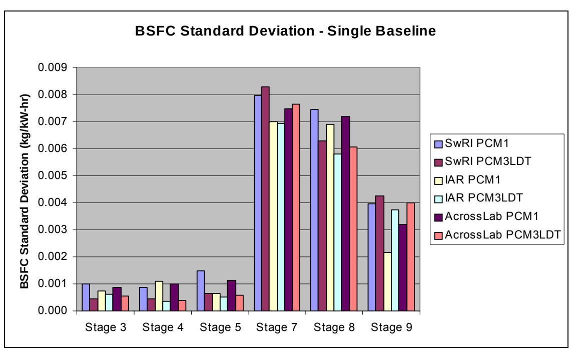
Step 2. Run Oil B using ECM-3 Dual Throttle (Determine to run double BL from Step1)
BL BL, Flush, Oil B (16 hours FEI 1), BL BL, Flush, Oil B (16 hours FEI 1), BL BL

Step 3. Smaller version of Matrix IV

Step 1 Analysis The BSFC variability from Matrix IV (with ECM-1) was compared with the BSFC variability in Step 1. The BSFC standard deviation using a single baseline only was included for comparison, and the results are compared below in Figure 111.

PCM1 Versus PCM3 with Dual Throttle

- Compares variation of single BLs for both PCM1 (Matrix IV) and PCM3 with Dual Throttle.
- Dual throttle appears to improve BSFC precision in high speed stages but does not do so consistently for idle stages.



% Improvement of PCM3 with Dual Throttle Versus PCM1 (Matrix IV)

	Stage 3	Stage 4	Stage 5	Stage 7	Stage 8	Stage 9
SwRI	54	50	57	-4	16	-7
IAR	18	68	20	1	16	-73
Across Lab	39	60	49	-2	16	-25

Figure 111. Comparing ECM-1 to ECM-3 with Dual Throttle

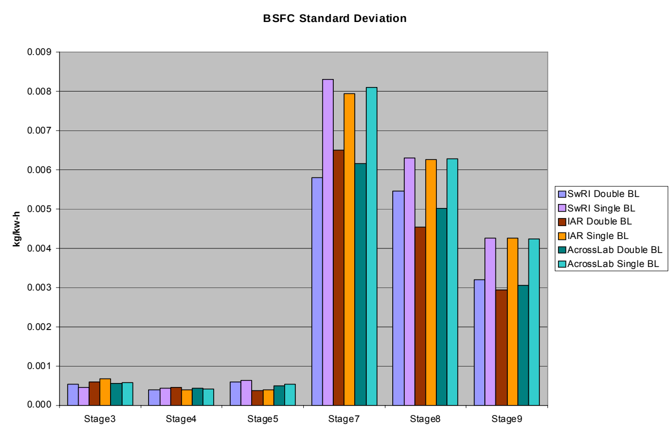
ECM-3 dual throttle appears to improve BSFC precision in high speed stages but does not do so consistently for idle stages.

The chart below, Figure 112, compares the BSFC standard deviation using single and double baselines from Step 1. The greatest improvement in BSFC precision was seen in idle stages using double baselines.

The chart below, Figure 113, shows the combined improvement using both ECM-3-DT and double baselines (Step 1) compared to ECM-1 and a single baseline (Matrix IV). The greatest improvement in precision was seen in stages 3, 4 & 5. Among idle stages stage 8 had the greatest improvement followed by stage 7. Stage 9 is the least improved stage with worse standard deviation using ECM-3-DT than ECM-1 at IAR.

BSFC Standard Deviation: Double BL vs Single BL

- Double BL – all 8 runs
- Single BL – runs 1,3,5,7 only
- Greatest improvement seen in idle stages with double BL.

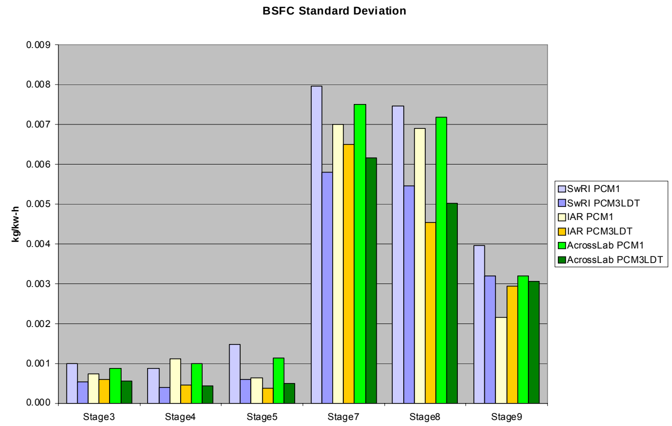


% Improvement	Stage3	Stage4	Stage5	Stage7	Stage8	Stage9
SwRI	-19	8	5	30	13	25
IAR	14	-19	6	18	27	31
AcrossLab	3	-5	5	24	20	28

Figure 112. Comparing Double Baseline and Single Baseline Results

BSFC Standard Deviation: PCM1 vs PCM3-DT

- Greatest improvement seen in stages 3, 4 & 5 with PCM3-LDT.
- Among the idle stages, stage 8 has greater improvement followed by stage 7.
- Stage 9 is the least improved stage with worse standard deviation using PCM3-LDT than with PCM1 at IAR.



% Improvement	Stage3	Stage4	Stage5	Stage7	Stage8	Stage9
SwRI	46	54	59	27	27	20
IAR	21	58	41	7	34	-37
AcrossLab	36	56	56	18	30	4

Figure 113. BSFC Standard Deviation- ECM-1 vs. ECM-3 and DT

Based on these results, it was the consensus of the Statistical Group to go into Step 2 using the Double BL measurements. The test schedule for Step 2 is shown in Table 41.

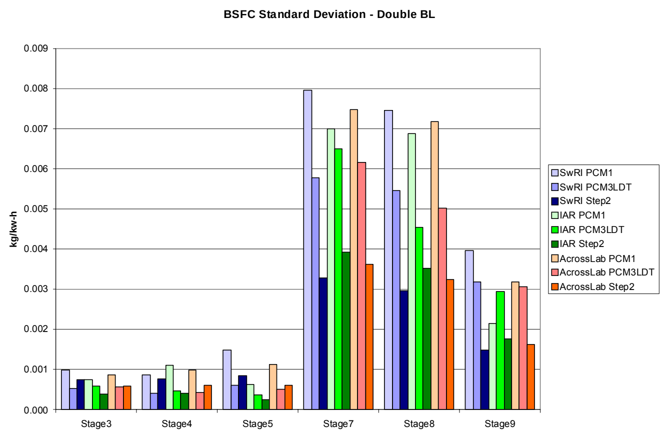
Table 41. Matrix IV-A Step 2 Test Schedule

Task	Time, h
Load Cal	1.0
Warm-up	0.5
Flush to BL	1.5
Run 6 Stages	9.0
Repeat 6 Stages	9.0
Flush to Oil B	1.5
16 hrs Aging	16.0
Run 6 Stages	9.0
Flush FO	2.0
Shutdown and restart at next step	
Flush to BL	1.5
Run 6 Stages	9.0
Repeat 6 Stages	9.0
Flush to Oil B	1.5
16 hrs Aging	16.0
Run 6 Stages	9.0
Flush FO	2.0
Flush to BL	1.5
Run 6 Stages	9.0
Repeat 6 Stages	9.0
	117.0

Step 2 Analysis BSFC standard deviation from Step 2 was compared with that of Matrix IV. Figure 114 below shows the comparison between ECM-1 and Step 2 ECM-3-DT and double baselines. The greatest improvement in precision was seen in stages 7, 8 & 9 across laboratories. Step 2 had lower BSFC standard deviation compared to Step 1 (labeled ECM-3-DT in the figure) for idle stages.

The greatest improvement was seen in stages 3, 4 & 5 when comparing ECM-3-DT and single baseline with ECM-1 as shown in Figure 115. Again Step 2 had lower BSFC standard deviation than Step 1.

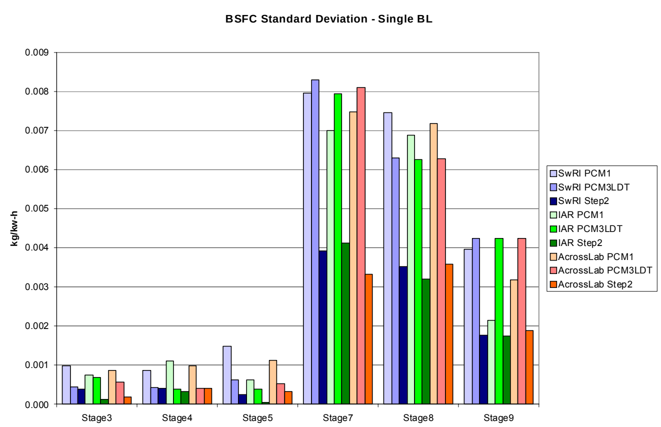
- Greatest improvement seen in stages 7, 8 & 9 with PCM3-LDT-Double BL across labs.
- Step 2 has lower standard deviation than Step 1 for idle stages.



% Improvement	Stage3	Stage4	Stage5	Stage7	Stage8	Stage9
SwRI	25	11	43	59	60	63
IAR	46	64	60	44	49	18
AcrossLab	32	38	46	52	55	49

Figure 114. BSFC Standard Deviation: ECM-1 vs. Step 2 ECM-3-DT and Double BL

- Greatest improvement seen in stages 3, 4 & 5 with PCM3-LDT-Single BL across labs.
- Step 2 has lower standard deviation than Step 1 for idle stages.

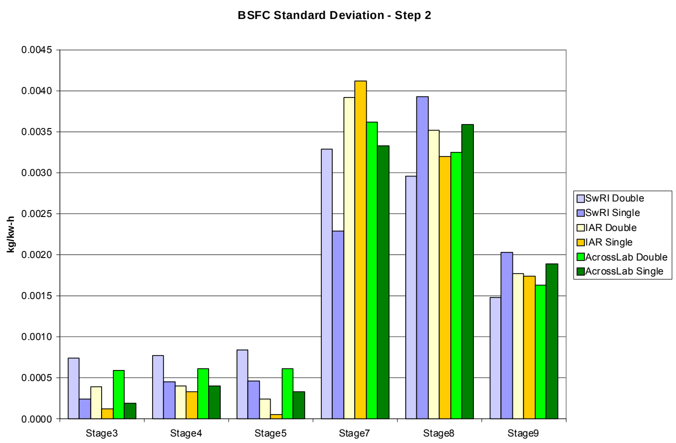


% Improvement	Stage3	Stage4	Stage5	Stage7	Stage8	Stage9
SwRI	75	47	68	71	47	49
IAR	83	70	92	41	53	19
AcrossLab	77	60	71	55	50	41

Figure 115. BSFC Standard Deviation: ECM-1 vs. Step 2 ECM-3-DT and Single BL

In comparing double baselines with a single baseline, double baselines generally showed larger BSFC standard deviation than with a single baseline as indicated in Figure 116.

- Double BL – all 6 runs
- Single BL – runs 1,3,5 only
- Generally lower standard deviation with single BL than double BL.
- 2nd BL generally lower than 1st BL



% Improvement	Stage3	Stage4	Stage5	Stage7	Stage8	Stage9
SwRI	-199	-70	-80	-44	25	27
IAR	-218	-19	-366	5	-10	-2
AcrossLab	-203	-54	-86	-9	9	14

Figure 116. BSFC Standard Deviation: Step 2 Double BL vs. Single BL

It was also noted that the 2nd baseline is consistently lower than the 1st in stages 3, 4, 5 & 7 as shown in Figure 117.

The Oil B fuel economy improvement data based on double baselines and a single baseline in Step 2 was compared with that of Matrix IV as shown in Figure 118. It was noted that the %FEI1 of Oil B is lower with the use of ECM-3-DT and single or double baselines in stages 8 and 9 in both laboratories.

Based on this analysis, it was concluded that ECM-3-DT reduces BSFC variability while there's not enough evidence to justify the use of double baselines to reduce variability.

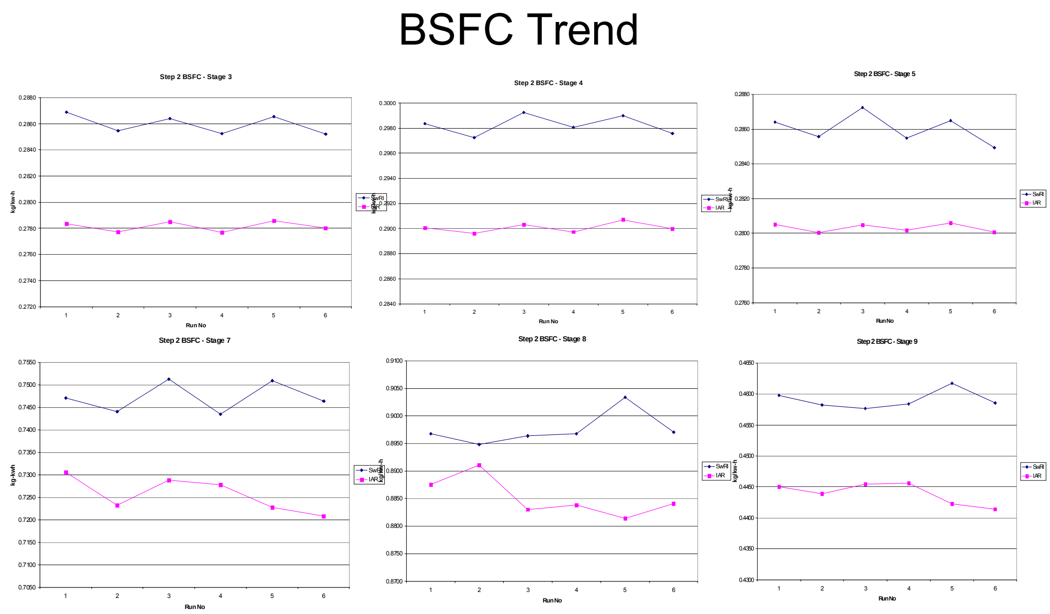


Figure 117. BSFC Trends

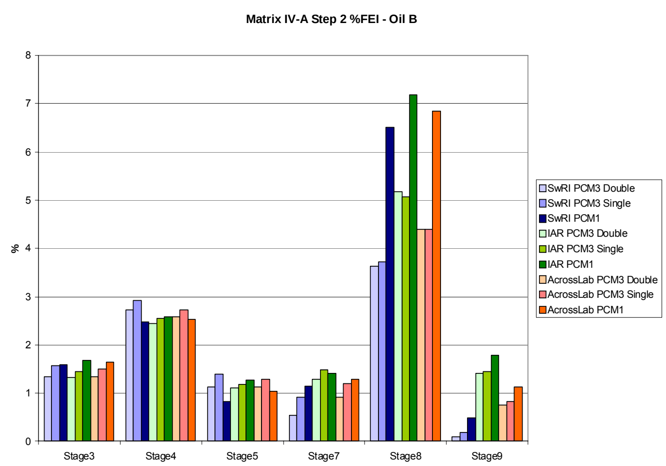


Figure 118. %FEI – Oil B: ECM-1 vs. ECM-3-DT

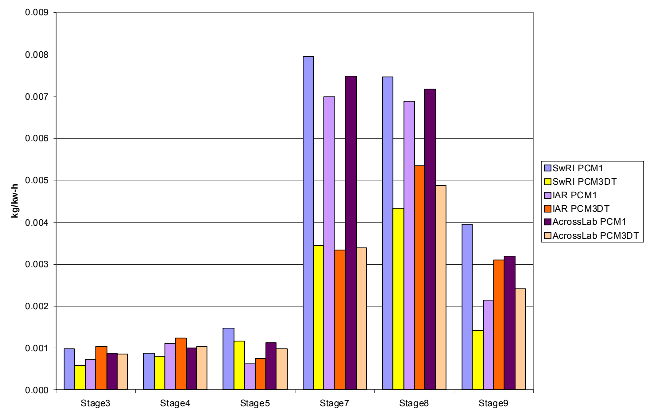
Step 3 Analysis The objective of Matrix IV-A Step 3 was to confirm the findings in Matrix IV with the use of ECM-3-DT. The 6-test matrix aimed to see the effect of changing to ECM-3-DT, to determine oil and lab effects, and to see if there's improvement in the precision of the test. The Step 3 design is shown in Table 42.

Table 42. Matrix IV-A Step 3 Design

Matrix	RunOrder	IAR	RunOrder	SwRI
IV	1	I: 2 5w30 Moly	1	A: 1 5w20
	2	G: 2 5w30	2	B: 1 5w20 OFM
	3	E: 1 10w30	3	E: 1 10w30
	4	B: 1 5w20 OFM	4	G: 2 5w30
	5 Invalid	A: 1 5w20	5	I: 2 5w30 Moly
	5a Invalid	A: 1 5w20	6	A: 1 5w20
	5b	A: 1 5w20		
	6	I: 2 5w30 Moly		
IV-A	1	A: 1 5w20	1	I: 2 5w30 Moly
	2	B: 1 5w20 OFM	2	G: 2 5w30
	3	E: 1 10w30	3	A: 1 5w20

Data in Matrix IV (12 tests) and data in Matrix IV-A Step 3 (6 tests) were combined and analyzed for effects of oil, lab and ECM-dual throttle, where Matrix IV had ECM-1 and Step 3 had ECM-3-DT. The greatest improvement in BSFC standard deviation was seen in stages 7, 8 & 9 with the use of ECM-3-DT as shown in Figure 119. It is evident that only stages 7 and 8 showed improvement at IAR using ECM-3-DT. Figures 120 and 121 indicate that there is significantly lower %FEI with ECM-3-DT than ECM-1 in stage 8 both at FEI-1 and FEI-2.

- Greatest improvement seen in stages 7, 8 & 9 with PCM3-DT across labs.
- Only stages 7 and 8 improved with PCM3-DT at IAR.



