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A Comparison of Gasoline Direct Injection and Port Fuel Injection Vehicles: Part II – Lubricant Oil Performance and Engine Wear

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The Lubrizol Corporation

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ABSTRACT

Four 1998 Mitsubishi Carismas, two equipped with direct injection (GDI) and two with port fuel injection engines (PFI) were tested in a designed experiment to determine the effect of mileage accumulation cycle, engine type, fuel and lubricant type on engine wear and engine oil performance parameters. Fuel types were represented by an unadditised base fuel meeting EEC year 2000 specifications and the same base fuel plus synthetic deposit control additive packages. Crankcase oils were represented by two types (1) a 5W-30 API SJ/ILSAC GF-2 type engine oil and (2) a 10W-40 API SH/CF ACEA A3/B3-96 engine oil. The program showed that specific selection of oil additive chemistry may reduce formation of intake valve deposits in GDI cars.. In general, G-DI engines produced more soot and more pentane insolubles and were found to be more prone to what appears to be soot induced wear than PFI engines. Again, proper selection of oil additive chemistry provided sufficient engine durability protection in both types of engines.

INTRODUCTION

For the last several decades, direct injection gasoline has been of interest to OEMs due to the potential for higher specific power and lower fuel consumption as compared to conventional fuel delivery systems. Since 1996, direct injection gasoline engine (GDI) technology has been commercially introduced by Mitsubishi (1,2), Toyota (3) and other automakers (4, 5, 6). At the same time, very little technical information has been published on fuel and lubricant performance in GDI engine technology compared to conventional port fuel injected (PFI) technolgy.

The subject of this paper is a vehicle fleet trial undertaken to provide some of this technical information. The objective of this trial was to compare the fuel and lubricant performance requirements of matched pairs of Mitsubishi Carisma PFI and GDI‰ vehicles over cycles emphasizing the severity of lean burn and near stoichiometric (rich) operations. Performance was measured via lubricant performance and wear evaluations. Other parameters such as vehicle emissions (including particulates), fuel economy, acceleration and driveability are described in a companion paper (7).

Initial results related to engine deposits and engine oil performance have been presented earlier this year (8). This paper follows up with subsequent data which gives us a clearer picture of the effect of fuel additive and lubricant on critical deposits and oil performance variables.

PROCEDURES

Four 1998 Mitsubishi Carismas, two equipped with direct injection and two with port fuel injection engines, were tested in 20,100 km intervals to determine the effect of mileage accumulation cycle, engine type, fuel and lubricant on engine deposits and oil performance parameters. Emissions, acceleration and driveability were measured at the beginning and end of each test to provide information on the effect of deposits. As part of a fractional factorial statistical design, two levels each of cycle, fuel and crankcase oil lubricant were tested along with an assessment of car-to-car variation. Descriptions of the Vehicles, Fuel and Crankcase Lubricants are common between this paper and the companion paper. Detailed explanations of the Drive Cycles, Vehicle Preparation and Data Acquisition are summarized here and presented in detail in the companion paper. Conversely, a detailed explanation of the Experimental Design is presented here with a summary in the companion paper. The descriptions of Engine Wear Measurements and Drain Oil Analysis are presented only in this paper, while descriptions of the Deposit Measurements and Performance Tests are presented only in the companion paper.

VEHICLES, FUELS AND CRANKCASE LUBRICANTS

Two 1998 model 1.8L GDI‰ Mitsubishi Carismas and two 1.6L PFI Carismas sourced from Germany were employed in this study. The GDITM engines utilized a dual overhead camshaft configuration while the PFI engines were of a single overhead cam design. With the exception of the engines and mandatory equipment related to the engine option, all vehicles were identically equipped which including automatic transmissions and air conditioning.

A total of four fuels were tested: F1, F2, F3, and F4. An unadditized base fuel meeting European Union year 2000 specifications is denoted F1. This fuel was chosen as being representative of base fuel properties in the European market where these vehicles are currently in use. Inspection data for the base fuel is given in Table 1.

Table 1. Fuel (F1) Inspection Data

Data Density 15°C		kg/m^3	0.7561
Reid Vapor Pressure		bar	0.57
Distillation ASTM D86			
	IBP @	°C	33.8
	10% vol @	°C	54.8
	50% vol @	°C	102.6
	90% vol @	°C	159.3
	95% vol @	°C	175.9
	FBP vol @	°C	195.8
	Recovery	% vol	98.3
Composition ASTM D1319			
	Saturates	% vol	57.8
	Olefins	% vol	9.2
	Aromatics	% vol	33.0
Sulfur ASTM D 2622		% mass	0.0119
Existent Gum		mg/100 mls	2.0
Washed Gum		mg/100 mls	0.6
Oxidation Stability		min	>980
ASTM D 2699 Octane		Research	94.3
		Motor	83.8
Fuel 2 Additive		Polyisobutylene amine 1 + polyether fluidizer 1	
Fuel 3 Additive		Polyetheramine	
Fuel 4 Additive		Polyisobutylene amine 2 + polyether fluidizer 2	

The same base fuel plus deposit control additives are denoted F2, F3 and F4. Fuel F2 was compared to the base fluel F1 in the half-fraction factorial design. The additive in F2 is a polyisobutylene amine dispersant/polyether fluidizer "synthetic" package. The additive in F3 is a polyetheramine and that in F4 is another synthetic package using a second type of PBU-amine combined in a different ratio with a second polyether fluidizer. These latter two were tested in single demonstration runs to see if significant differences in performance between any of the chemistry types would be found. Between them they cover the majority of chemistry and package types in use in the North American and European marketplace. The doses chosen may be characterized as providing top tier intake valve and injector cleanliness in conventional PFI engines.

A total of two lubricants were tested: O1 and O2. A multipurpose 5W-30 API SJ/ILSAC GF-2 type crankcase oil representing formulations predominant in the Japanese market (where these vehicles have first been introduced) is denoted O1. A 10W-40 API SH/CF ACEA A3/B3-96 partial synthetic crankcase lubricant is denoted O2. This lubricant represents the type of oil used in the European market. Both oils contain similar level of antiwear protection (0.09% phosphorous) delivered as a secondary ZDP. Both oils contain non-dispersant olefin copolymers as viscosity modifiers. The chemical profiles of both lubricants are listed in Table 2.

Table 2. Lubricants' Analysis

		Oil O1	**Oil O2**
Treat Level (%)		10.1	14.2
TBN (mg KOH/g)		5.5	9.5
Sulphated Ash (5)		0.67	1.2
Chemical Characteristics (%):			
	Calcium	0.152	0.31
	Phosphorous	0.09	0.09
	Sulphur	0.448	0.61
	Zinc	0.105	0.10
	Nitrogen	0.07	0.09
	Magnesium	0	0

These two oils are compared in the design in combination with both fuels F1 and F2, while F3 and F4 are tested exclusively with lubricant O2.

EXPERIMENTAL DESIGN AND TEST MATRIX

The base matrix of 16 tests employed in this fleet trial is shown in Table 5 and Figure 1. A test is defined as accumulating 20,100 km by repetition of a specified drive cycle on a test track employing a defined fuel and lubricant combination. The goals of the program are to distinguish the effects of factors:

- CYCLE – Rich versus Lean
- ENGINE – G-DI versus PFI
- FUEL – F1 versus F2
- OIL – O1versus O2

Because of the unknowns associated with the variability of the vehicles, particularly the new technology G-DI vehicles, a fifth factor was taken into account:

- VEHICLE – car-to-car variation

Both of the G-DI and PFI vehicles were run in a half-fraction factorial design on the variables CYCLE, VEHICLE and FLUID, where fluid is the combination of F1/O1 or F2/O2 (circled runs in Figure 1). In order to avoid confounding the Cycle x Fluid interaction with vehicle, two design points were tested in both vehicles of each type. Since fuelxoil interaction effects in PFI vehicles are fairly well understood decoupling the fuel and oil effects was not of immediate interest in these cars.

The design was augmented in G-DI cars to a 23-1 design in the factors CYCLE, FUEL and OIL. We chose to not confound vehicle with the interactions among the other factors by using it as a blocking factor, and instead repeated the half-fraction design in both cars (Figure 2a), along with two additional runs. Relatively good repeatability between the two engines and a desire to explore run order and other fuel effects (F3 and F4) prompted design changes and an additional run. The final set of 17 runs is shown in Table 3 and Figure 2b. While the final design is a 23 design minus 1 run (and vehicle is not confounded with any 2- or 3-way interactions), an apparent shift in test severity prompted removal of one of the runs, along with the two tests on F3 and F4 from the formal statistical analysis of drain results.

Table 3. Experimental Matrix

	GDI #1	GDI #2	PFI #1	PFI #2
LEAN Cycle	F1/O1 F2/O1	F2/O2 F1/O2	F1/O1	F2/O2
RICH Cycle	F1/O1 F2/O2 F1/O2 F3/O2	F1/O1 F2/O2 F4/O2	F1/O1 F2/O2	F1/O1 F2/O2

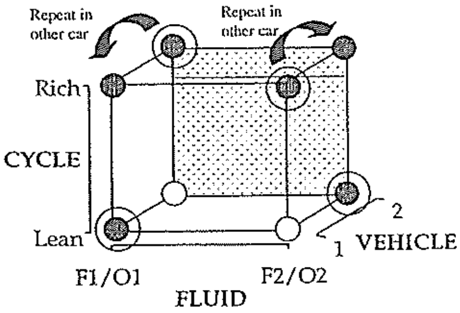
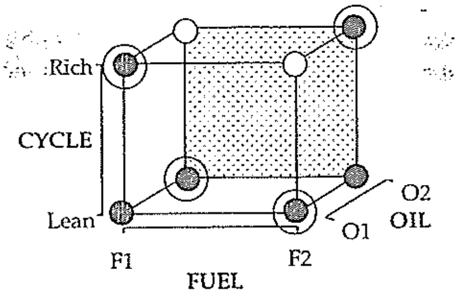
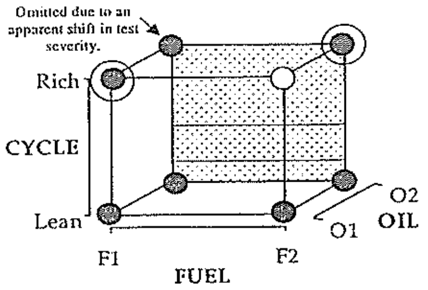


Figure 1. Tests Run on Both G-DI and PFI Cars



(a) Planned Tests Run in G-DI Cars
Circled runs to be run in both vehicles.



(b) Actual Tests Run in G-DI Cars
Circled runs done in both vehicles.

Figure 2.

EXPERIMENTAL MEASUREMENTS

Prior to each test, the top end of the engine was rebuilt and the engine flushed clean. Paired camshafts were used on each vehicle so surface wear measurements could be obtained after each run. During mileage accumulation, 150 ml oil samples were taken at 3000, 6000, 9000, and 12000 miles for lubricant analysis. A triple oil flush was conducted between each run.

OIL DRAIN ANALYSIS – Kinematic viscosities were measured at 40°C and 100°C using the ASTM D445 method.

Levels of wear metals were determined by an Inductively Coupled Plasma (ICP) spectroscopic technique. ASTM D4739 was used to measure the total base number (TBN) of the drains. Level of pentane insolubles was determined by a method equivalent to ASTM D893. Pentane insolubles can include oil-insoluble material produced in the combustion chamber, such as soot, as well as some oil-insoluble resinous matter originating from oil and/or additive degradation.

Oxidation of the used oils was measured using Fourier-Transform Infrared Spectroscopy. An infrared spectrum of the oils was taken and the amount of oxidation was reported as the area of the carbonyl peak (1650-1800 cm-1) divided by the path length of the cell.

The weight percent carbonaceous material, or soot, in the drains was determined using a thermogravimetric analyser (TGA) according to the procedure outlined in ASTM D5967.