% Improvement	Stage3	Stage4	Stage5	Stage7	Stage8	Stage9
SwRI	40	7	21	57	42	64
IAR	-41	-12	-21	52	22	-44
AcrossLab	3	-5	13	55	32	24

Figure 119. BSFC Standard Deviation: ECM-1 vs. Step 3 ECM-3-Dual Throttle

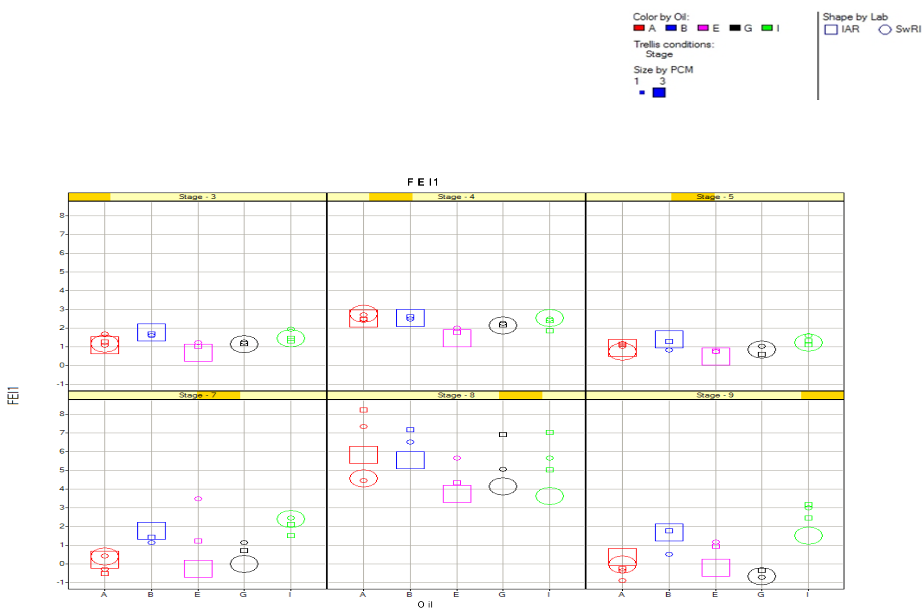


Figure 120. Fuel Economy Improvement FEI-1: ECM-1 vs. ECM-3-Dual Throttle

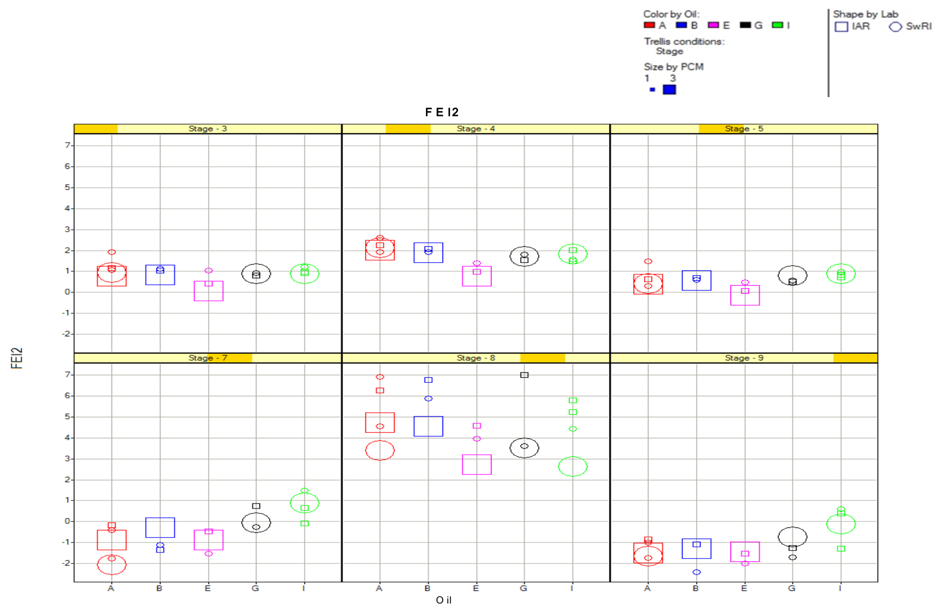


Figure 121. Fuel Economy Improvement FEI-2: ECM-1 vs. ECM-3-Dual Throttle

Figure 122 shows the %FEI Least Square (LS) Means by oil and phase for each of the 6 stages. Based on the statistical analysis,

- FEI 1 O-FM (B > A) response is statistically significant in stages 3, 7 and 9, directionally correct for all stages *except stage 8 where a friction modifier response would be unexpected*
- FEI 1 Moly (I > G) response is statistically significant in stages 5, 7 & 9, directionally correct for all stages *except stage 8 where a friction modifier response would be unexpected*
- FEI 1 Viscosity Grade (A > E) response is statistically significant in stages 4, 7 & 8, all stages favor lower viscosity *except stages 7 & 9 where a favorable viscosity response may not be expected*
- No significant FEI 2 O-FM and Moly responses
- Significant FEI 2 Viscosity Grade response in stages 3, 4 & 8

It was also noted that there is a significant lab difference in Phase 1 stages 4 & 8 and Phase 2 stages 3 and 8, as shown in Figure 123.

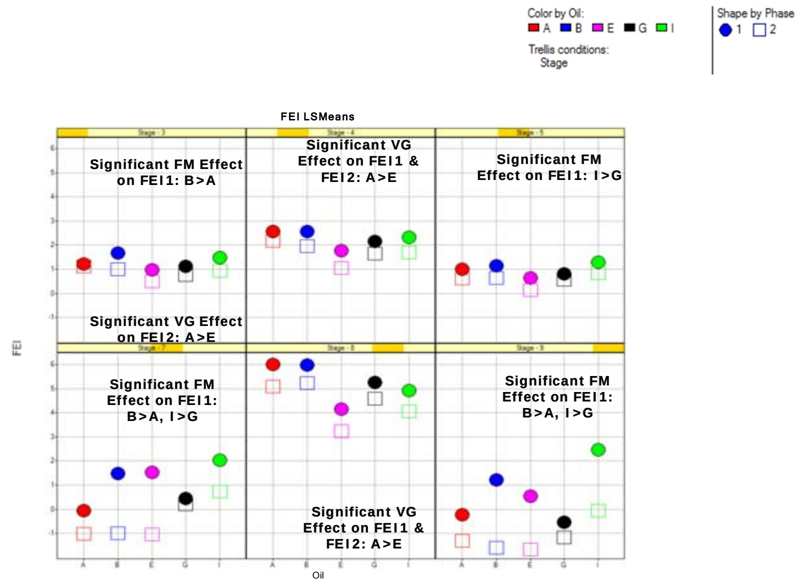


Figure 122. Percent Fuel Economy Improvement Least Squares Means by Oil

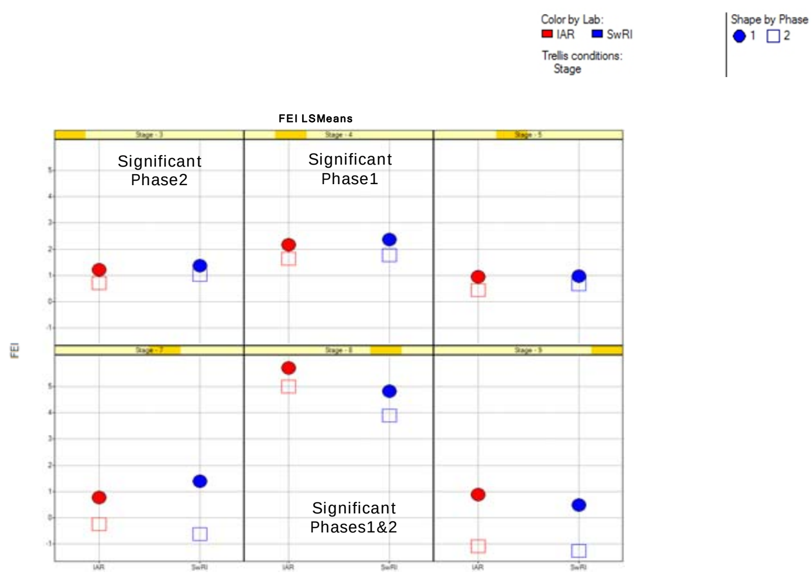


Figure 123. Percent Fuel Economy Improvement Least Squares Means by Lab

Based on this analysis, it was concluded that ECM-3-Dual throttle improved BSCF variability, and the Statistical Group endorsed moving forward with this configuration. Table 43 was also presented to aid in selection of stages to move forward with for the Prove-out Matrix. With much discussion, the members of the Consortium agreed to retain the 6 stages as the final stages for the Prove-out Matrix.

Table 43. Matrix IV & IV-A Synopsis

Matrix IV & IV-A Synopsis - FEI1

Condition	3	4	5	7	8	9
Load (Nm)	105	105	105	20	20	40
Speed (rpm)	2000	2000	1500	695	695	695
Oil Temperature (degC)	115	65	115	115	35	115
Decision Parameter						
Lab Effect		S			S	
Match to FTP Optg Cond., %	**26**	8	12	**23**	3	5
Vis Grade Effect	A>E	**S A>E**	A>E	**S E>A**	**S A>E**	E>A
OFM1	**S DC**	DC	DC	**S DC**	DI	**S DC**
Moly2	DC	DC	**S DC**	**S DC**	DI	**S DC**
FEI RMSE (%)	0.20	0.19	0.22	0.81	0.98	0.60
FEI CV (%)	15	8	23	75	19	86
Boundary/Hydrodynamic (ZN/P)	243	1043	178	136	2304	112
Stage FEI1 - GM FTP FEI 2k, r	**0.89**	0.46	0.67	0.54	0.36	0.58
Stage FEI1 - GM FFE FEI 2k, r	0.28	0.28	0.44	0.29	0.04	0.56
Stage FEI1 - GM Comb FEI 2k, r	**0.96**	0.56	**0.82**	0.62	0.37	0.77

Matrix IV & IV-A Synopsis - FEI2

Condition	3	4	5	7	8	9
Load (Nm)	105	105	105	20	20	40
Speed (rpm)	2000	2000	1500	695	695	695
Oil Temperature (degC)	115	65	115	115	35	115
Decision Parameter						
Lab Effect	S				S	
Match to FTP Optg Cond., %	**26**	8	12	**23**	3	5
Vis Grade Effect	**S A>E**	**S A>E**	A>E	A>E	**S A>E**	A>E
OFM1	DI	DI	DC	DC	DC	DI
Moly2	DC	DC	DC	DC	DI	DC
FEI RMSE (%)	0.23	0.24	0.30	0.69	0.77	0.62
Boundary/Hydrodynamic (ZN/P)	243	1043	178	136	2304	112
Stage FEI2 - GM FTP FEI 6.5k, r	-0.64	-0.53	-0.76	-0.26	-0.44	-0.48
Stage FEI2 - GM FFE FEI 6.5k, r	**-0.83**	**-0.90**	-0.76	-0.20	**-0.91**	-0.18
Stage FEI2 - GM Comb FEI 6.5k, r	**-0.91**	**-0.89**	**-0.92**	-0.26	**-0.83**	-0.39

9.7 Matrix V – Prove Out The purpose of the Prove-Out Matrix was to demonstrate that the test run under final conditions (number of stages, aging, engine test hardware and protocols) is capable of discriminating fuel economy performance between oils differing in viscometric properties or friction modifying capabilities.

Oil Selection An objective of the Sequence VID development was to design a test which is capable of detecting viscosity grade and friction modifier effects on fuel economy. Therefore, oils were selected to test these capabilities - in particular, Oils A, B and E were selected as the test oils. The FEIs of Oils B and A can be compared to determine the FM effect, and those of Oils A and E can be compared to determine the viscosity grade effect. Having all oils from one supplier allows for a minimum number of tests to be performed given a number of repeats as each of the oils have the same DI package and, therefore, can use the same “control” oil.

Prove Out Matrix Test Protocol Figure 124 shows schematically, the testing protocol used for the Prove Out Matrix.

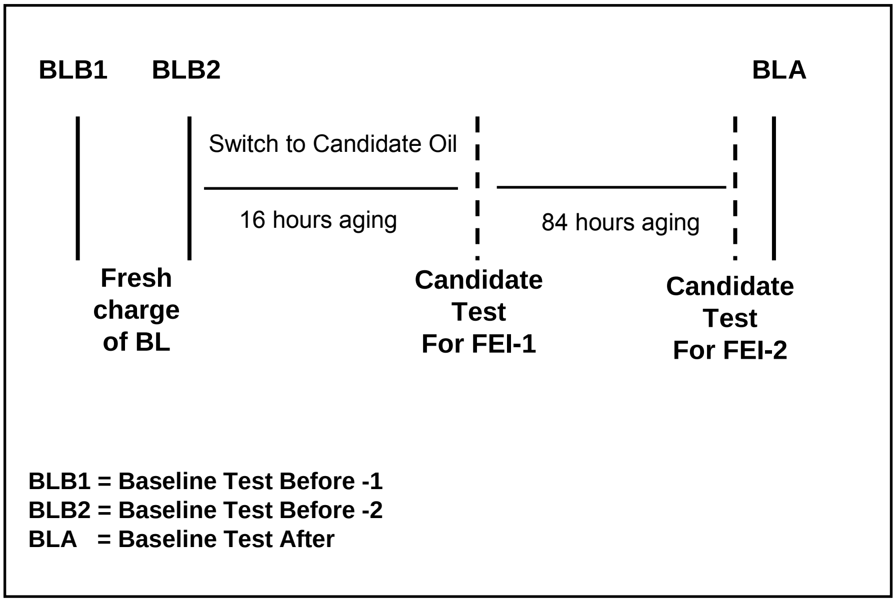


Figure 124. Prove Out Matrix Test Protocol

Test Matrix Design The test matrix design is composed of 16 tests performed in two labs (8 tests per lab). The “control” oil (Oil A) is tested 6 times and Oils B and E are each tested 5 times. Table 45 provides the matrix design.

Table 44. Test Matrix Design

Run Order	IAR	SwRI
1	A	E
2	B	B
3	E	A
4	E	A
5	B	B
6	A	E
7	A	E
8	B	A

The matrix was completed with two invalid runs from SWRI. Test #4 on Oil A was invalid because of load shift caused by a dyno bearing flat spot. This test was re-run and completed as a valid run. Test #5 on Oil B was aborted at 49 hours due to dyno overheat. A re-run was aborted during stage 5 of BLB1 due to an optical encoder failure. A second re-run was completed as a valid run. It was found that there was an oil pump issue in the SWRI engine and a repeat of Test #8 at SWRI was done with a new oil pump installed. IAR ran an additional test on Oil B making the total number of tests for the Prove-out matrix equal to 18 tests. Table 45 shows the final Matrix V design.

Table 45. Final Design of Matrix V

Run Order	IAR	SWRI
1	A	E
2	B	B
3	E	A
4	E	A
5	B	B
6	A	E
7	A	E
8	B	A
9	B*	A**
*Extra Test ** Extra Test with New Oil Pump Installed		

The Statistical Group (SG) analyzed the Prove-out matrix data with the objective of determining discrimination and at the same time recommending the final baseline and stage weighting to be used in the VID procedure. Several analyses were presented and the SG came up with the following agreements:

- Significant fuel consumption (FC) and fuel economy improvements (FEI) differences and baseline (BL) variability exist between SwRI and IAR

- No friction modifier (FM) carry-over was identified. However, consecutive BL FC differences appear to be oil dependent

- All three BL runs are required
    - For minimum RMSE and maximum discrimination

- Baseline Weight
    - FEI1: 0-20 BLB1, **80 BLB2** & 0-20 BLA

    - FEI2: **0 BLB1**, 10-50 BLB2 & 50-90 BLA

- Discrimination
    - Practical stage weights exist that discriminate FM and viscosity (VG) for FEI1
    - The same stage weights discriminate for VG for FEI2, FM is directionally correct
- Guidelines for oil pressure, MAP, and/or baseline fuel consumption should be established for test validity (BLB1, BLB2), and interpretability (BLB2, BLA) before the precision matrix.
    - BLB1-BLB2 FC shift: -0.20% to 0.40%
    - If outside range, run BLB3 and compare with BLB2

- Statistics Group could not completely agree on BL weights or stage weights.

Figure 125 shows the total fuel consumed for the 9 tests conducted in each lab in the order of Baseline Before 1 (BLB1), Baseline Before 2 (BLB2) and Baseline After (BLA) for each test. The candidate oils run in each test are also indicated in this plot. The plot shows that there is a significant difference in the fuel consumed between labs and that the variability is also different. The larger fuel consumed variability in the SWRI engine as compared to the IAR engine is also evident at each stage as shown in Figures 126 and 127.

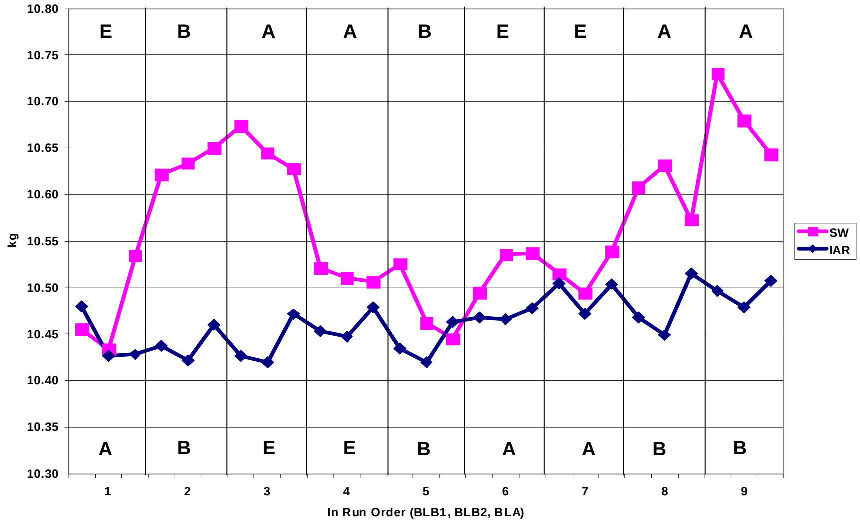


Figure 125. Fuel Consumption of Baseline Portions of Matrix V Testing

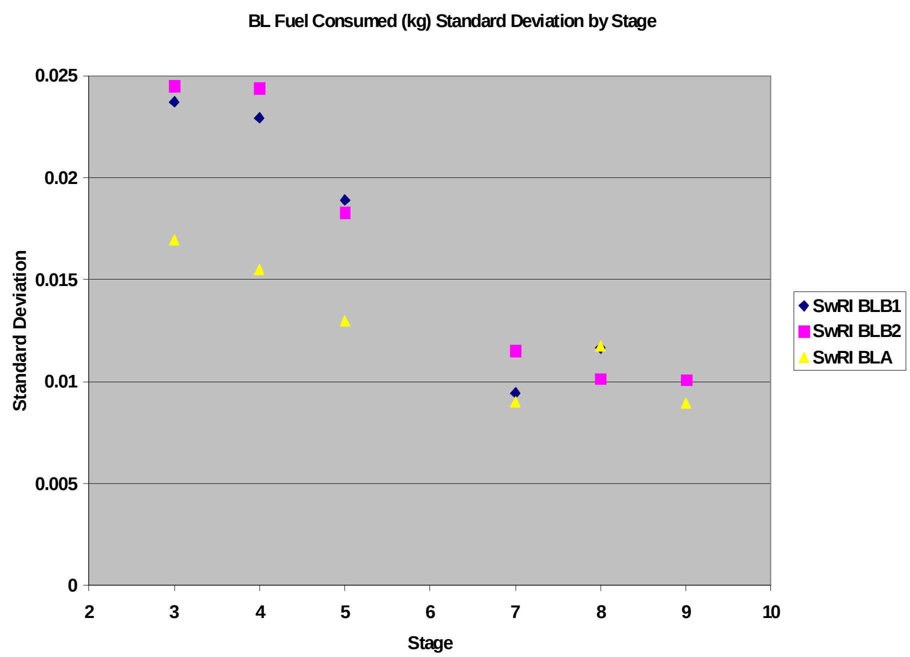


Figure 126. Baseline Fuel Consumption at SwRI – Standard Deviation by Stage

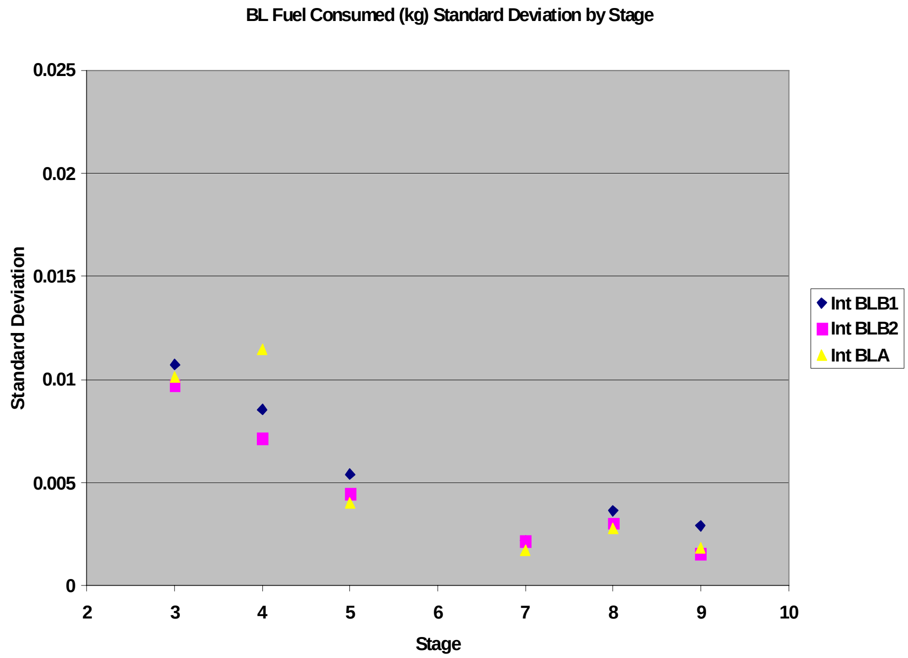


Figure 127 Baseline Fuel Consumption at IAR – Standard Deviation by Stage

In analyzing baseline shifts, the SG concluded that there was no friction modifier carry-over effect. However, consecutive baseline differences appeared to be oil dependent. Based on Figure 128, below, the shift from BLB2 to BLA is significantly larger when running Oil E than Oil A. This BL shift difference is true for stages 3, 4 and 5 as seen in Figure 129.