SLUDGE & VARNISH EVALUATION – Rocker arm covers and oil pans were evaluated for presence of sludge and varnish deposits. Total of ten steel coupons per car (five per location) were strategically since the vehicle materials were non-ratable. Sludge and varnish were rated at the end of each CYCLE according to procedures described in CRC Manual No 12 and No 14. These procedures offer a standarized approach in assigning numerical ratings to the level of sludge and varnish ormed on engine parts. A merit rating of 10 represents a clean surface.

ENGINE WEAR EVALUATION – Two nontraditional methods were utilized to assess the magnitude, location and overall extent of engine wear: surface profilometry was used to measure wear on the camshaft lobes and cylinder bore wear was evaluated using surface replication.

Due to the limited wear encountered on the camshaft lobes, traditional measurement techniques, such as using a three point contact snap gage, could not provide the necessary resolution. The required resolution was obtained by first removing the cams from the engine and placing them in an environment with controlled temperature and humidity. Following a soak period of no less than 4 hours, the camshafts were measured using a Precision Devices system 2000 surface analyzer. The device has a profiler type tracer head with a motorized column. The instrument provides Dx and Dy measurement capabilities with a resolution of 0.15 microinches. In order to permit rapid vehicle turnaround and minimize delays in testing, several sets of cams were usedto complete the test matrix.

Surface replication techniques have not been widely used in automotive trials. This approach has been applied successfully over the years in field analyses fracture and metallographic surfaces where direct sectioning and laboratory work are not feasible or practical. In this technique, the cylinder bore wear is measured using a thin acetate film. Approximately 2 cm2 of acetate was soaked in acetone and applied to the cylinder bore. As the softened film is applied to the cylinder, a negative replica of the bore is generated. The film then hardens as the acetone evaporates. After several minutes, the film can be carefully removed with an accurate negative image of the bore surface.

Bore replicates were made of the top, middle and bottom of the thrust and the middle of the anti-thrust side of each cylinder (Appendix A). Replicas, "as received", consist of the acetate film mounted on a labeled microscope slide by means of double coated scotch brand tape. For both optical surface profilometry and optical microscopy, mounted replicas were coated with gold to provide a reflective surface. After a 30 second etch cleaning step, replicas were sputter coated using a current of 45mA for approximately 1 minute. The gold coating produced is approximately 100 mm thick. Coated replicas were examined using a LECO/OLYMPUS PMG Inverted Metallurgical Microscope, at a magnification of approximately 50X. Replicas were scanned to obtain a representative assessment of the surface topography, and appropriate photos taken.

RESULTS AND DISCUSSSION

OVERALL EFFECT OF OIL VS. FUEL – While fuel and oil were confounded in all of the PFI runs, the GDI results allow some decoundfounding of fuel and oil effects. Based on these data, it appears that all of the significant Fluid effects are associated with Oil changes, rather than Fuel changes. Appendix B lists all of the responses and their statistical significance.

SLUDGE AND VARNISH ANALYSIS – As expected, both G-DI and PFI technologies showed very little, if any, sludge formation under either Rich or Lean driving cycle, for any oil/fuel combination (Figure 3).

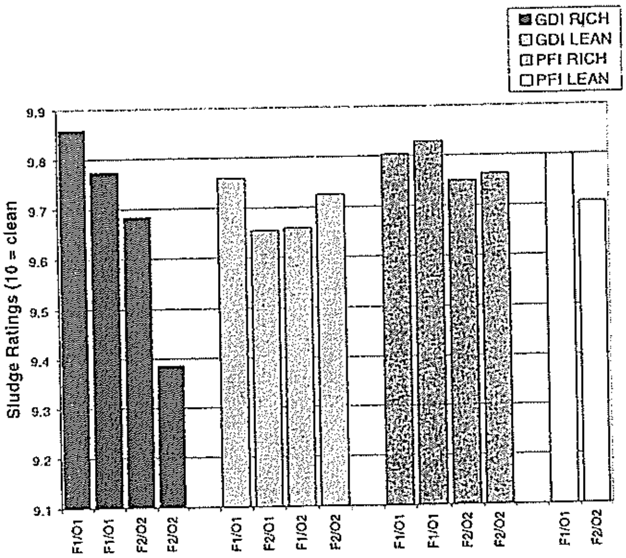


Figure 3. Drain Oil Analysis: Sludge Rating

Sludge ratings varied the most for GDI/RICH CYCLE combination. Ratings spanned values from 9.86 (F1/O1) to 9.38 (F2/O2). This difference in oils' performance in (GDI cars) was correlated with run order. No clear chemistry effects were detected for sludge deposits.

An example, of a typical view of the sludge coupon is shown in Figure 4.

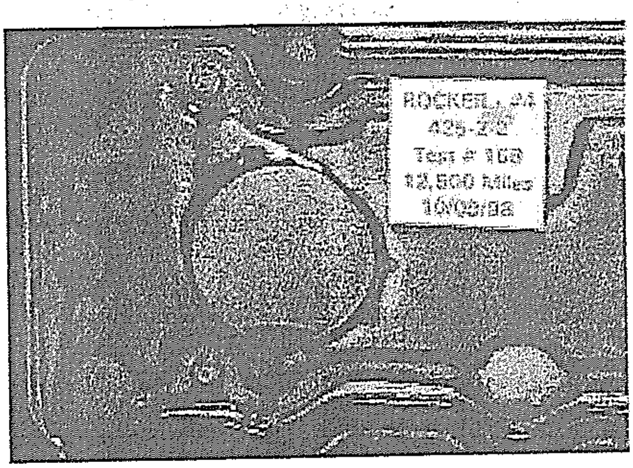


Figure 4. Example of Typical Sludge Performance: GDI, F2/O2, rating = 9.6

More varnish deposits than sludge deposits were observed, especially in PFI engines. Ratings recorded varied from 9.75 (F1/O1) to 9.81 (F2/O2). GDI engines were respectively cleaner than PFI engines (Figure 5). Again, no clear chemistry effects were detected.

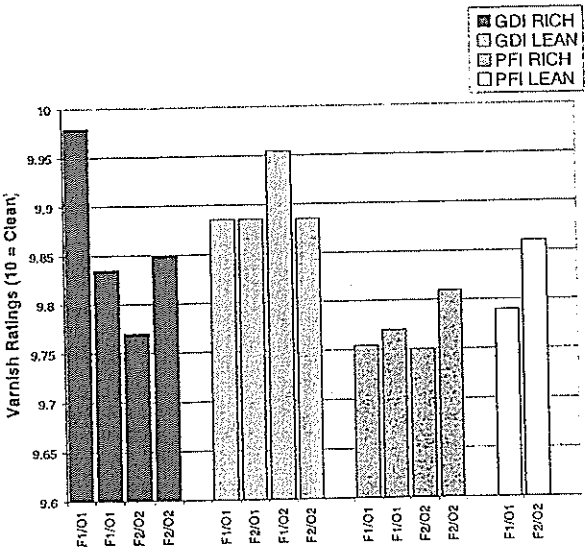


Figure 5. Drain Oil Analysis: Varnish Rating

CONVENTIONAL DRAIN ANALYSIS – Figures 6 and 7 summarize changes in kinematic viscosity @ 40 C and @ 100 C observed during mileage accumulation runs. As expected, both oils have shown some viscosity loss (probably due to shearing phenomena). Only limited oil thickening was observed for Oil 2 during the Rich cycle, for both GDI and PFI technology.

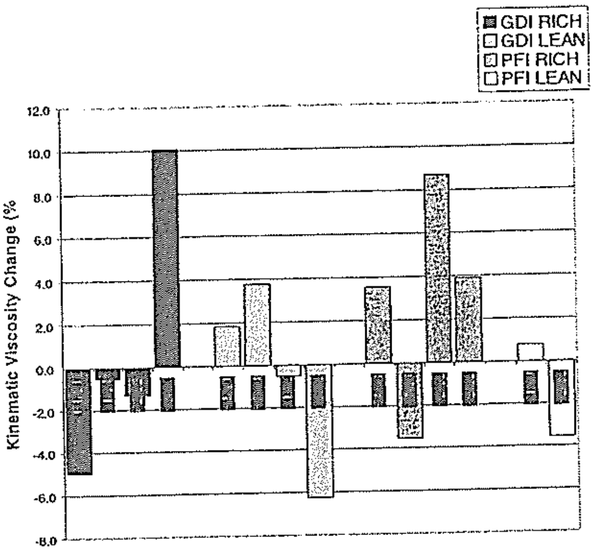


Figure 6. Drain Oil Analysis: % Change in Vis @ 40

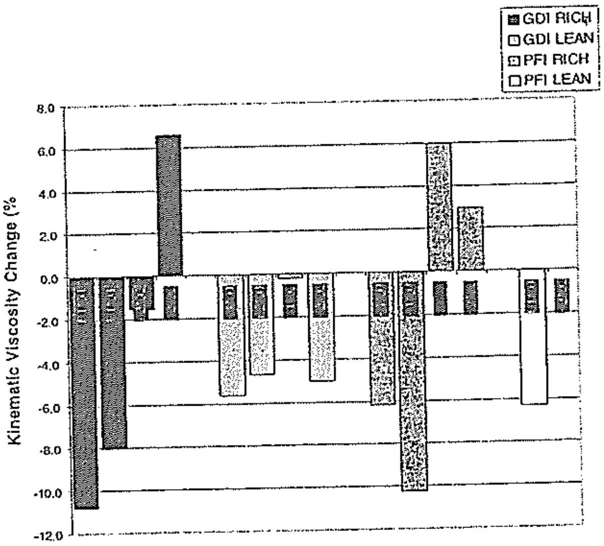


Figure 7. Drain Oil Analysis: % Change in Vis @ 100

In contrast, all fluids showed a significant increase in oxidation (as measured by IR). Specifically, some significant differences were observed between the two engine technologies (Figure 8).

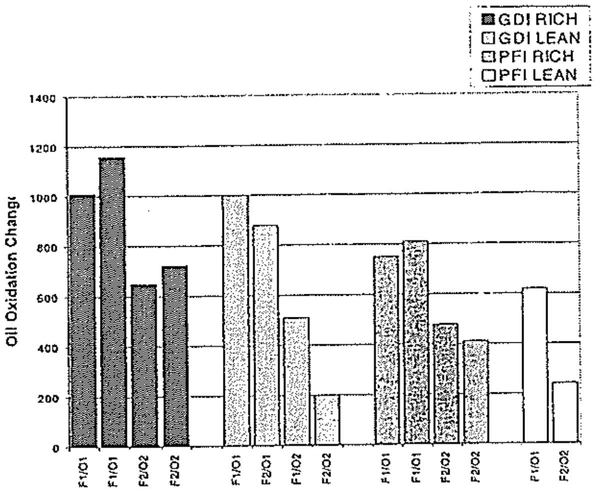


Figure 8. Drain Oil Analysis: Change in C = O

CYCLE had the biggest impact on oil oxidation (higher for the Rich cycle). The GDI vehicles tend to oxidise oils to a higher degree than the PFI cars. In comparison to the viscosity data, the chemistry effects were more consistent, as oxidation was higher in GDI cars using O1 fluid regardless of cycle.

This specific difference in performance between the two oils was not unexpected. As was indicated before, O2 lubricant contains a more robust antioxidant additive package and is formulated with partially synthetic base stock.

One striking phenomenon observed in the drain oil analysis relates to a significant decrease in Total Base Number (TBN) levels as measured by ASTM D4739. In all cases the TBN levels had decreased at least 70% from its original value and in several instances a 100% decrease occurred. Figure 9 summarises percentage TBN change grouped by CYCLE, ENGINE and FLUID. It is apparent that the O2 fluid has superior TBN retention qualities in comparison to fluid O1.