The SG recommended that guidelines on oil pressure, MAP and/or baseline fuel consumed should be established for test validity using BLB1 and BLB2 and for test interpretability using BLB2 and BLA before the precision matrix is conducted. The SG recommended that the limit for the BLB1-BLB2 shift should be within -0.20% to 0.40% based on the chart shown in Figure 130. If the shift falls outside this range, another baseline should be run and compared to BLB2. Procedural details were deferred to the Sequence VI Surveillance Panel.

Aside from the fuel consumed differences between labs, it was also noted that there are differences in the FEIs between the labs. Using the time weighted baseline weighting (FEI1: 80% BLB2 and 20% BLA, FEI2: 10%BLB2 and 90% BLA) and no stage weighting applied, the following charts, Figures 131 and 132, show the FEI differences between the labs.

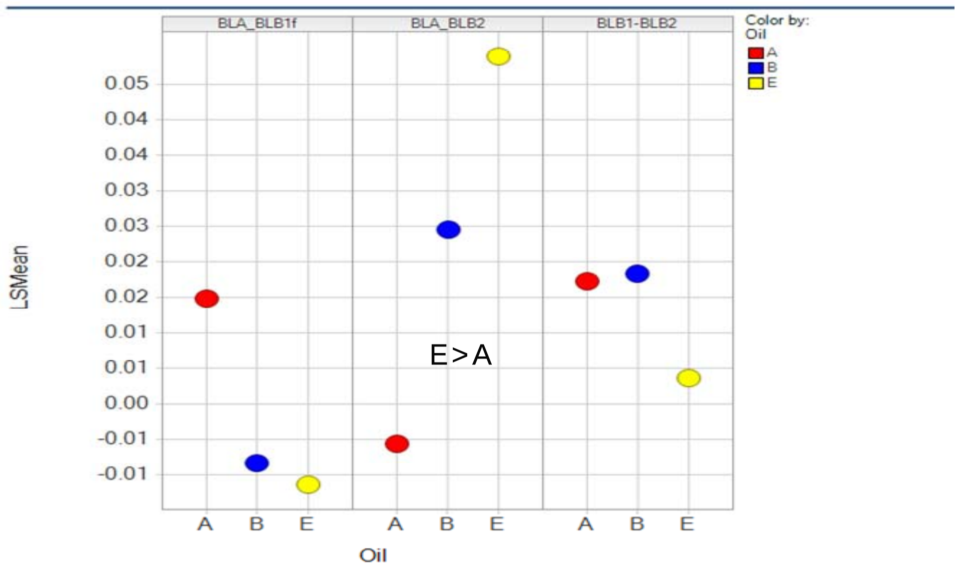


Figure 128. Baseline Differences Across Labs

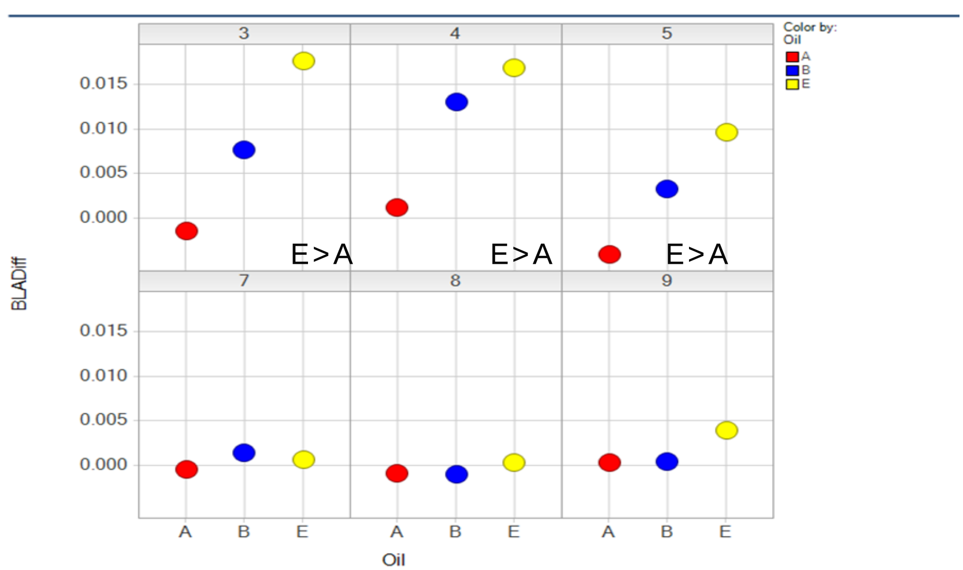


Figure 129. Baseline Differences by Stage

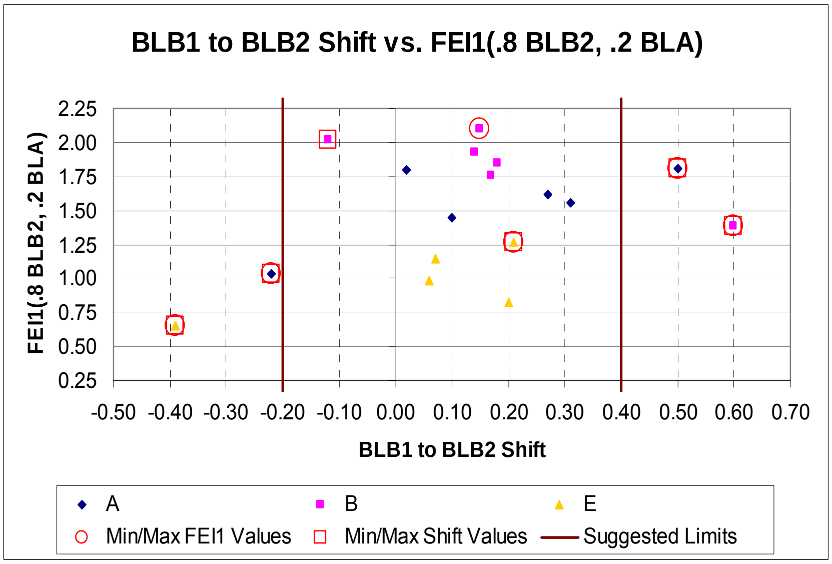


Figure 130. Baseline Shift Criteria for BLB1 vs. BLB2

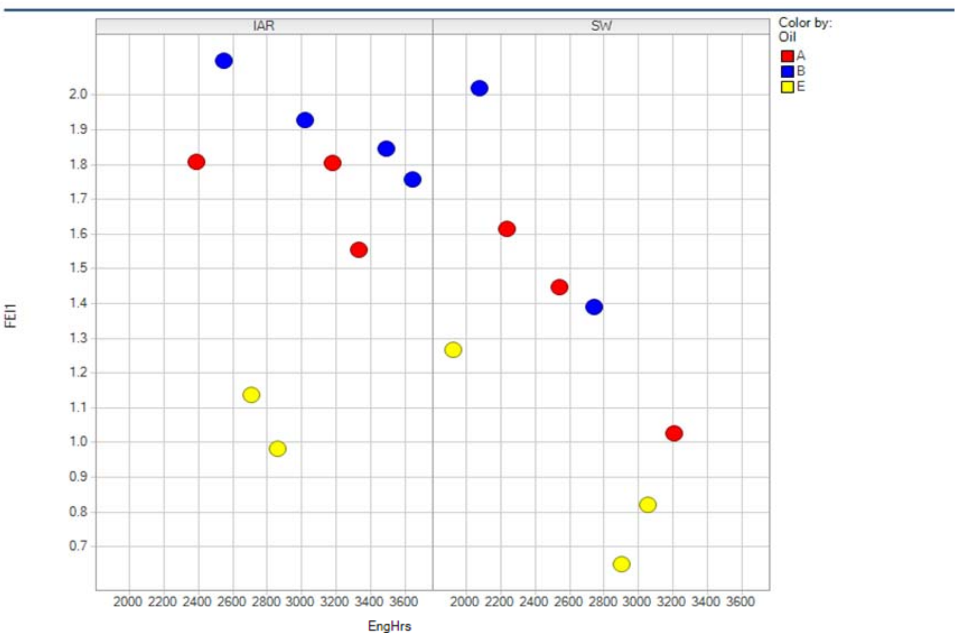


Figure 131. FEI1 (80BLB2, 20BLA) by Engine Hours

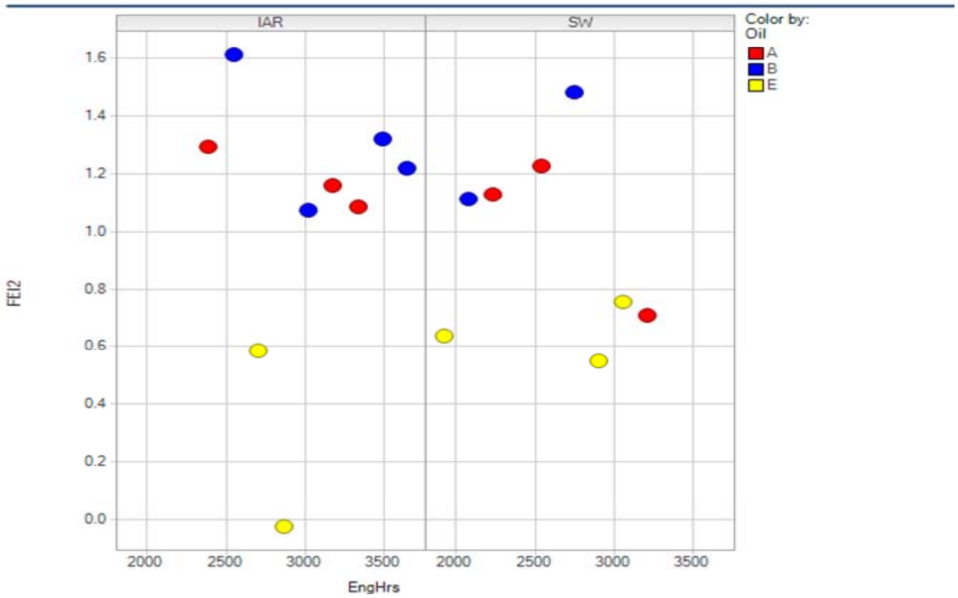


Figure 132. FEI2 (10BLB2, 90BLA) by Engine Hours

Given the result on BL shift differences and by calculating different scenarios of the Baseline weighting, the SG concluded that the three baseline runs are required in the VID procedure in order to minimize variability and maximize discrimination. The SG agreed that for calculating FEI1, 80% of BLB2 should be used and 20% should be applied to either BLB1 or BLA. For the FEI2 calculation, it was agreed that BLB1 will not be used and that 10%-50% will be applied to BLB2 and 50%-90% to BLA. Based on the different scenarios of stage weighting presented, the SG agreed that practical stage weightings exist that discriminate FM and VG for FEI1 and VG for FEI2, and which are directionally correct for FM at phase 2. No consensus stage weighting recommendation was reached within the SG.

Baseline and Stage Weighting Decisions The decisions made by the Consortium relative to Baseline and Stage weighting were based upon the desire to meet the three primary objectives of the Consortium. The three objectives which have been previously discussed elsewhere in the report were to develop a test that:

1) Would be responsive to both viscometric and friction modifier effects in oils,
2) Should show improved test precision over the current Sequence VIB fuel economy test, and

3) Would be based on the operating conditions mapped proportionally to the FTP-75 and Highway Fuel Economy tests, and which generally agrees with the FTP fuel economy data generated by the Consortium.

Several proposals for Baseline weightings and Stage weightings were provided by the Statistics Group. These proposals differed by placing more or less priority on the three individual objectives of the Consortium. The decisions ultimately made on the Baseline and Stage weightings were based upon meeting objective 3, above, but these weightings also allowed the Consortium to meet the other two objectives.

The following section describes the methodology of determining the correlation of the final six stages to the conditions mapped during FTP and Highway testing.

Method of Stage Weighting Correlating to FTP Operating Conditions The purpose of this method is to estimate stage weights that correlate with their frequency of occurrence during the FTP cycles. The FTP ECM output for a Buick LaCrosse test was utilized for this task. The output includes a set of parameters defining the immediate operating condition collected every 0.1 seconds. This data included the engine speed (RPM), corrected MAP (kPa), and engine oil temperature (°C). Depending on the cycle, there were between 5000 and 8700 sets of operating conditions collected for each phase (Cold Start, Stabilization, Hot Start and Highway). For each operating condition, the normalized Euclidean distance from each of the stages was collected. The expression for the normalized Euclidean distance follows:

$$\text{Distance} = \sqrt{\left(\frac{\text{Stage Speed - FTP Speed}}{\text{FTP Speed Range}}\right)^2 + \left(\frac{\text{Stage MAP - FTP MAP}}{\text{FTP MAP Range}}\right)^2 + \left(\frac{\text{Stage Temp - FTP Temp}}{\text{FTP Temp Range}}\right)^2}$$

For each parameter, the value observed in the FTP is subtracted from the stage condition. That difference is normalized by dividing by the range of that condition observed in the entire FTP. This normalization results in a dimensionless quantity. Because the stage conditions are within the FTP range, the value for each quotient ranges from 0 to 1. Therefore, the distance is bounded by 0 and 1.71 (square root of 3).

The next step is to determine the percentage of data within a specified limit. The percentages for each phase are combined by taking a weighted average of the stages with the weights corresponding to those discussed in the “Test Schedule and Fuel Economy Calculations” section of 7.1.

The last step is to select a limit for the distance. Table 46 lists, for each phase, the percentages of data that are within a given distance of each stage. Note that within a distance of 0.1, a very small proportion of the data is utilized indicating the specified limit should be larger than 0.1. As expected the proportion of data captured increases as the distance increases. The percentage of data within a distance of at least one stage for each phase and overall is listed in Table 47. The table indicates that at distances of 0.3 and 0.4, 78 and 95% of the data is included, respectively. Table 48 lists the corresponding normalized weights for the six remaining stages corresponding to each distance. Note that in the range of distances from 0.3 to 0.4, the majority of the data is utilized. Also, note that the resulting stage weights differ very little indicating a degree of robustness in this range. A distance of 0.35 was selected and is highlighted in yellow in Tables 46-48

Table 46. Percentage of FTP Conditions within a Distance of Each Stage

P1 - Cold Start

Distance	Stage 1	Stage 2	**Stage 3**	**Stage 4**	**Stage 5**	Stage 6	**Stage 7**	**Stage 8**	**Stage 9**	Stage 10
0.1	0.0	0.4	**0.0**	**2.5**	**0.0**	1.2	**0.0**	**1.6**	**0.0**	9.1
0.2	0.0	5.7	**0.0**	**11.7**	**0.0**	9.7	**0.0**	**12.6**	**0.0**	13.6
0.3	0.0	12.3	**0.1**	**26.6**	**1.1**	23.5	**2.5**	**15.0**	**1.6**	16.1
0.35	0.2	18.0	**2.8**	**34.5**	**3.6**	36.3	**9.1**	**16.3**	**8.4**	21.5
0.4	4.7	28.8	**6.2**	**40.9**	**8.5**	53.1	**15.7**	**21.6**	**15.1**	25.1
0.5	13.4	48.5	**15.9**	**56.5**	**16.5**	64.3	**27.5**	**36.9**	**26.9**	39.8
0.6	31.4	89.7	**28.3**	**73.3**	**38.3**	86.3	**31.9**	**64.0**	**32.2**	67.7
0.7	51.8	98.1	**51.1**	**99.1**	**58.4**	97.5	**38.4**	**82.0**	**39.6**	87.7

P2 - Stabilization

Distance	Stage 1	Stage 2	**Stage 3**	**Stage 4**	**Stage 5**	Stage 6	**Stage 7**	**Stage 8**	**Stage 9**	Stage 10
0.1	0.0	0.0	**0.0**	**0.0**	**0.0**	0.0	**0.7**	**0.0**	**0.0**	0.0
0.2	2.5	0.0	**4.9**	**0.0**	**6.8**	5.7	**29.2**	**0.0**	**24.0**	0.0
0.3	17.2	0.0	**22.5**	**0.7**	**25.6**	33.9	**55.7**	**0.0**	**52.5**	0.0
0.35	32.2	2.0	**28.7**	**5.7**	**33.4**	47.9	**65.2**	**0.0**	**63.3**	0.0
0.4	45.4	6.9	**34.8**	**13.4**	**40.7**	69.6	**73.2**	**0.0**	**75.7**	0.0
0.5	59.7	40.3	**49.1**	**31.6**	**81.7**	99.9	**85.1**	**0.0**	**89.5**	0.0
0.6	99.6	60.9	**61.5**	**49.8**	**100.0**	100.0	**93.9**	**0.8**	**96.3**	0.8
0.7	100.0	100.0	**100.0**	**74.7**	**100.0**	100.0	**98.5**	**26.0**	**99.5**	24.4

P3 - Hot Start

Distance	Stage 1	Stage 2	**Stage 3**	**Stage 4**	**Stage 5**	Stage 6	**Stage 7**	**Stage 8**	**Stage 9**	Stage 10
0.1	0.3	0.0	**1.7**	**0.0**	**1.0**	0.0	**14.5**	**0.0**	**5.5**	0.0
0.2	9.0	0.0	**17.1**	**0.0**	**20.9**	0.0	**35.4**	**0.0**	**32.3**	0.0
0.3	24.8	0.0	**38.7**	**0.0**	**40.8**	15.3	**47.2**	**0.0**	**47.7**	0.0
0.35	34.2	0.0	**44.6**	**0.0**	**48.4**	34.2	**51.0**	**0.0**	**53.0**	0.0
0.4	45.4	0.1	**50.4**	**0.9**	**54.6**	47.4	**56.6**	**0.0**	**58.6**	0.0
0.5	64.0	19.8	**63.5**	**32.2**	**94.1**	93.7	**72.1**	**0.0**	**75.8**	0.0
0.6	97.6	52.0	**74.1**	**56.1**	**99.7**	97.5	**82.6**	**0.0**	**88.6**	0.0
0.7	99.4	82.9	**99.6**	**67.9**	**99.7**	99.4	**91.5**	**0.8**	**94.4**	1.0