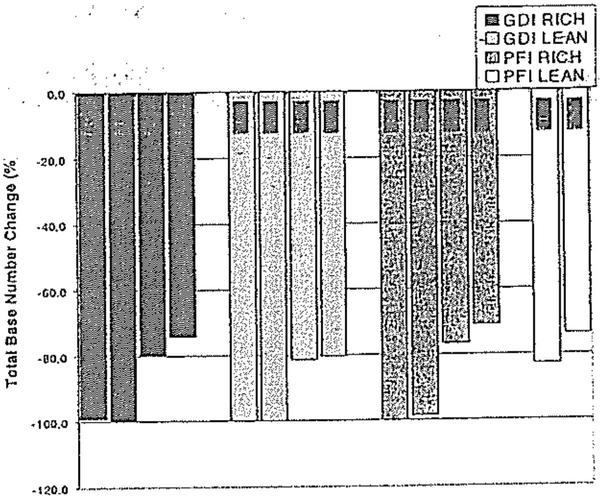


Figure 9. Drain Oil Analysis: % Change in TBN

It is generally known fact that TBN depletion and TAN formation can eventually lead to corrosive wear. In order to check the possibility of this occurrence, an extensive wear metal analysis was carried out. ICP data indicate presence of only iron and aluminium elements. Iron levels ranged from 21 to 153 ppm. Figure 10 summarises iron levels recorded at the end of all tests.

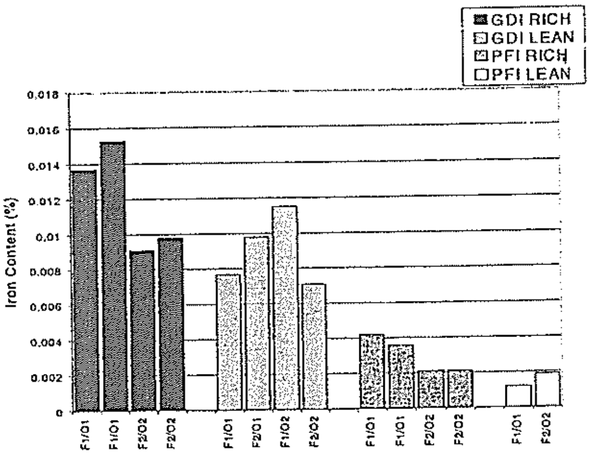
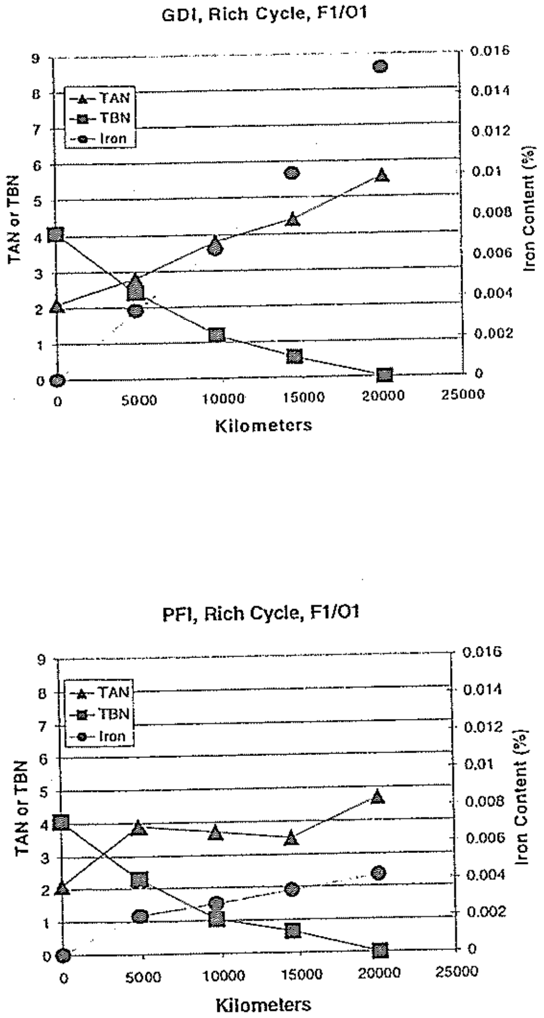


Figure 10. Drain Oil Analysis: Iron at EOT

Clearly, these data suggest that the GDI engines are more prone towards potential wear problems as indicated by higher iron levels present in the oil drains .

In order to assess details of the potential corrosive attack, we plotted TBN, TAN and iron level profiles vs. accumulated milage. Figures 11(a)/(b) and 12 (a)/(b) provide such side by side comparisons.

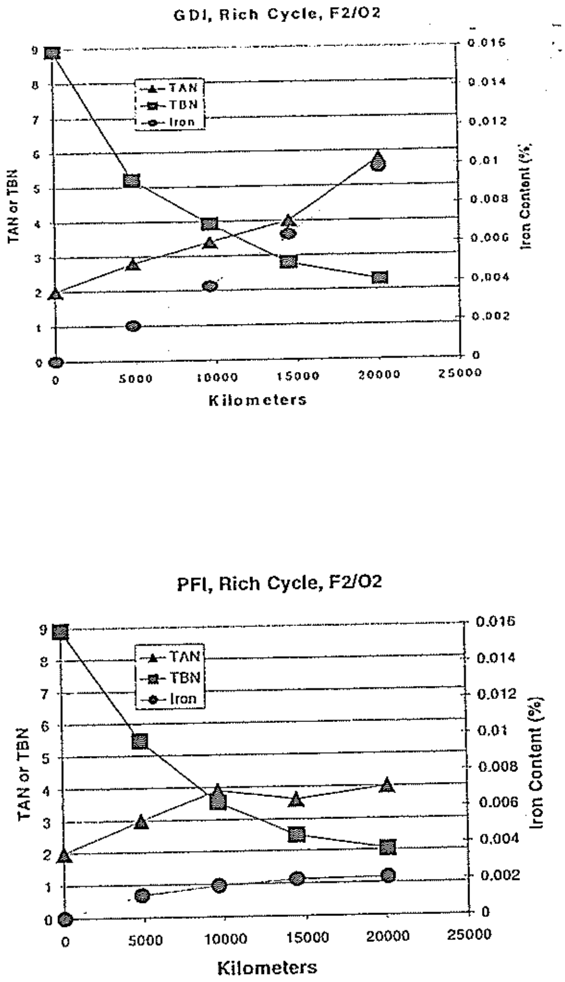

GDI, Rich Cycle, F1/O1

(a)

PFI, Rich Cycle, F1/O1

(b)

Figure 11. (a) & (b). F1/O1 TBN, TAN, Fe Profiles in GDI/ PFI During Rich Cycle Operation


GDI, Rich Cycle, F2/O2

(a)

PFI, Rich Cycle, F2/O2

(b)

Figure 12. (a) & (b). F2/O2 TBN, TAN, Fe Profiles in GDI/ PFI During Lean Cycle Operation

In the GDI vehicle, independent of the fuel/lubricant combination, the iron level climbs fast and reaches a relatively high level (100 – 160 ppm) as observed in Figures 11 (a) and 12 (a). In contrast, the iron level profiles in the PFI vehicles stay relatively flat and at low level throughout the test duration (80 ppm max). Interestingly, residual TBN has only minimal effect on iron level. Based on the drain data we can conclude that Oil 2 delivers better performance in GDI engines.

WEAR PATTERNS ANALYSIS AND DISCUSSION

Although the practice of rotating the cams sets permitted rapid vehicle turnaround, it resulted in the ability to conduct only a semi-quantitative evaluation of camshaft lobe wear. Figures 13 and 14 depict representative profiles.

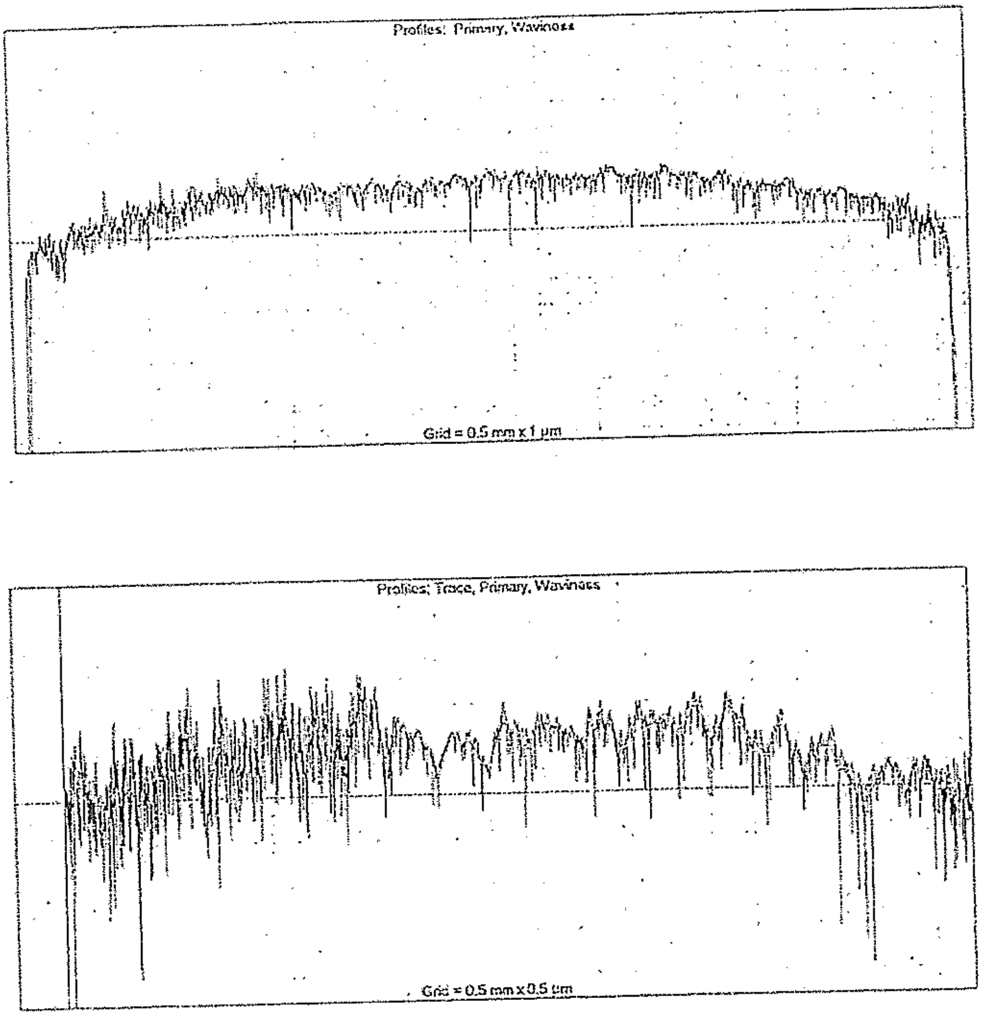


Figure 13. PFI (a) Exhaust Valve Cam Lobe (b) Intake Valve Cam Lobe

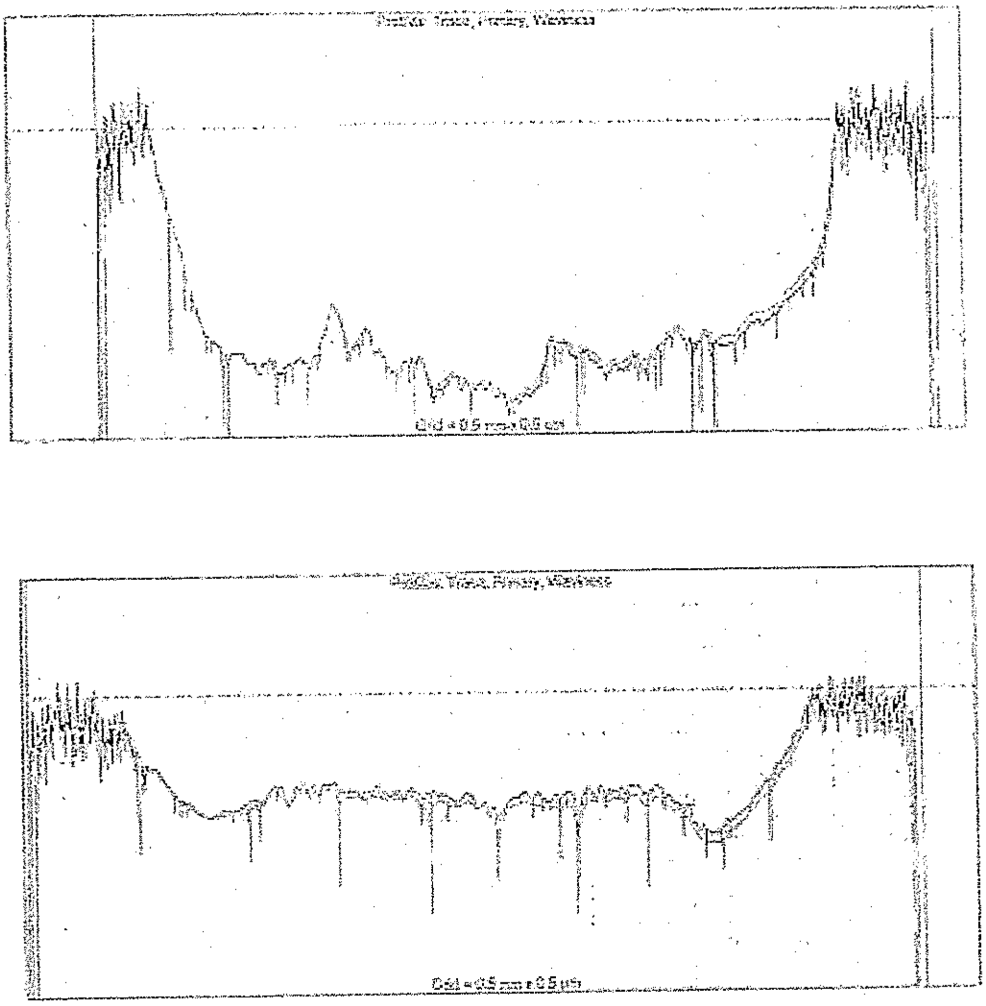


Figure 14. GDI (a) Exhaust Valve Cam Lobe (b) Intake Valve Cam Lobe

However, the following observations were noted:

- In all cases, camshaft lobe wear was minimal as would be expected with a roller follower valve train configuration.