Highway

Distance	Stage 1	Stage 2	**Stage 3**	**Stage 4**	**Stage 5**	Stage 6	**Stage 7**	**Stage 8**	**Stage 9**	Stage 10
0.1	3.6	0.0	**17.2**	**0.0**	**11.4**	0.0	**1.7**	**0.0**	**0.6**	0.0
0.2	27.0	0.0	**55.4**	**0.0**	**50.9**	0.0	**2.7**	**0.0**	**2.1**	0.0
0.3	60.9	0.0	**77.5**	**0.0**	**77.2**	0.0	**4.2**	**0.0**	**4.0**	0.0
0.35	71.5	0.0	**82.4**	**0.0**	**81.8**	21.4	**7.3**	**0.0**	**7.2**	0.0
0.4	80.6	0.0	**87.7**	**0.0**	**85.7**	61.4	**21.3**	**0.0**	**24.6**	0.0
0.5	93.1	4.2	**97.0**	**19.0**	**99.9**	94.9	**49.4**	**0.0**	**62.0**	0.0
0.6	99.3	73.5	**98.5**	**83.1**	**100.0**	99.6	**82.2**	**0.0**	**93.3**	0.0
0.7	100.0	93.6	**100.0**	**97.5**	**100.0**	100.0	**97.1**	**0.0**	**99.3**	0.0

Table 47. Percentage of FTP Conditions within a Specified Distance

Distance	P1	P2	P3	Highway	Total
0.1	4	1	31	30	16
0.2	24	39	70	68	51
0.3	45	84	91	84	78
0.35	61	94	95	89	87
0.4	78	99	98	99	95
0.5	98	100	100	100	100
0.6	99	100	100	100	100
0.7	99	100	100	100	100

Table 48. Normalized Stage Weights

Distance	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10
0.1			44.1	1.6	29.2		17.7	1.1	6.3	
0.2			33.2	1.6	32.1		17.0	1.7	14.4	
0.3			31.6	2.2	32.3		16.7	1.2	16.0	
0.35			30.0	3.2	31.0		17.4	1.1	17.2	
0.4			27.3	4.1	28.0		19.1	1.2	20.3	
0.5			22.0	9.2	26.8		19.2	1.4	21.5	
0.6			18.5	16.7	22.5		19.4	1.9	21.0	
0.7			19.9	18.3	20.0		18.9	3.6	19.3	

Based upon statistical analysis of Stage conditions and FTP and Highway conditions, ability to discriminate for FM and for Viscosity effects, and to improve test precision the following baseline weighting and stage weighting was selected:

- Baseline weighting for FEI-1 will be: 0% BLB1, 80% BLB2, 20% BLA
- Baseline weighting for FEI-2 will be: 0% BLB1, 10% BLB2, 90% BLA

Stage	3	4	5	7	8	9
Weight, %	30	3.2	31	17.4	1.1	17.2

Using the above Stage weighting and the agreed upon Baseline weighting:

- For FEI-1: Friction Modifier and Viscosity effects were statistically significant (p-Value of 0.025 and 0.015, respectively, with RMSE at 0.225)

- For FEI-2: Viscosity effect was significant (p-Value of 0.029), Friction Modifier effect was directionally correct (p-Value of 0.279) with a RMSE of 0.264)

In addition, Matrix IV and Matrix IVA Step3 data were analyzed again using the selected stage weighting above. The BL weighting applied to this analysis was 80-20 BLB2-BLA split for FEI1 and 10-90 BLB2-BLA split for FEI2.

As shown in Table 49, based on the FEI analysis with variables Oil, Lab and PCM (versions 1 and 3), there is a significant Moly friction modifier effect by comparing oils G and I for FEI1 and for FEI2. The organic friction modifier effect (oils A and B comparison) is significant for FEI1, but no significant effect was found for FEI2 (as previously reported in the Matrix V analysis). There's no significant Viscosity grade effect (oils A and E comparison) both for FEI1 and FEI2 as the RMSE for both FEI1 and FEI2 are significantly higher than the RSMEs in Matrix V.

Table 49. Statistics for Matrix IV and IV-A3 Re-calculated using Final Stage Weightings

T- Statistic for FEI-1*			RMSE for FEI-1	T- Statistic for FEI-2*			RMSE for FEI-2
Org FM	Mo FM	Vis Grade		Org FM	Mo FM	Vis Grade	
2.98	4.73	-0.77	0.3549	1.36	2.65	-0.45	0.2404

* Significant T-Statistic = 2.42

Although there are significant effects shown in this analysis, especially for Moly friction modifier in FEI2 (which was not observed in Matrix V since oils G and I were not selected), it is worth noting that the test procedure used for this matrix was different from the final one, that is, the procedure used in Matrix V – Prove Out, which included double Baseline runs (BLB1 and BLB2) using separate charges of BL prior to switching oils to the test oil, whereas the Matrix IV testing had only single baseline before tests, and Matrix IV-A had double baseline runs but using the same charge of oil for both baseline runs before the test oil.

Based upon the results of the Prove Out Matrix, as well as all previous testing done by the Consortium, the Consortium recommended to the ILSAC/Oil Committee, that the ILSAC/Oil Committee request that the ASTM Passenger Car Engine Oil Classification Panel (PCEOCP) proceed with the ASTM Precision Matrix Test program. A successful Precision Matrix Test program is necessary before the PCEOCP would accept the test for use in an ILSAC GF-category oil specification. In a meeting of the PCEOCP on September 4, 2008, the PCEOCP voted to proceed with the Precision Matrix for the Sequence VID Test.

Appendix A

Sequence VID Consortium Agreement

Red Cavaney
President and Chief Executive Officer

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API CONTRACT NO. 2006-102203

SEQUENCE VID TESTING PROGRAM SOLICITATION AGREEMENT

A) Purpose: This is an Agreement by and between the undersigned companies ("Consortium Participants") and the American Petroleum Institute ("API") to establish and fund research to develop a new Sequence VID test. ("Program").

B) Scope: The scope of the Program is described in the *Invitation to Join Consortium to Develop New Sequence VID Fuel Efficiency Test for Engine Oils. ("Procedures")* (Attachment 1).

C) Membership: Participation in the Program is open to all interested parties that agree to comply with the terms and conditions of the Agreement and satisfy the requirements specified in the Procedures. Consortium Participants will be identified as either Cash-Contributing Participants or Original Equipment Manufacturer (OEM) Participants.

D) Finance and Administration: Consortium Participants (check one):

☐ Cash-Contributing Participant ("Cash Participant") agrees to pay its assigned portion of the cost of the Program. Upon the execution of this Agreement by a minimum of eight (8) Cash Participants on or before May 31, 2006, API will submit an invoice to each Cash Participant for $300,000. Cash Participant agrees to pay the invoice in a single payment within 90 days of receipt of the invoice or in two payments, $200,000 within 90 days of receipt of the invoice and $100,000 by January 31, 2007. API agrees that in the event that there are funds remaining after the completion of the Program, any remaining uncommitted funds will be disbursed to the Cash Participants on a prorated basis. However, should the Consortium Participants decide to change the scope of work, resulting in expenses and/or commitments greater than the amount originally collected, Cash Participant agrees to pay its proportional share of additional moneys to make up the shortfall, or the Consortium Participants may agree to reprioritize Program elements within the existing budget.

Failure by a Cash Participant to pay the amount invoiced by August 31, 2006, may result in the Cash Participant's suspension from the Consortium. Suspension of the Cash Participant for non-payment will not relieve the Cash Participant of its financial obligations. A suspended Cash Participant will be reinstated into the Consortium after receipt of its payment.

☐ Original Equipment Manufacturer (OEM) Participant ("OEM Participant") agrees to contribute the Federal Test Procedure (FTP) field correlation data on engines specified in Attachment 2. OEM Participant agrees that any data that is provided shall become part of the research deliverables. The OEM Participant understands and agrees that its membership is contingent upon a determination that its in-kind contribution satisfies the technical needs of the Program. In the event a proposed in-kind contribution is determined to be insufficient for the needs of the Program, (a) all of such in-kind materials (e.g., data) shall be returned to the OEM immediately, with no rights retained by API, the Consortium Participants or third parties whatsoever, and (b) such parties will be obligated to maintain the confidentiality of the materials pursuant to Paragraph P.

Any change in the scope of the Program that exceeds the budgeted amount must be unanimously approved by the Consortium. This change must also be documented in an addendum to this Agreement. Any change to the scope that is within the budget of the Program only requires a simple majority (>50%) of the Consortium. Note the approved budget cannot exceed the maximum amount to be contributed by the Cash Participants.

E) Contractors: Southwest Research Institute, Intertek Automotive Research, and others as directed by the Consortium will serve as the Consortium Contractors ("Contractors").

F) Solicitation Fees and Payments: Cash Participant shall make payment as follows:

Send checks to:	**Send wires to:**
American Petroleum Institute PO Box 1425 Merrifield, VA 22116 Reference: SS-2100-D9112-7601	Citibank, F.S.B. Washington, DC 20036-0967 ABA # 254070116 for further credit to American Petroleum Institute Account # 6672 0060 Reference: SS-2100-D9112-7601

G) Late Entry: Any Cash Participant that is not a party to this Agreement on the date of API signature may enter into this Agreement after its initial execution. The cost to such Cash Participant shall be the dollar amount the newly joining Participant would have paid if such Participant had joined the Program at the effective date of this Agreement ($300,000), plus a 10% penalty ($30,000), for a total payment of $330,000.

H) Program Supervision: The Consortium Participants will be responsible for the management and development of the Program pursuant to the process defined in the Procedures.

I) API Responsibilities: API will negotiate, enter into, and administer contracts for the conduct of the Program with direction from the Consortium. API will provide administrative oversight and support for the Program and collect and disburse the financial contributions required of the Program under this Agreement. API agrees to submit financial reports to the Consortium on the status of the Program when requested by the Consortium. API shall be reimbursed for its services at the rate specified in the Procedures.

J) **Incorporation by Reference:** With respect to the conduct of the Program by API, this Agreement incorporates by reference the Procedures and API policies and procedures relating to contracting, financial transactions, and research. Copies of all applicable policies will be provided upon request.

K) **Program Deliverables:** All reports, data, and intellectual property derived out of this Program shall belong to API, and each Consortium Participant shall automatically receive a royalty-free, non-exclusive, irrevocable, worldwide, perpetual license with the right to sublicense all such material. The Consortium Participants agree that the distribution and use of data, reports, and intellectual property to third parties shall be governed by the process defined in the Procedures and in this Agreement. Consortium Participants agree that the use of the proposed Sequence VID test procedure by Consortium Participants during the development process shall be governed by the process defined in Procedures (see Attachment 1). API agrees to include a provision in contracts with Contractors that requires the assignment of any intellectual property rights arising out of the work to API. Nothing in this paragraph shall require API to pursue protection of any intellectual property rights.

L) **Termination by Consortium Participants:** This Agreement may be terminated by a Consortium Participant by providing API with at least 90 days written notice of the Participant's intent to terminate. In the event that this Agreement is terminated for any reason, the Consortium Participant shall be entitled to receive all of the privileges, benefits, and rights which have accrued to the Participant up to the date of termination. If a Consortium Participant leaves the Project prior to completion of the Program, it shall remain liable for the payment of its full assigned portion of the total costs of the completed Program. Termination of this Agreement will not release Consortium Participant of any other obligations or liabilities that arise out of activities that occur prior to the date of termination.

M) **Termination by API:** API may terminate this Agreement at any time for reasonable cause after giving Consortium Participants at least 90 days written notice. In the event that API terminates the Program prior to its completion, API reserves the right to retain all funds necessary to pay for work already contracted for and will use reasonable efforts to minimize termination expenses. API shall disburse any remaining uncommitted funds to each Cash Participant on a prorated basis.

N) **Indemnification:** Each of the Consortium Participants (the "Indemnifying Party") agrees to indemnify API against all liabilities arising out of the acts or omissions of such Indemnifying Party pursuant to this Agreement to the extent not covered by insurance or from third parties. This indemnification obligation shall not include claims that arise out of API's negligence or due to a failure of API to satisfy its obligations under this Agreement. API agrees to include in each research contract executed by API a provision stating that the Contractor will indemnify and hold harmless API and all Consortium Participants from and against any and all liability, loss, cost, expense, damages, claims, or demands on account of injuries to Contractor's employees or third parties arising out of the Contractor's negligent conduct or breach.

O) Warranty: API does not make any representations or warranties concerning the results of this Program and disclaims any liability to the Consortium Participants or third parties for claims arising out of the Program.

P) Confidentiality: Except as otherwise expressly provided in this Agreement, the Consortium Participant agrees to treat any data or reports contributed to or arising out of the Program as confidential and not to disclose or cause to be disclosed any such information to third parties except as necessary to perform its services hereunder or as may be specifically authorized by the Procedures. The Consortium Participant agrees to use reasonable efforts to ensure compliance with the provisions of this section by its employees, agents, affiliates, and sub-contractors. Notwithstanding the foregoing, Consortium Participant may disclose Confidential Information if required by law or court or governmental order or process; provided, however, Consortium Participant shall immediately notify the other participants of the receipt of such an order and shall provide a copy of such order to the other participants prior to disclosing any information. Confidential Information shall not include information that (i) is or becomes part of the public domain through no act or omission of the Consortium Participant; (ii) was in Consortium Participant's lawful possession prior to the disclosure and was received by API without restriction on disclosure; (iii) is lawfully disclosed to Consortium Participant by a third party without restriction on disclosure; or (iv) is independently developed by Consortium Participant without use of or reference to the Confidential Information. The obligations with respect to the treatment of all Confidential Information that is received under this Agreement shall survive termination and shall remain in effect for a period of two (2) years from the date of first receipt of such Confidential Information or until this Program is completed, whichever is later. API agrees to include a similar confidentiality clause in contracts with the Consortium Contractors.

Notwithstanding the foregoing, Participant may disclose Confidential Information to Affiliates. Affiliate(s) as used in this Agreement shall mean the Consortium Participant, any parent thereof, and any company, partnership, limited liability company, association, venture, or other form of entity of which participant now or hereafter owns or controls, directly or indirectly, fifty percent (50%) or more of Rights therein. For the purpose of this definition, the Rights owned or controlled by Participant shall be deemed to include all Rights owned or controlled, directly or indirectly, by any other company, partnership, limited liability company, association, venture, or other form of entity of which participant owns or controls, directly or indirectly, fifty percent (50%) or more of Rights therein. For the purpose of this definition, the term "Rights" shall mean stock, shares, interests, indicia of equity or other rights entitled to vote for directors, or other functional equivalents, thereof. The term "Affiliate" shall additionally include any other business entity managed by said company or partnership having the above-described relation with Participant with respect to ownership or control.

Q) **Disputes:** The Consortium Participants agree to attempt in good faith to resolve any dispute arising out of or relating to this Agreement promptly by negotiations between executives, or their designees, who have authority to settle the dispute. Any Consortium Participant may give the other participant written notice on any dispute and request negotiation, and within 20 days after delivery thereof, the representatives of both Consortium Participants shall meet in an effort to resolve the dispute. If the dispute has not been resolved by negotiation within 45 days after receipt of a request of negotiation, either Consortium Participant may submit the dispute to binding arbitration, to which both participants agree to be bound. Any such arbitration shall be conducted under the commercial rules and auspices of the American Arbitration Association ("AAA") before a panel of three (3) arbitrators. The arbitrators shall have experience in the areas related to the subject matter of this Agreement and shall be selected by the AAA in accordance with its commercial rules therein in force. The award of the arbitrators may be entered and, in the absence of fraud, enforced in any court of competent jurisdiction.

R) **API's Tax Exempt Status:** API is a nonprofit corporation exempt from United States Federal income tax under section 501(c)(6) of the Internal Revenue Code of 1986 as amended. No provision of this Agreement shall obligate API to take any action that is inconsistent with or that could jeopardize its tax-exempt status.

S) **Taxes:** The Consortium Participants recognize that under current law, there are no sales, use, excise, or any similar taxes imposed by the District of Columbia on the transaction contemplated herein. For future purposes, however, the parties agree that each Consortium Participant should be responsible for its own tax liability and cannot hold API liable for any or all such taxes.

T) **Lobby Tax:** In invoices issued under this Agreement, API will include the following language: In response to the Omnibus Reconciliation Act of 1993, API has estimated that 15% of the 2006 dues is allocable to lobbying expenditures to which section 162(e)(1) of the Internal Revenue Code of 1986, as amended, applies. Although this special solicitation is outside of the API budget process, it is included in the computation of the total 2006 API dues to which section 162(e)(1) applies. Consequently, 15% of your payment is not deductible as an ordinary and necessary business expense for federal income tax purposes. Further, contributions or gifts to the American Petroleum Institute are not tax deductible as charitable contributions.

U) **Relationship of the Consortium Participants:** Nothing contained in this Agreement shall be construed as establishing any partnership nor as establishing any joint obligations except those specifically set forth herein. Each party hereto retains the right to conduct its own business as it sees fit. Nothing contained herein shall be interpreted or construed as precluding any Consortium Participant from carrying out its own research or participating in other research, even though it may parallel or overlap the work done in connection with this Program. No Consortium Participant shall have any rights, including but not limited to rights to or under any patents, in any such other research conducted by another Participant.

V) Successor Liability: The obligations imposed under this Agreement shall apply to the legal successors and assigns of the Consortium Participants, including any purchasers of all or substantially all of the assets of a company or companies, and API.

W) Compliance: Each Consortium Participant agrees that it will comply with all applicable laws and regulations while participating in this Program.

X) Governing Law: This Agreement shall be interpreted and governed by the laws of the District of Columbia, United States of America.

Y) Incorporation of Agreement: This instrument contains the entire and only agreement between the Consortium Participants. No oral statements or representations not herein contained shall have any force and effect.

Z) Effective Date: This Agreement shall become effective upon API's signature below. Consortium Participant agrees and understands that this Program and the Agreement is contingent upon a sufficient number of organizations agreeing to fund the research. If API by August 31, 2006, determines that the number of participants is not sufficient to support the Program, API shall notify all Consortium Participants of this decision and refund all fees within 60 days.

AA) Signature: This Agreement may be signed in multiple counterparts that together shall constitute a single agreement. This Agreement, including any modifications, waivers, or notifications relating thereto, may be executed and delivered by facsimile or electronic mail. Any such facsimile or electronic mail transmission shall constitute the final agreement of the parties and conclusive proof of such agreement.

BB) Notice: Notices required to be given by this Agreement shall be in writing and shall be effective as of the date on which such notice is delivered to: (a) for API: Kevin Ferrick, 1220 L Street, N.W., Washington, D.C. 20005; and (b) for Participant: ____.

CC) Paragraphs K, L, M, N, P, Q, R, S, X and BB shall survive the termination of this Agreement.

IN WITNESS WHEREOF, intending to be bound hereby, the parties hereto cause this Agreement to be duly executed by their authorized representatives as of the date noted below.

Appendix B

Sequence VID Consortium Budget

The Sequence VID Consortium developed a budget in response to ILSAC's "Invitation to Join Consortium to Develop New Sequence VID Fuel Efficiency Test for Engine Oils" issued in May 2006. The budget estimated the costs for developing a new fuel efficiency test and included stand rental and lab management fees. The original budget line items for developing the tests are shown in the table below. This does not include changes approved by the Consortium once test development began. For example, additional testing occurred under Matrix IV, and Matrix V in effect became the Prove-out Matrix.