- Generally, the GDI vehicles exhibited greater wear on both the exhaust and intake cams than seen on the PFI vehicles.

- The greatest wear was typically seen on the exhaust cam of the GDI vehicles. However, the magnitude of the wear was small, amounting to no more than 4 um over 100,000 kilometers of operation.

Representative optical micrographs of replicas from the GDI and PFI vehicles are shown in Figures 15 and 16.

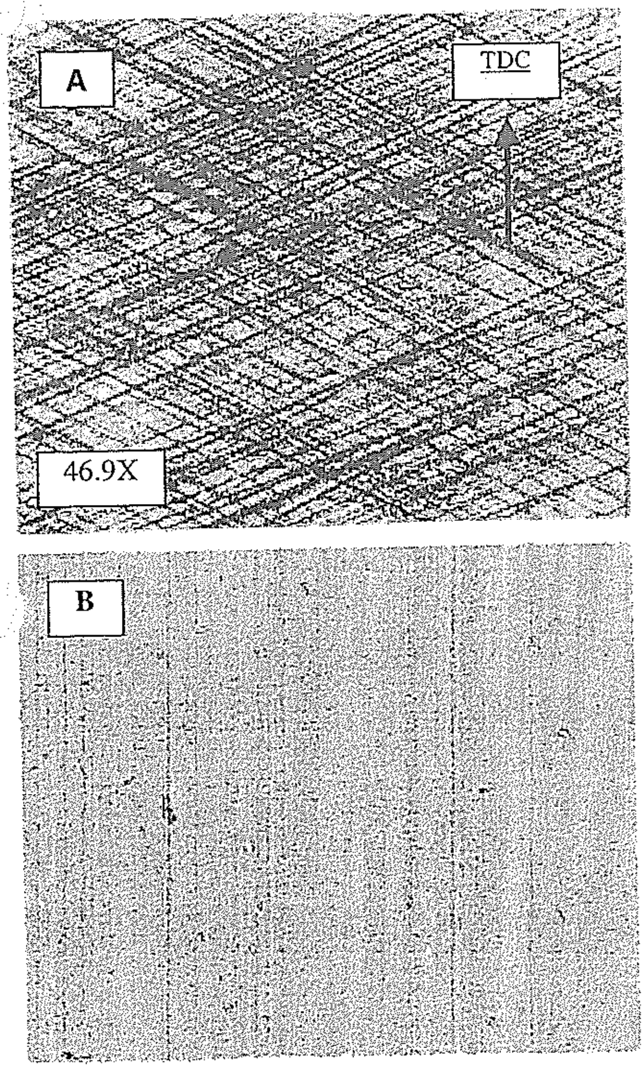


Figure 15. Cylinder Liner Surface Replicas GDI Vehicle
(a) Original (b) 60,000 km

For each vehicle/run, there is a clear difference between the "before" and "after" surface topography. In both cases there is a significant reduction in the cross-honing. In the GDI vehicle there was a complete removal of the cross-honing from the middle region of the cylinder surface, and evidence of abrasive wear (vertically oriented grooves). The abrasive wear is presumed to be a result of sliding contact with the piston rings, under thin-film conditions. In the corresponding area of the PFI liner surface, the wear is less severe, since the cross-honing is still visible (Figure 16).

The observed difference between the two vehicles is consistent with the routine analytical results, which clearly show higher levels of iron in the drain samples from GDI vehicles, as compared to the PFI. It also appears that cylinder wear may be a major contributor to the observed levels.