Task	**Hours Test**	**# Tests**
Initial Stand/Hardware Configuration		
Engine mapping matrix	14	3
Engine break-in new engine	200	1
Matrix I - Aging Conditions		
Determine aging conditions and time for Phases 1 & 2 (Oil C)		
Matrix design of 12 tests (6/lab) total at 2,000 RPM to evaluate effects of temperature (oil/water), load, lab, time. Use both labs A & B. Compare periodic used oil sample analyses with FTP 6,500-mile oil sample analyses	672	6
Matrix II - Initial Operating Conditions Mapping		
Lab A		
Test 1: Oil A [Oil Z 12 stages (18hr), Oil A aging 32 hrs, Oil A 12 stages (18 hr), Oil Z 12 stages (18hrs)]	93	1
Test 2: Oil C [Same sequence as for Oil A]	93	1
Test 3: Oil E [Same sequence as for Oil A]	93	1
Test 4: Oil I [Same sequence as for Oil A]	93	1
Test 5: Oil J [Same sequence as for Oil A]	93	1
Tests 6-10 run at Lab B		
Matrix III - Evaluation of Initial Operating Conditions Selected (12 test total)		
Tests 11 to 16 same as above except with only 6 conditions selected from above Matrix II. Run 6 different oils	66	6
Tests 17-22 run at Lab B		
Matrix IV - Confirm Final Stage Conditions Proposed (6 tests)		
Test 23: Oil C [Oil Z 4 stages (6hr), Oil C aging 32 hrs, Oil C 4 stages (6hr), Oil C aging 80 hrs, Oil C 4 stages (6hr), Oil Z 4 stages (6hr)]	143	1
Test 24: Oil A [Oil Z 4 stages (6hr), Oil A aging 32 hrs, Oil A 4 stages (6hr), Oil A aging 80 hrs, Oil A 4 stages (6hr), Oil Z 4 stages (6 hr)]	143	1
Test 25: Oil I [Oil Z 4 stages (6hr), Oil I aging 32 hrs, Oil I 4 stages (6hr), Oil I aging 80 hrs, Oil I 4 stages (6hr), Oil Z 4 stages (6hr)]	143	1

Task	Hours Test	# Tests
Tests 26-28 run at Lab B		
Matrix V - Final Test Development Runs (FEI 1 & 2) to Verify Oil Responses and Test Conditions (2 tests)		
Test 29: Oil C [Oil Z 4 stages (6hr), Oil C aging 32 hrs, Oil C 4 stages (6hr), Oil C 80 aging hrs, Oil C 4 stages (6hr), Oil Z 4 stages (6hr)]	143	1
Additional Test Oils TBD, 4 stages TDB	143	3
Engine Break-in 1 engine	200	1
Prove-out/Precision Matrix		
# of tests		
Run 40 test Prove-out/Precision Matrix (10 tests run by other labs)	143	15
Additional costs	$ K/Months	#Months
Stand rental/month/lab	10	23
Engineering/Administration/Travel/month/lab	9	23
Final document & data dictionary		
FTP Oil Analysis		6

Appendix C

GM Vehicle Fuel Economy Test Data

Available at the TMC Website

Appendix D

Ford Vehicle Fuel Economy Test Data

Available at the TMC Website

Appendix E

Vehicle Used Oil Analysis

An array of analytical tests was performed on each oil at different stages of aging: fresh, after brief run-in, after 2000 miles aging, and after 6500 miles aging. The data are available at the TMC website.

Due to the limited number of oils run in the Cadillac DHS, those analytical results were omitted from the analysis of the used oil results. Also excluded are results for Oil Z as aging was not performed on Oil Z.

In the following cases, the analytical results were suspect or missing. The suspect data were omitted from the analysis. For the run-in cases, the corresponding fresh results were substituted for those results in the regression analyses discussed subsequently.

Table E.1: Missing or Suspect Analytical Results

Oil	Vehicle	Sample (Miles)	Analytical Test
B	Buick-1	0 (Run-in)	DIR Ox
B	Pontiac-1	0 (Run-in)	DIR Ox
D	Pontiac-1	0 (Run-in)	DIR Ox
E	Buick-1	0 (Run-in)	V40, V100, HTHS
E	Pontiac-2	0 (Run-in)	V40, V100, HTHS
G	Buick-2	0 (Run-in)	V40
G	Chevrolet	2000	HTHS
H	Buick-2	2000	HTHS
I	Pontiac-2	0 (Run-in)	DIR Ox
J	Buick-1	0 (Run-in)	TAN

E.2 Analytical Tests

Table E.2 lists the analytical tests included in this analysis.

Table E.2: Analytical Tests Included in Analysis

Abbreviated Name	Analytical Test Description
DIR Ox	Differential Infrared, Oxidation
V40	Kinematic Viscosity at 40°C (cSt)
V100	Kinematic Viscosity at 100°C (cSt)
TAN	Total Acid Number (mg KOH/g)
TBN	Total Base Number (mg KOH/g)
HTHS100	High Temperature/High Shear Viscosity at 100°C (cP)
HTHS150	High Temperature/High Shear Viscosity at 150°C (cP)
HFRR40	High Frequency Reciprocating Rig coefficient of friction at 40°C
HFRR60	High Frequency Reciprocating Rig coefficient of friction at 60°C
HFRR80	High Frequency Reciprocating Rig coefficient of friction at 80°C
HFRR100	High Frequency Reciprocating Rig coefficient of friction at 100°C
HFRR120	High Frequency Reciprocating Rig coefficient of friction at 120°C
HFRR140	High Frequency Reciprocating Rig coefficient of friction at 140°C

E.3 Regression Analysis

Regression analysis was performed on a subset of the results from the analytical tests performed on the oils. The subset was selected as those analytical tests having results which would be most likely to be affected by oil aging. The change (delta) in each analytical result was calculated from run-in to 2000 miles, 2000 miles to 6500 miles and run-in to 6500 miles. Regression analyses were performed on each set of deltas. The independent variables for each analysis were oil and vehicle make. For those cases for which there was more than one vehicle of a particular make tested, the data for the individual vehicles was pooled into one term for that particular make. The intercept for each regression equation is the estimate of the overall (average oil) aging effect.

The results of the analyses discussed in this section are somewhat different from those presented to the VID Consortium in May 2007 due to those analyses being completed prior to all analytical results being available.

E.3.1 Aging Effect of Run-in (0 Miles) to 2000 Miles

Table E.3 provides the estimated overall 2000 mile aging effect for each of the analytical tests considered. Each of them, other than TAN and HFRR40, are statistically significant at $\alpha = 0.1$. Though the overall aging effect may be statistically significant, it may not be for a particular oil as the aging effect differs by oil as indicated by Figures E.1 through E.12. The plots indicate that the analytical test results with the most directionally consistent aging effects for all oils are DIR Ox, V100 and HFRR80. The changes in DIR Ox and V100 are statistically significant for each oil (using Bonferroni multiple comparison test with $\alpha = 0.1$). For each of the analytical test results, other than that of TBN, there is statistically significant discrimination among the oils (using Tukey HSD multiple comparison test with $\alpha = 0.1$). Also, the Buick delta, with respect to V40, V100 and HTHS, is statistically significantly different (larger drop) from that of the other vehicles (via Tukey HSD multiple comparison test with $\alpha = 0.1$).

Table E.3: Estimated Overall Aging Effect for 0 to 2000 Miles

Analytical	2000 Mile Effect	p-Value
DIR Ox	5.1	4.81E-21
V40	-3.6	2.32E-14
V100	-0.75	1.00E-31
TAN	0.0	0.933
TBN	-0.4	0.002
HTHS100	-0.07	0.043
HFRR40	0.001	0.232
HFRR60	0.015	7.12E-09
HFRR80	0.026	7.44E-12
HFRR100	0.030	1.01E-11
HFRR120	0.025	2.02E-08
HFRR140	0.012	0.004

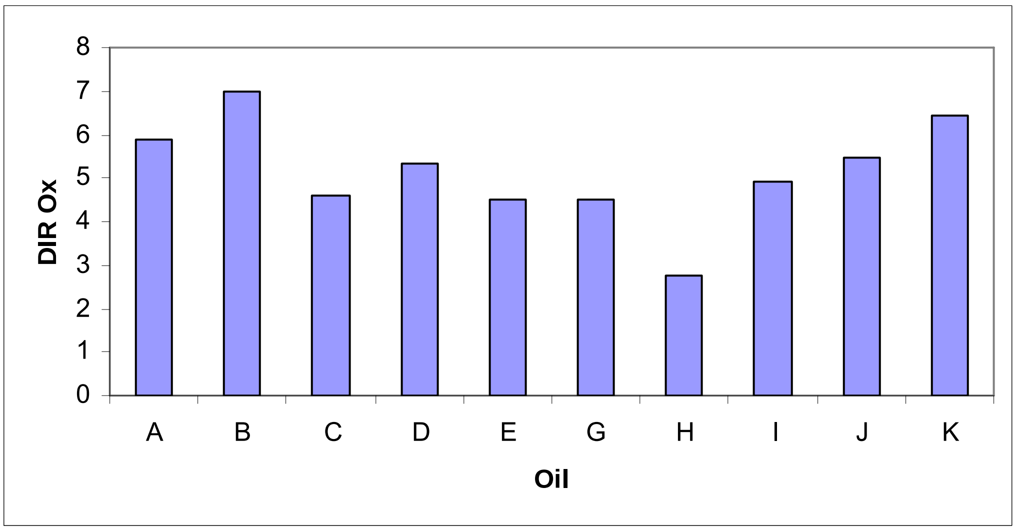

Figure E.1: Estimated Aging Effect on DIR Ox for 0 to 2000 Miles

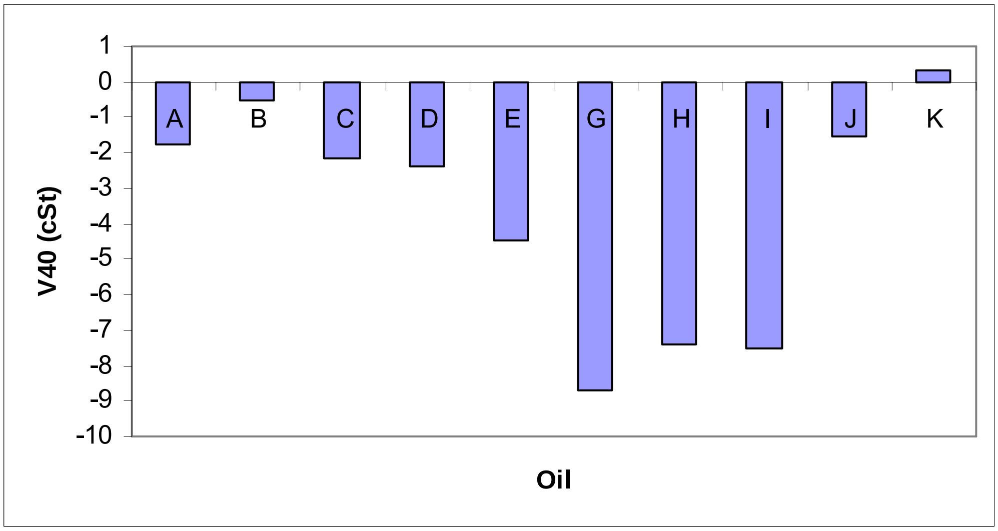

Figure E.2: Estimated Aging Effect on V40 for 0 to 2000 Miles

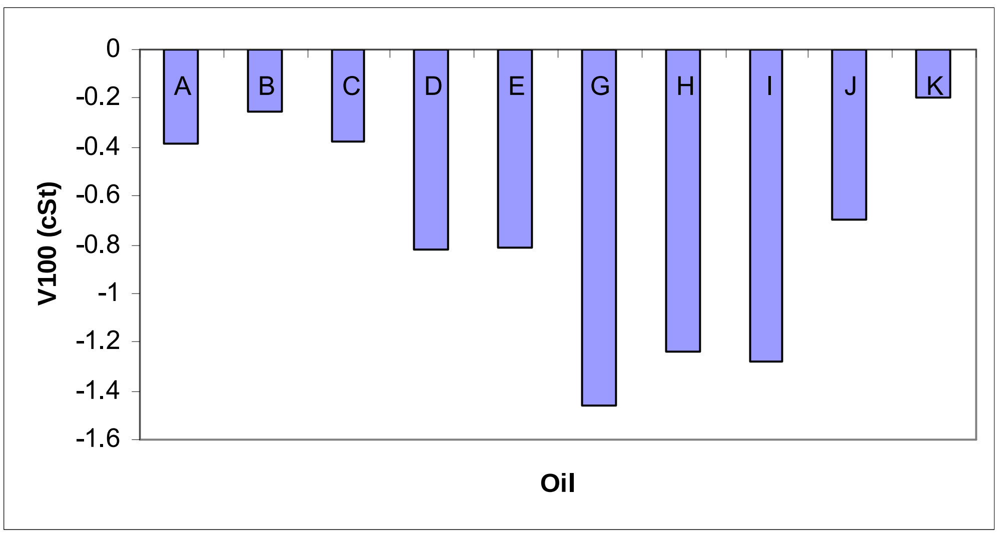

Figure E.3: Estimated Aging Effect on V100 for 0 to 2000 Miles

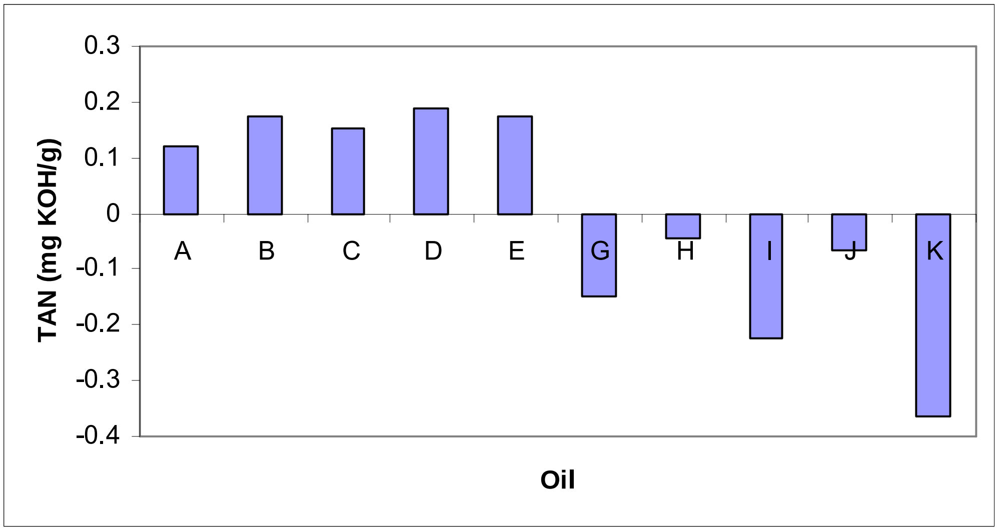

Figure E.4: Estimated Aging Effect on TAN for 0 to 2000 Miles

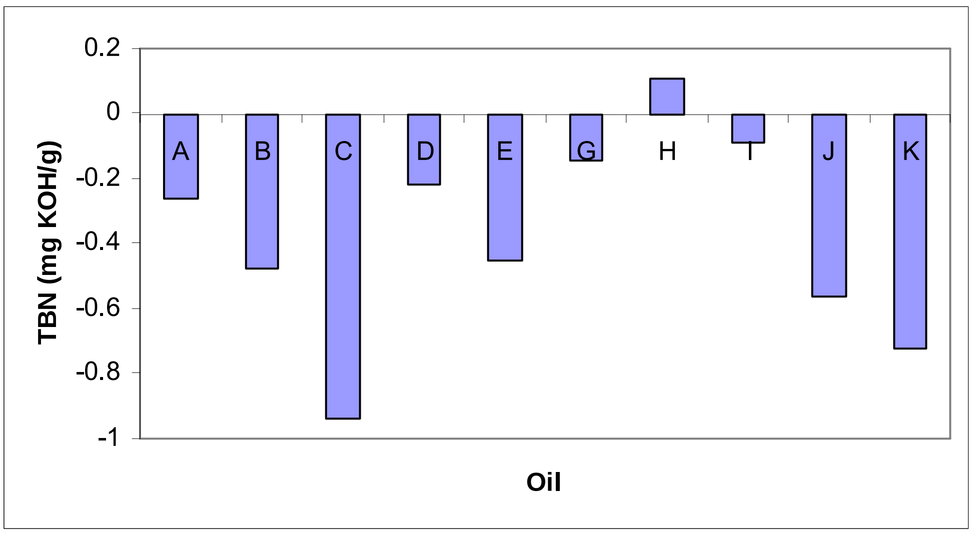

Figure E.5: Estimated Aging Effect on TBN for 0 to 2000 Miles

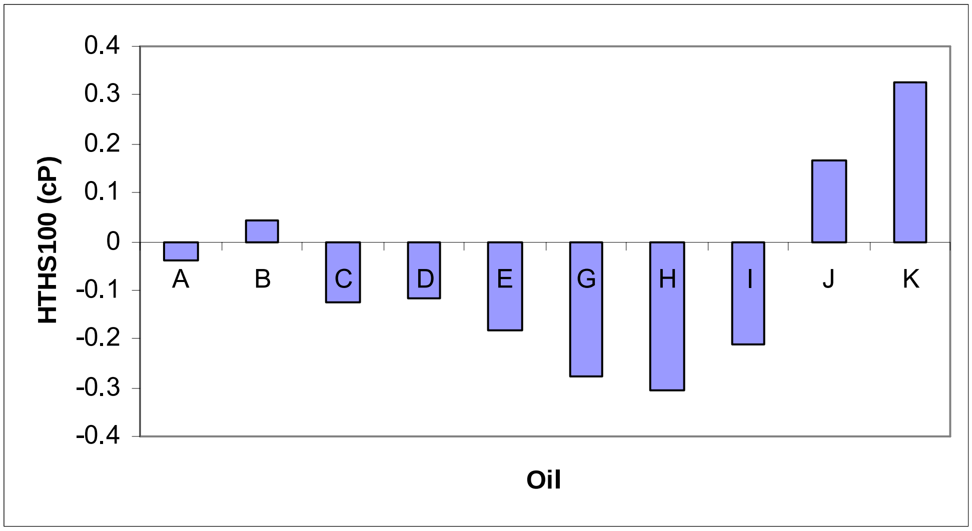

Figure E.6: Estimated Aging Effect on HTHS100 for 0 to 2000 Miles

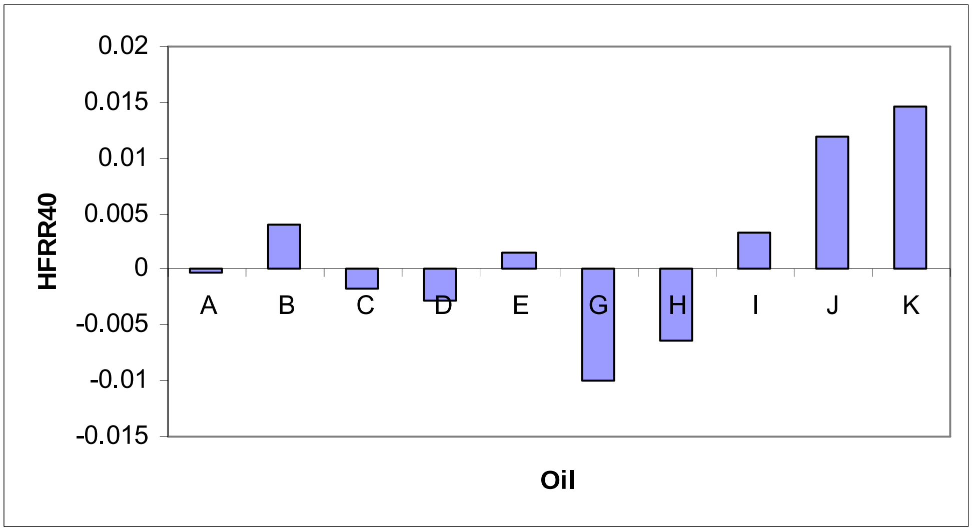

Figure E.7: Estimated Aging Effect on HFRR40 for 0 to 2000 Miles

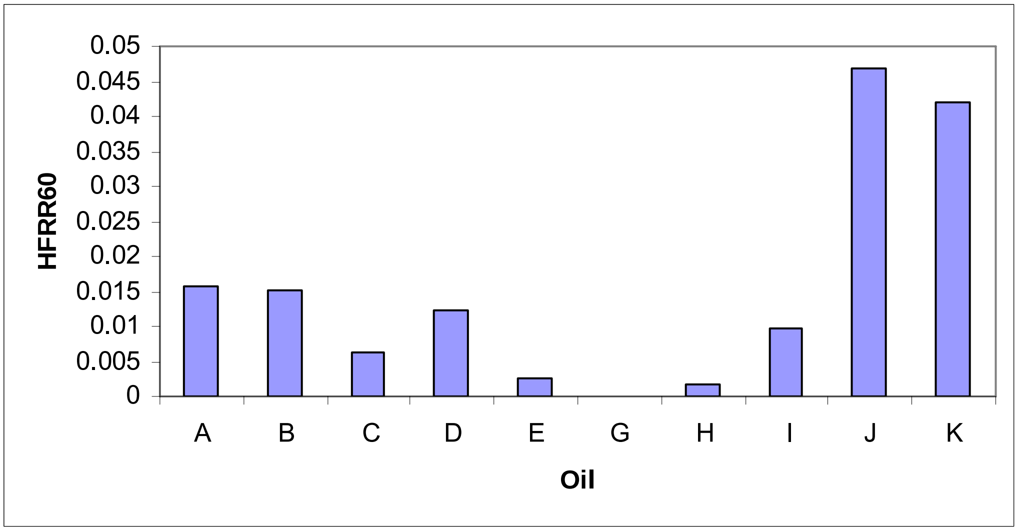

Figure E.8: Estimated Aging Effect on HFRR60 for 0 to 2000 Miles

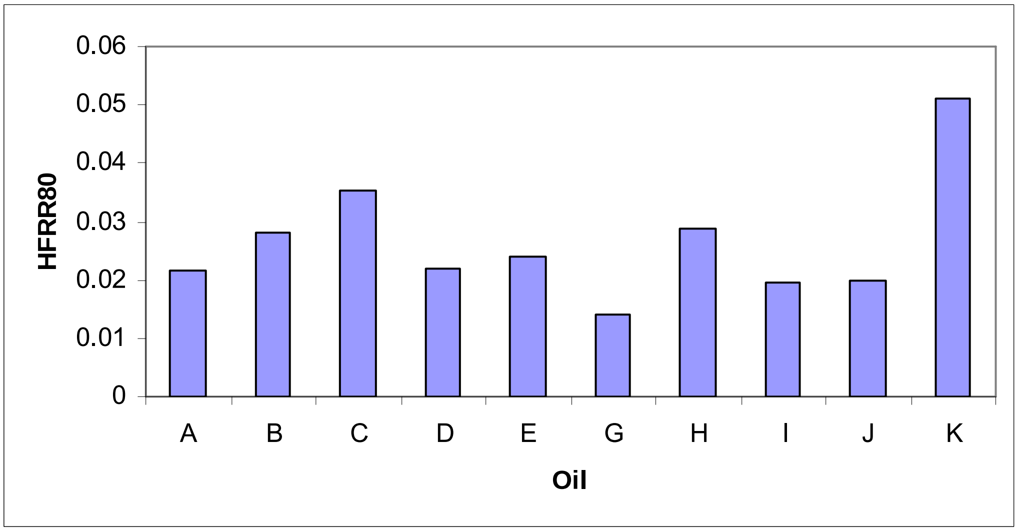

Figure E.9: Estimated Aging Effect on HFRR80 for 0 to 2000 Miles

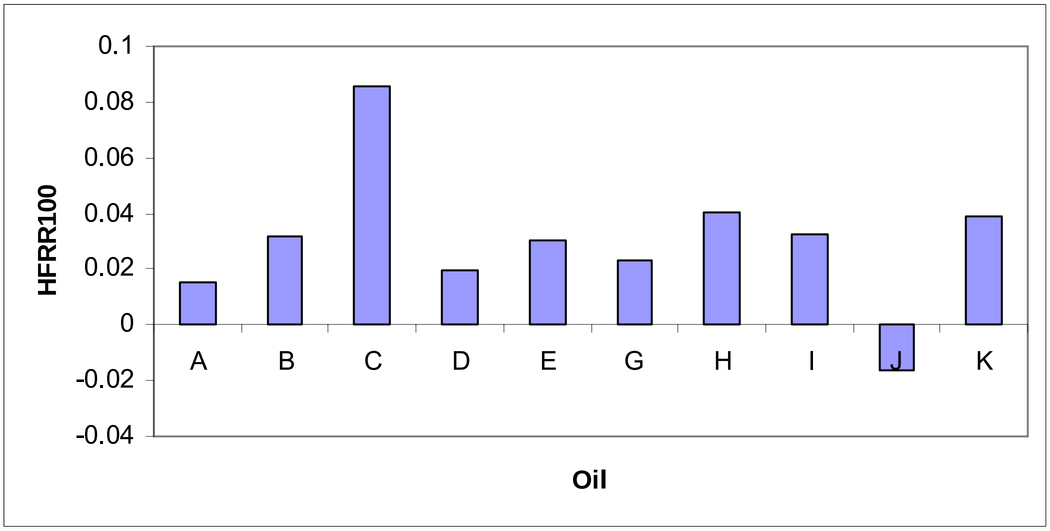

Figure E.10: Estimated Aging Effect on HFRR100 for 0 to 2000 Miles

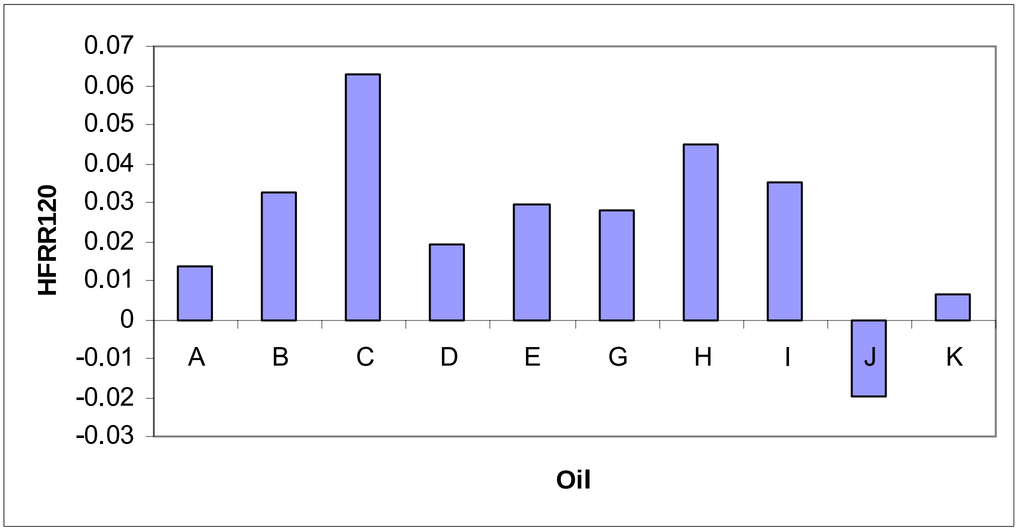

Figure E.11: Estimated Aging Effect on HFRR120 for 0 to 2000 Miles

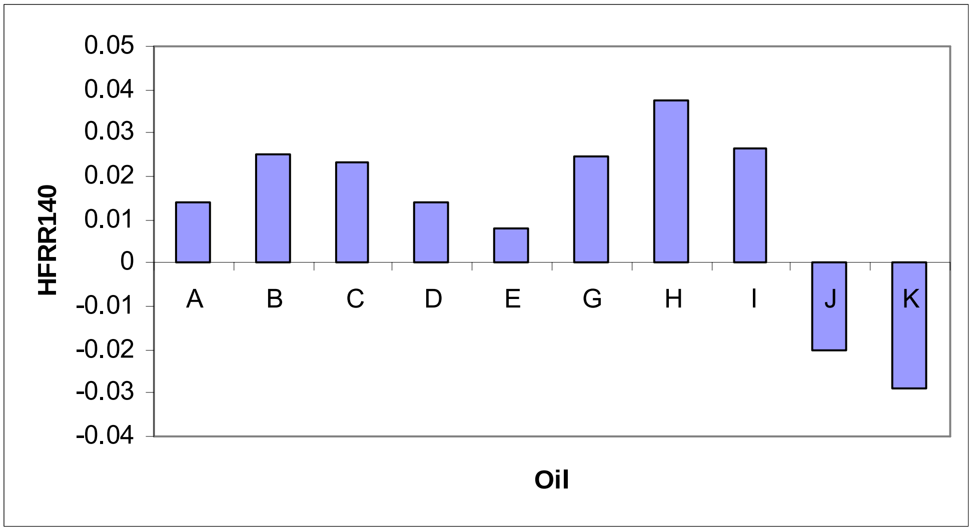

Figure E.12: Estimated Aging Effect on HFRR140 for 0 to 2000 Miles

E.3.2 Aging Effect of 2000 to 6500 Miles

For each analytical test, regression analysis was performed on the delta of the 2000 mile to the 6500 mile result. Table E.4 lists the estimated aging effect for each analytical test. The estimated aging effect is statistically significant for each analytical test result other than that of HFRR40 (α = 0.1). As with the initial 2000 mile phase, the aging effect differs by oil as shown in Figures E.13 to E.24. The direction of the aging effects is consistent for all oils for DIR Ox, V100, TAN, TBN, and HTHS100. Each of the oils increased in V40 during 2000 to 6500 mile aging except for Oil D, which was heavily influenced by the Saab result. Consistent with the 0 to 2000 mile phase, the changes in DIR Ox and V100 are statistically significant for each oil (using Bonferroni multiple comparison test with α = 0.1). There is statistical discrimination among the oils regarding aging effect of V40, V100, TAN, and HFRR at each temperature tested.

Table E.4: Estimated Overall Aging Effect for 2000 to 6500 Miles

Analytical	Aging Effect	p-Value
DIR Ox	6.6	5.87E-20
V40	1.8	1.30E-05
V100	0.25	6.21E-15
TAN	0.7	4.52E-11
TBN	-1.5	1.06E-13
HTHS100	0.36	1.61E-08
HFRR40	0.002	0.242
HFRR60	0.009	4.55E-04
HFRR80	0.011	1.47E-03
HFRR100	0.013	6.93E-05
HFRR120	0.020	2.44E-05
HFRR140	0.028	5.31E-07

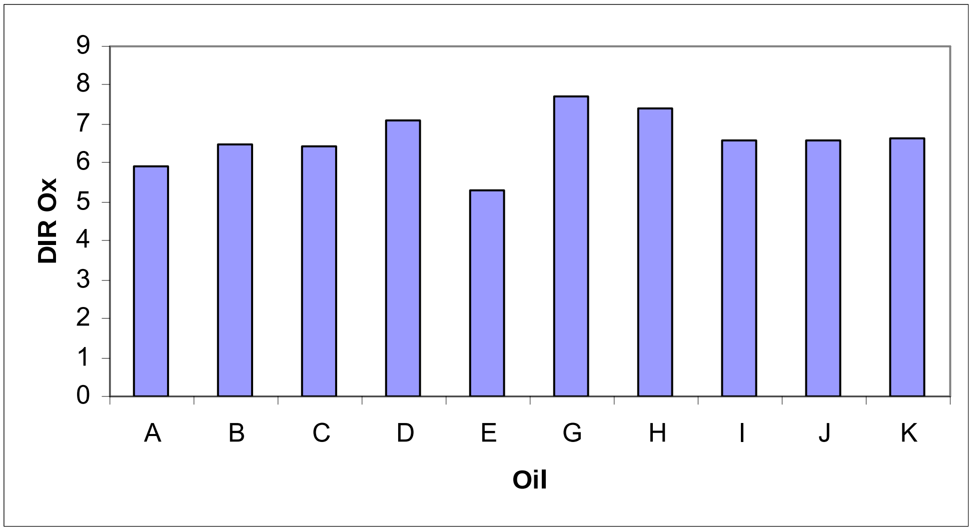

Figure E.13: Estimated Aging Effect on DIR Ox for 2000 to 6500 Miles

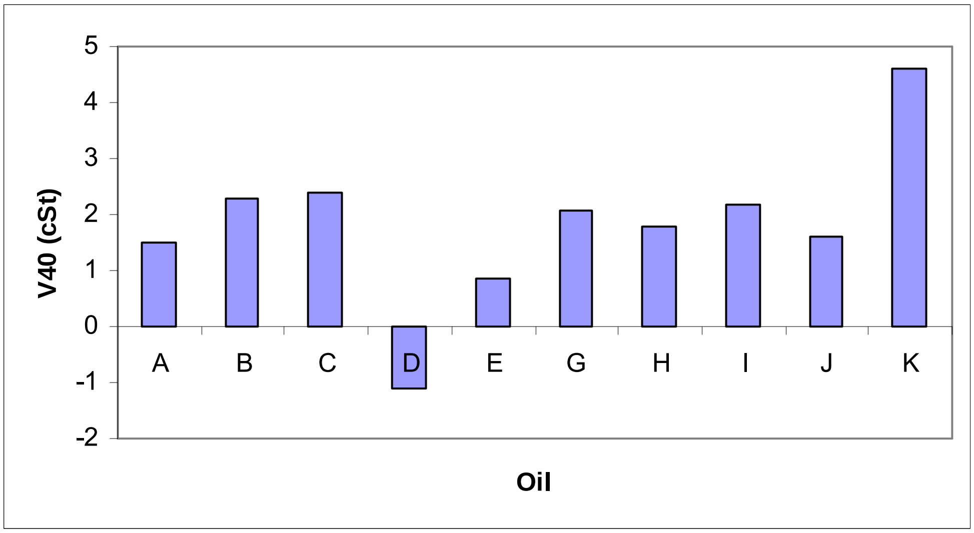

Figure E.14: Estimated Aging Effect on V40 for 2000 to 6500 Miles

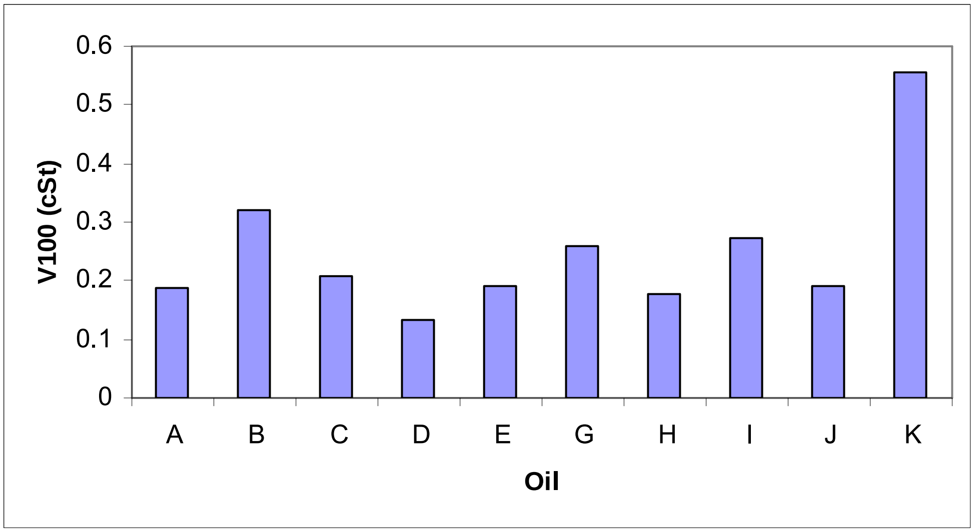

Figure E.15: Estimated Aging Effect on V100 for 2000 to 6500 Miles

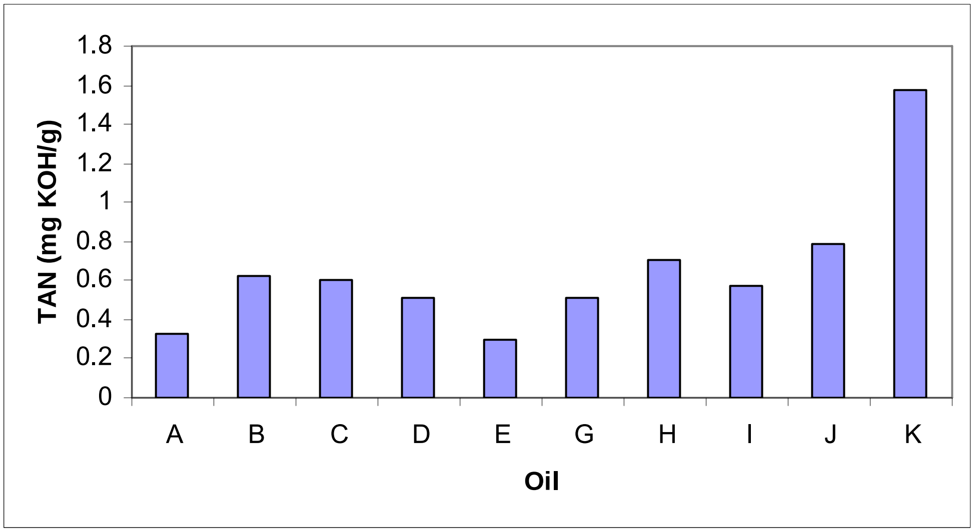

Figure E.16: Estimated Aging Effect on TAN for 2000 to 6500 Miles

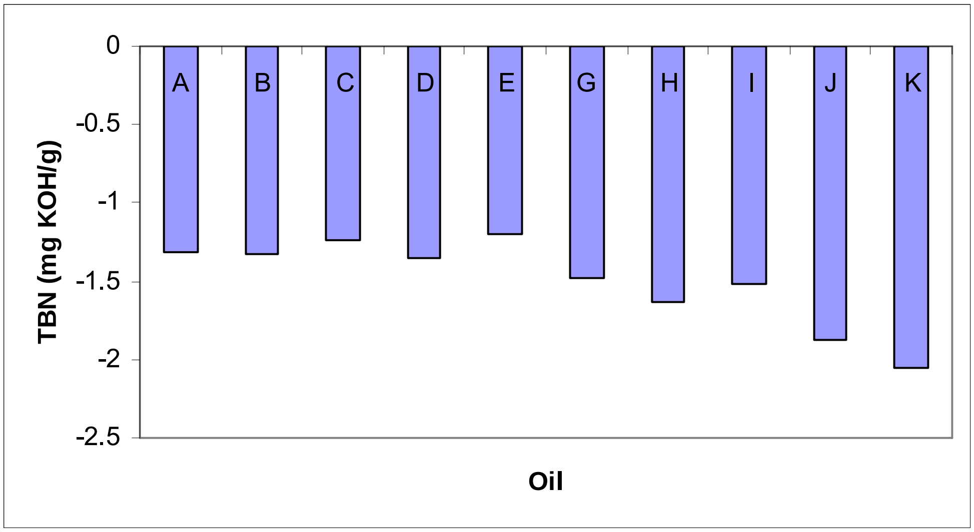

Figure E.17: Estimated Aging Effect on TBN for 2000 to 6500 Miles

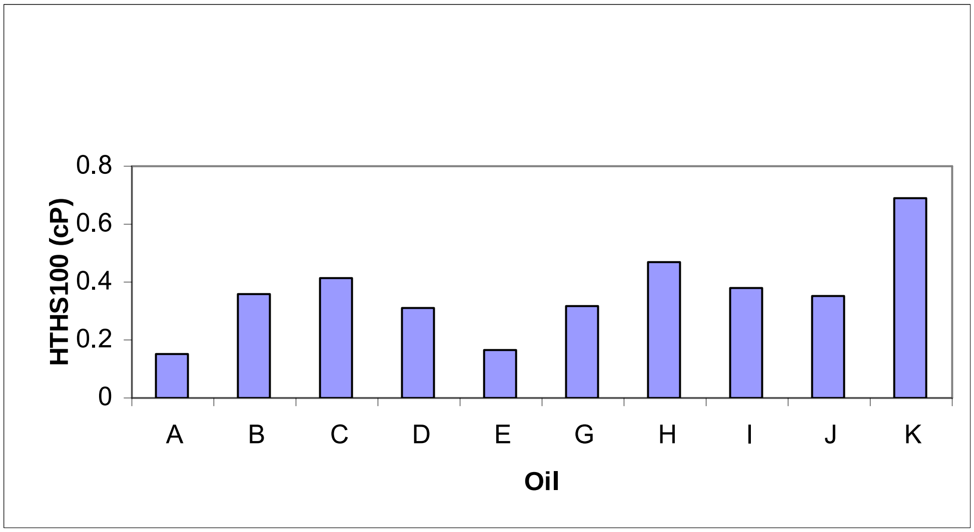

Figure E.18: Estimated Aging Effect on HTHS100 for 2000 to 6500 Miles

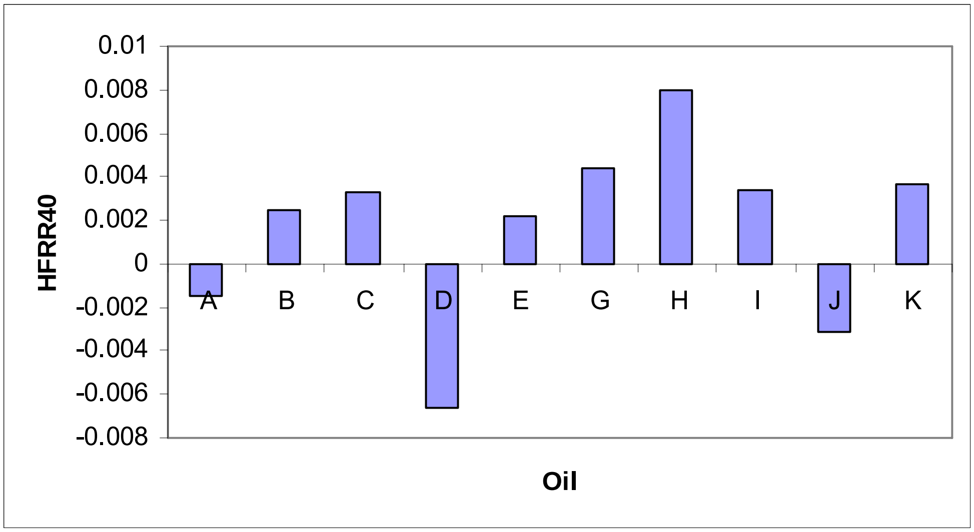

Figure E.19: Estimated Aging Effect on HFRR40 for 2000 to 6500 Miles

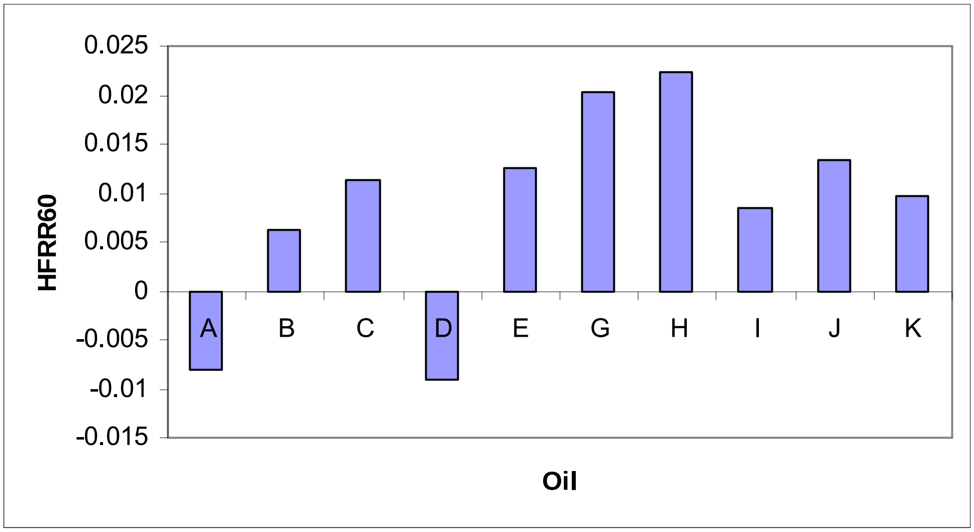

Figure E.20: Estimated Aging Effect on HFRR60 for 2000 to 6500 Miles

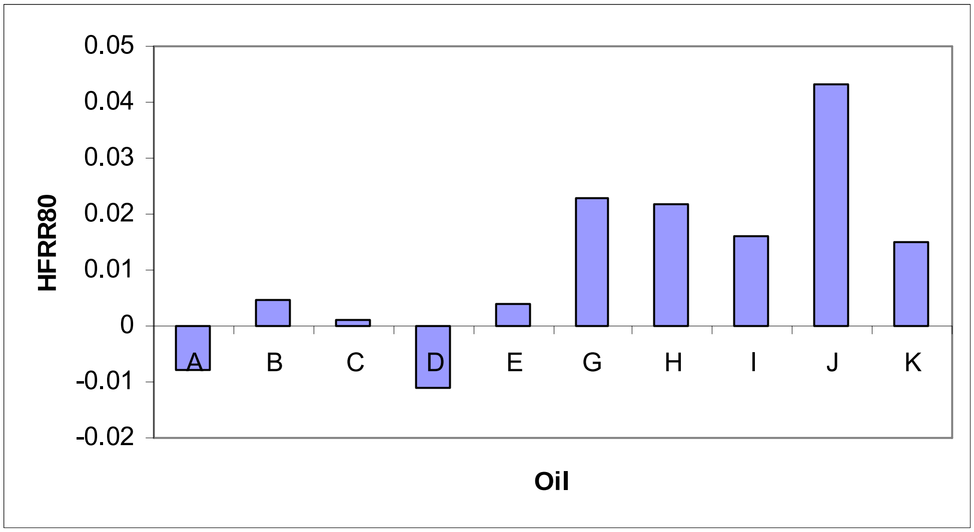

Figure E.21: Estimated Aging Effect on HFRR80 for 2000 to 6500 Miles

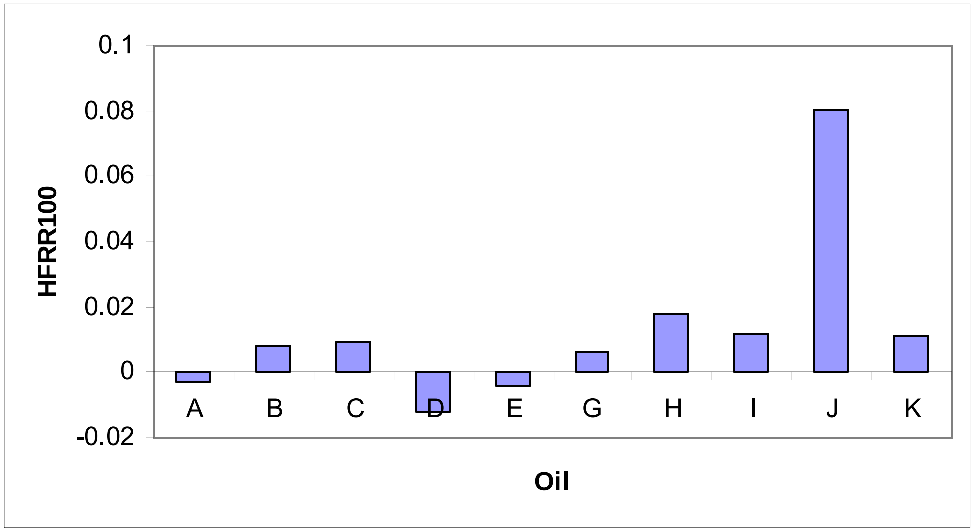

Figure E.22: Estimated Aging Effect on HFRR100 for 2000 to 6500 Miles

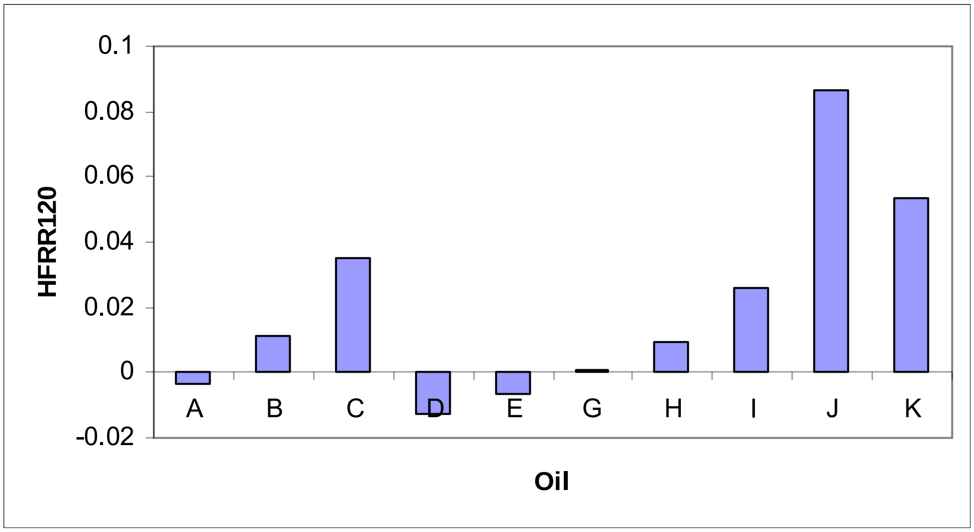

Figure E.23: Estimated Aging Effect on HFRR120 for 2000 to 6500 Miles

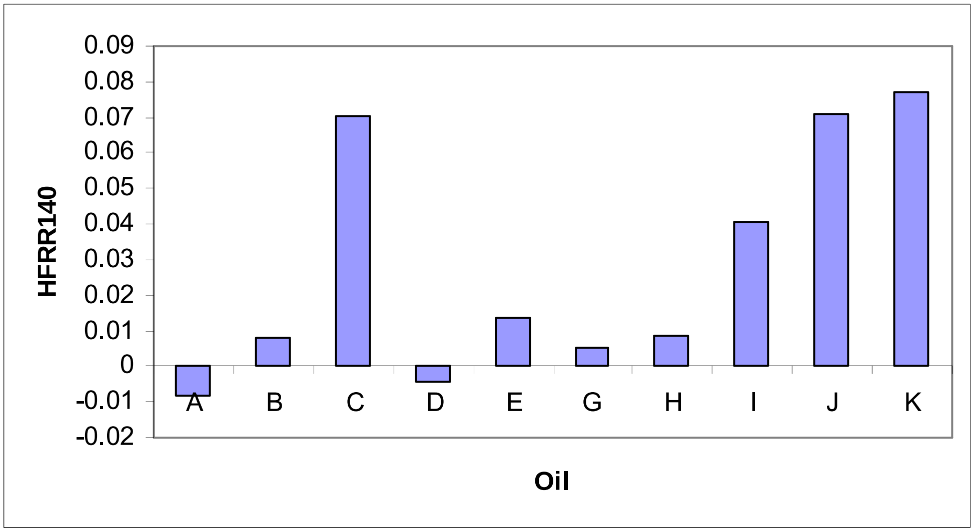

Figure E.24: Estimated Aging Effect on HFRR140 for 2000 to 6500 Miles

E.3.3 Aging Effect of 0 to 6500 Miles

The change from the run-in to the 6500 mile sample of the results for select analytical tests was calculated. Regression analysis was performed on each to estimate the aging effect. Table E.5 lists the estimated aging effect and p-value for the results of each analytical test. The overall aging effect is statistically significant for the results of each analytical test at $\alpha = 0.1$. The estimated aging effect for each analytical test is plotted by oil in Figures E.25 through E.37. The aging effect is directionally consistent for DIR Ox, TAN, TBN, HTHS100, and HFRR for all temperatures other than 40°C. The aging effect on DIR Ox and TBN is statistically significant for each oil (using Bonferonni multiple comparison test with $\alpha = 0.1$). There was statistical discrimination of the aging effect among oils of the results for all analytical tests other than DIR Ox and TBN (using Tukey HSD multiple comparison test with $\alpha = 0.1$).

Table E.5: Estimated Overall Aging Effect for 0 to 6500 Miles

Analytical	Aging Effect	p-Value
DIR Ox	11.9	2.18E-24
V40	-1.7	2.25E-08
V100	-0.49	5.61E-19
TAN	0.7	3.15E-10
TBN	-2.0	7.78E-17
HTHS100	0.30	6.96E-10
HTHS150	0.07	3.68E-09
HFRR40	0.004	0.011
HFRR60	0.022	1.72E-16
HFRR80	0.038	3.15E-18
HFRR100	0.046	3.16E-21
HFRR120	0.047	1.24E-22
HFRR140	0.042	2.61E-18

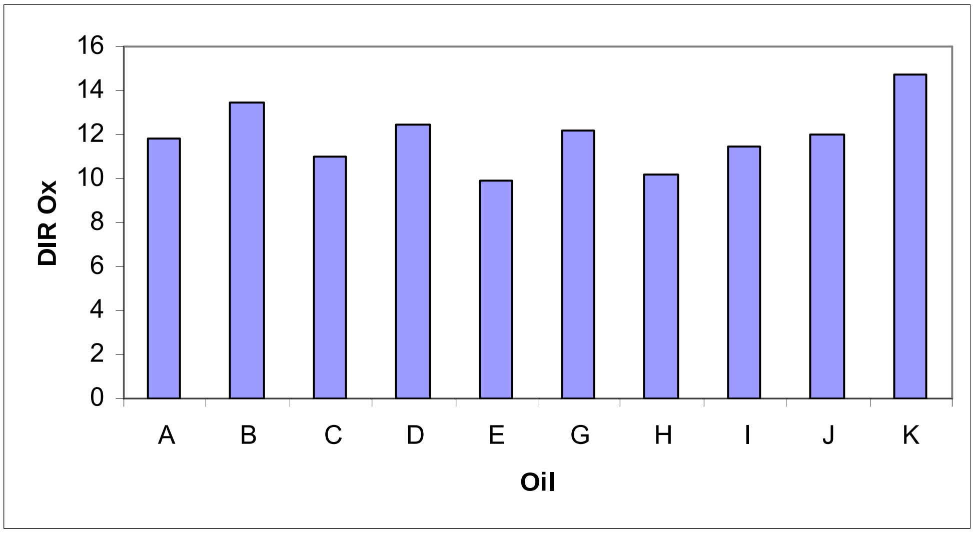

Figure E.25: Estimated Aging Effect on DIR Ox for 0 to 6500 Miles

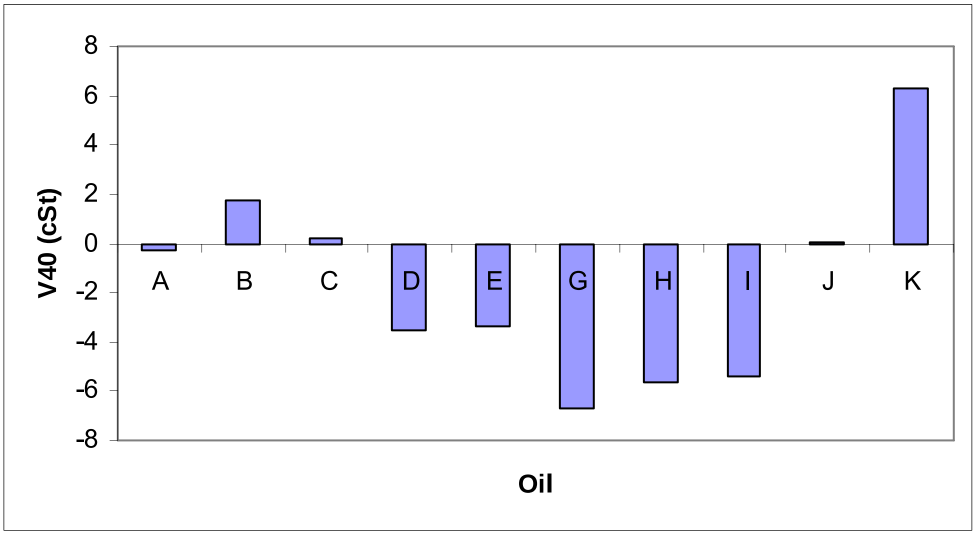

Figure E.26: Estimated Aging Effect on V40 for 0 to 6500 Miles

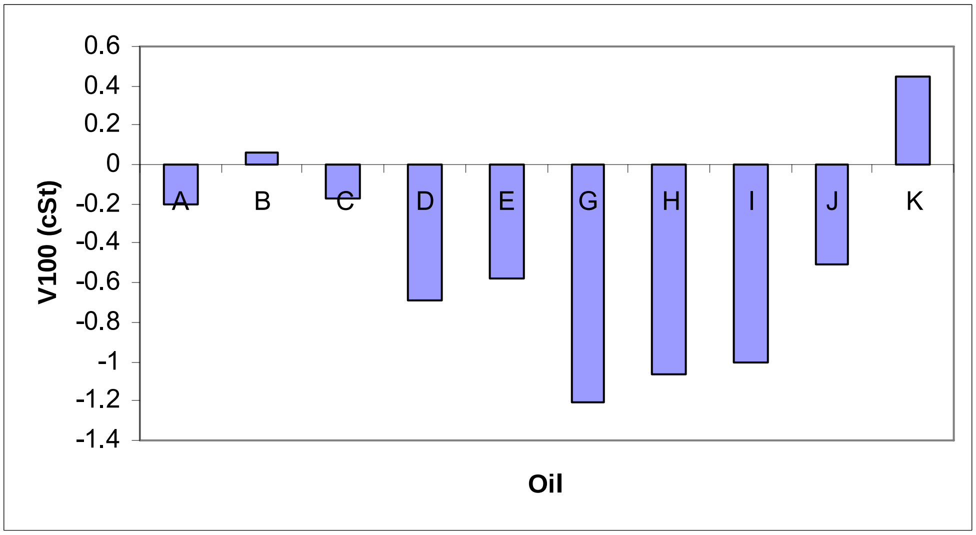

Figure E.27: Estimated Aging Effect on V100 for 0 to 6500 Miles

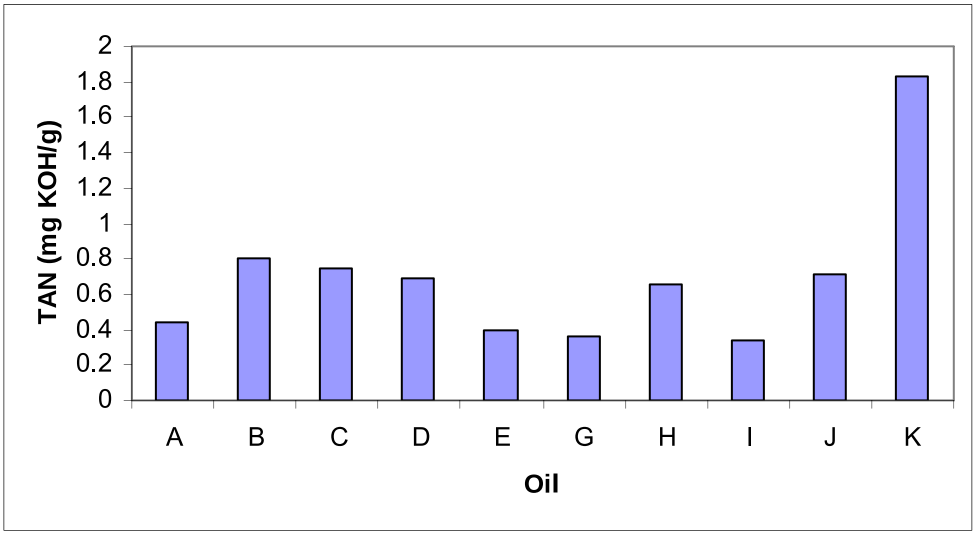

Figure E.28: Estimated Aging Effect on TAN for 0 to 6500 Miles

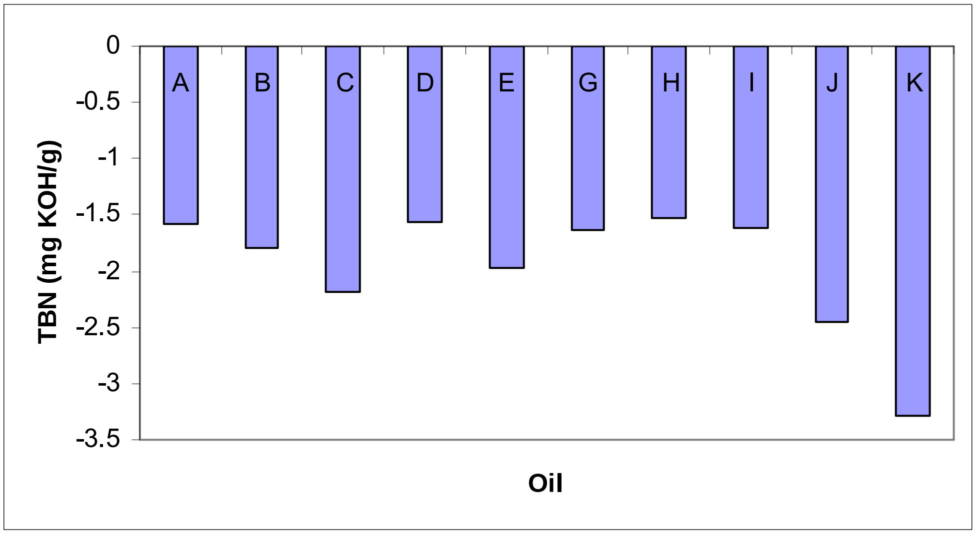

Figure E.29: Estimated Aging Effect on TBN for 0 to 6500 Miles

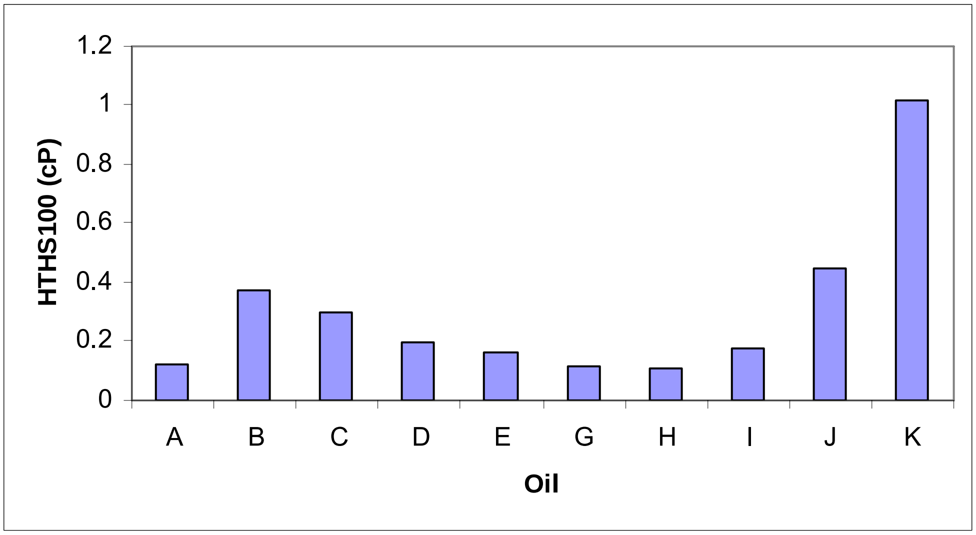

Figure E.30: Estimated Aging Effect on HTHS100 for 0 to 6500 Miles

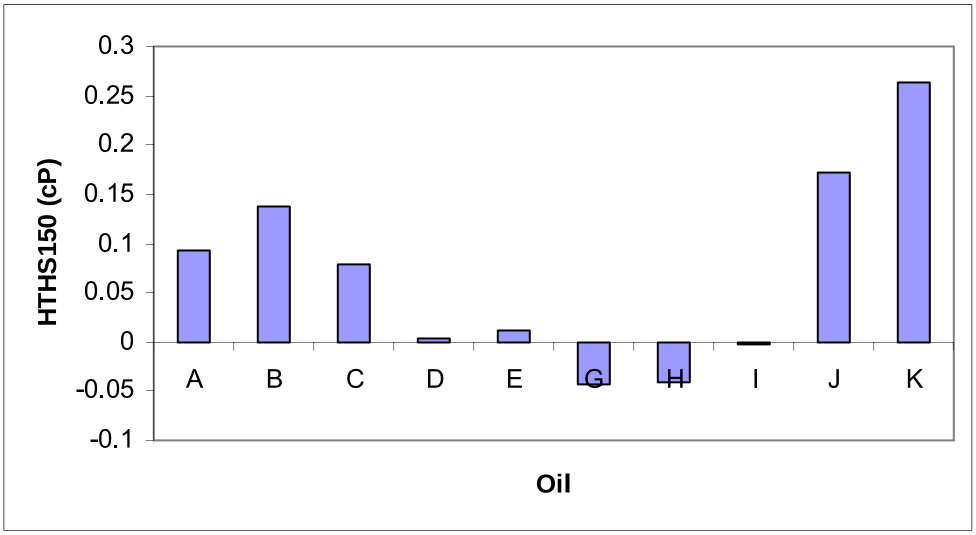

Figure E.31: Estimated Aging Effect on HTHS150 for 0 to 6500 Miles

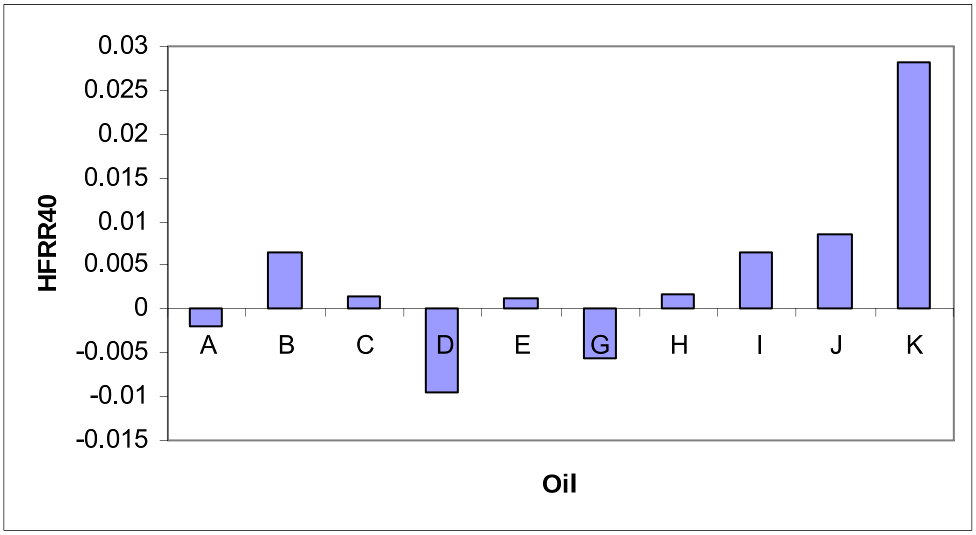

Figure E.32: Estimated Aging Effect on HFRR40 for 0 to 6500 Miles

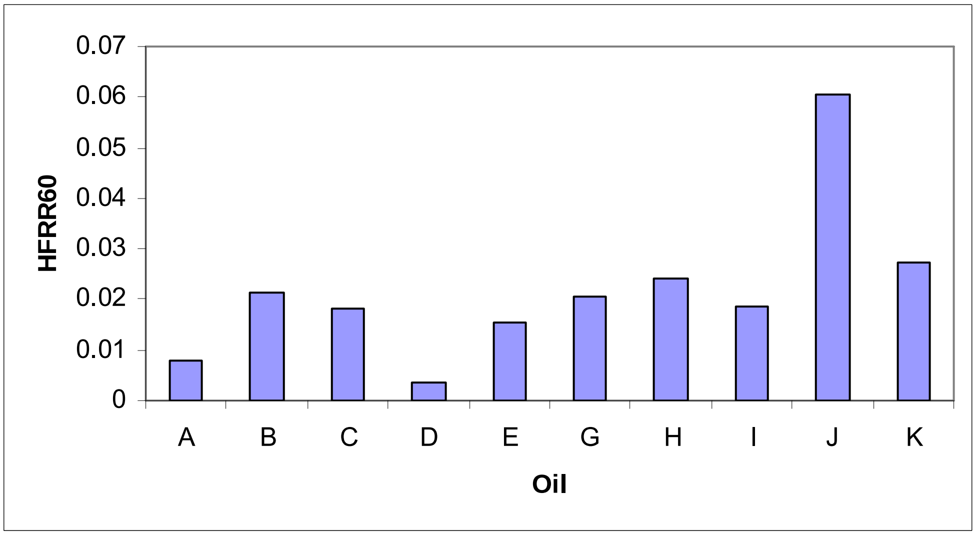

Figure E.33: Estimated Aging Effect on HFRR60 for 0 to 6500 Miles

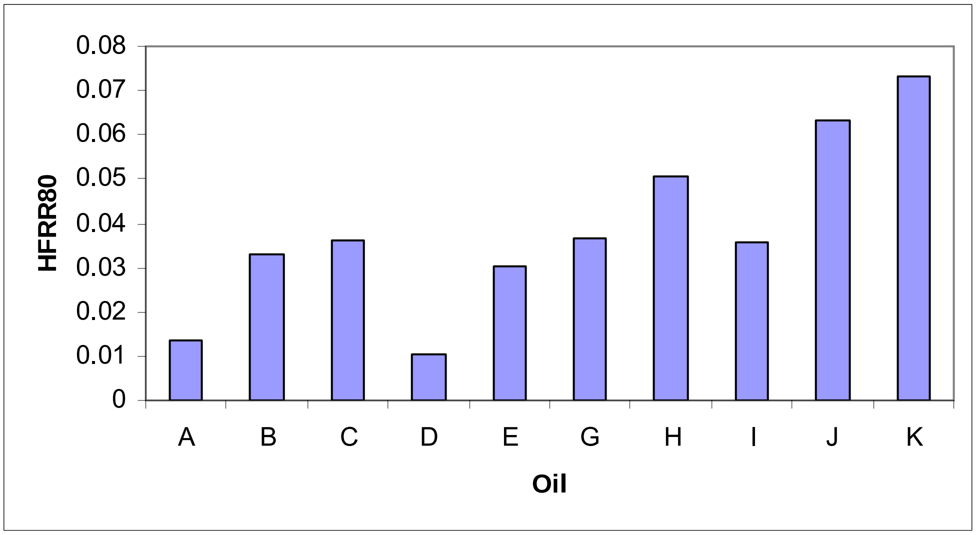

Figure E.34: Estimated Aging Effect on HFRR80 for 0 to 6500 Miles

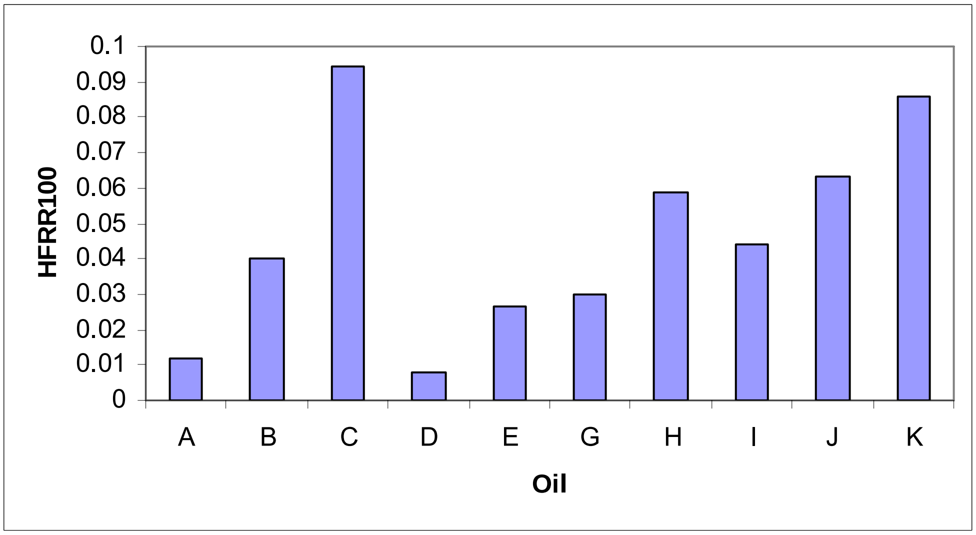

Figure E.35: Estimated Aging Effect on HFRR100 for 0 to 6500 Miles

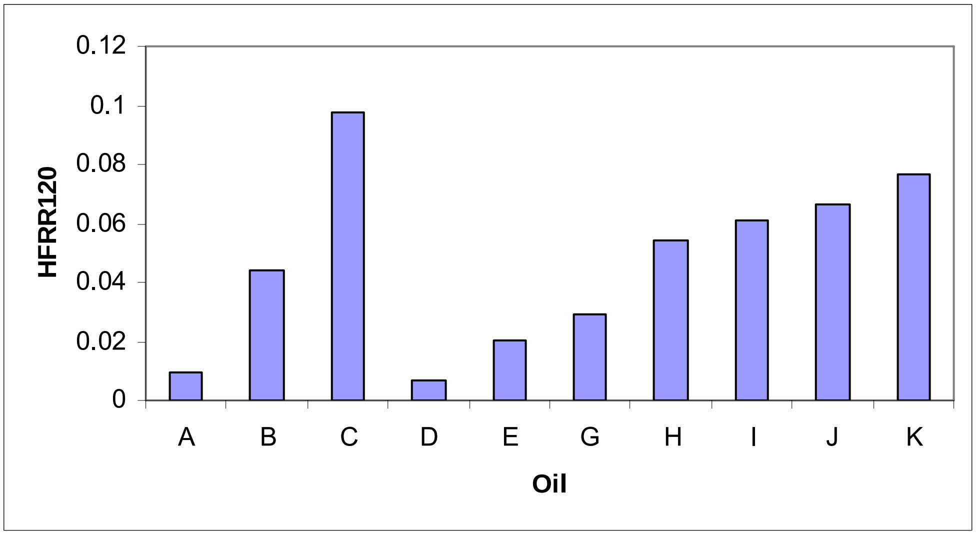

Figure E.36: Estimated Aging Effect on HFRR120 for 0 to 6500 Miles

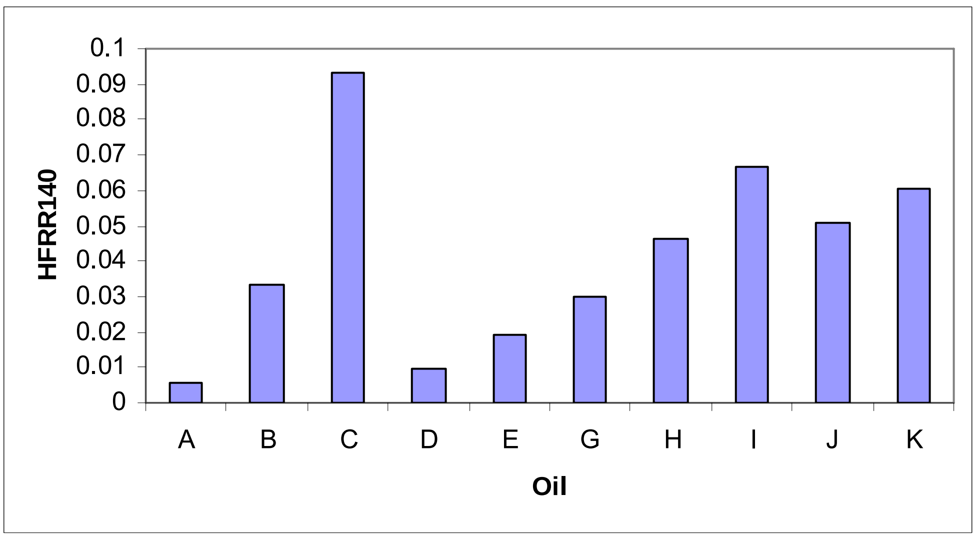

Figure E.37: Estimated Aging Effect on HFRR140 for 0 to 6500 Miles

Appendix F

Special Engine/Stand Hardware

Sequence VID Parts List
June 20, 2008

OHT Part Number Description
OHT6D-100-S1 Seq. VID Initial Stand Setup Kit
Kit Includes the following items:
OHT3H-002-1 BLOCK, FLYWHEEL TORQUE
OHT3H-003-1 TOOL, BALANCER TORQUE
OHT3H-025-1 MOUNT, REAR
OHT3H-026-1 MOUNT, FRONT
OHT6D-009-1 TUBE, TAKE DOWN ASSY, RIGHT, SEQ. VID
OHT6D-010-1 TUBE, TAKE DOWN ASSY, LEFT, SEQ. VID
OHT3H-020-X FLYWHEEL, UNIVERSAL IIIH/VID
3H020-0X/6D020-0X ADAPTER, FLYWHEEL (LAB SPECIFIC)

OHT6D-001-1 PAN, OIL, SEQ. VID
(w/ Gems Sensor and Displacement Block)
OHT6D-003-1 PLATE, ADAPTER, OIL FILTER
OHT6D-004-1 PLATE, BLOCK-OFF, THERMOSTAT
OHT6D-005-1 PLATE, WATER PUMP
OHT6D-013-1 PCV VALVE, DUMMY
OHT6D-011-2 HARNESS, ENGINE, FOR E77 CONTROLLER
OHT6D-012-4 E77 ECU, HFV6 PFI, LY7, REV. 3
OHT3H-011-1 THROTTLE CONTROL, ENGINE DYNO
OHT6D-040-1 METER, MASS AIR FLOW (HFM), SEQ. VID
OHT6D-042-1 INJECTOR FUEL, SEQ. VID
OHT6D-043-1 PLUG, SPARK, SEQ VID.
OHT6D-044-1 SENSOR, CRANKSHAFT POSITION, SEQ. VID
OHT6D-045-1 SENSOR, CAMSHAFT POSITION, SEQ. VID
OHT6D-046-1 SENSOR, KNOCK, SEQ. VID
OHT6D-047-1 SENSOR, PRE-CAT O2, SEQ. VID
OHT6D-048-1 SENSOR, COOLANT TEMP, SEQ. VID
OHT6D-050-1 THROTTLE BODY, DUAL
OHT6D-099-1 LY7, HFV6 ENGINE, SEQ. VID

Appendix G

Sequence VID Engine Assembly Manual

Available at the TMC Website

Appendix H

Sequence VID Procedure

Available at the TMC Website