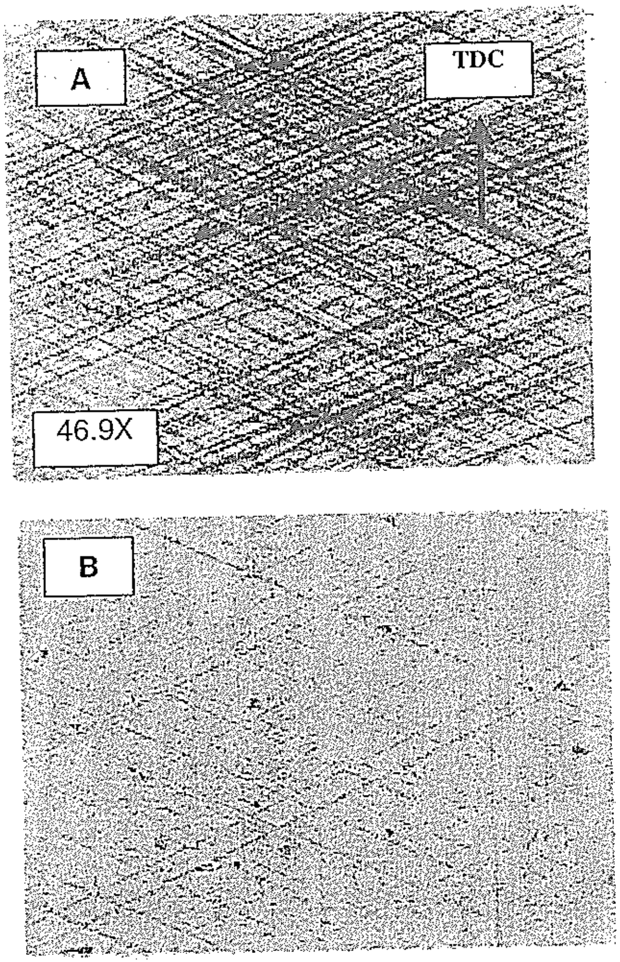


Figure 16. Cylinder Liner Surface Replicas PFI Vehicle
(a) Original (b) 60,000 km

It is our hypothesis that the critical role in the wear phenomena observed in our study is actually more strongly related to the type and the amount of soot present in the oil drains rather than to the corrosive wear associated with TBN/TAN equilibrium.

In order to test our hypothesis, we focused our attention on soot level, and soot particulate size. Figures 17 and 18 show soot formation profiles vs. accumulated mileage.

A linear relationship between the amount of soot and mileage accumulation can be observed. GDI vehicles consistently produce more soot than PFI units. Rich cycle operation also results in greater soot production. Futhermore, soot particle size analysis (Figure 19) indicates that the particles formed in PFI engines are significantly larger than these formed in GDI engines.

Actually, internal data indicate that the PFI particle size matches the size formed during Seq. VE testing.

If we plot the amount of iron vs. soot level for both PFI and GDI engine technologies, we are observing a strong linear relationship (Figure 20). This type of relationship may indicate possible contribution of the gasoline combustion by-products on soot induced wear.

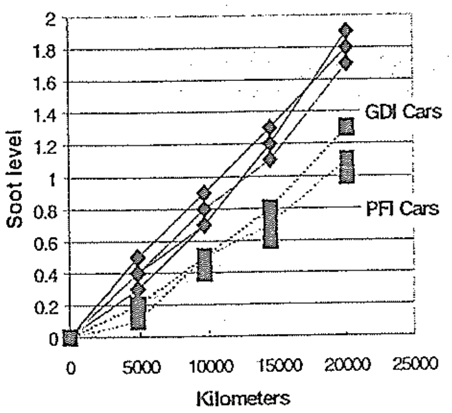


Figure 17. Soot vs. Distance Profile (Rich Cycle)

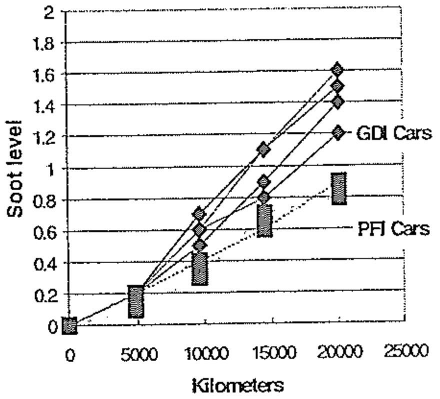


Figure 18. Soot vs. Distance Profile (Lean Cycle)

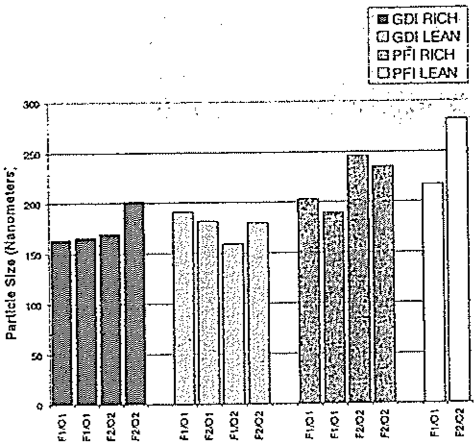


Figure 19. Drain Oil Analysis: Particle Size

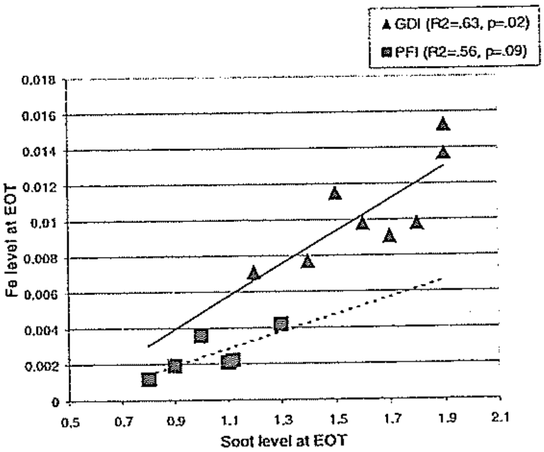


Figure 20. Fe Vs. End of Test Soot Level

CONCLUSIONS

The statistically designed program enables us to make a number of significant conclusions. Appendix B lists all responses and their statistical significance.

In terms of crankcase oil performance:

1. Oil 1 was found to reduce Intake Valve Deposits (7)
2. Oil 2 was found to offer a very good engine protection: TBN retention, oxidation control, sludge/varnish control.
3. Neither oil tested offered both both IVD and engine performance, thus a need for specialized fluid capable to deliver both engine protection and deposit control (see Figure 21) was identified.
4. The GDI engine was more severe in terms of varnish, and soot and iron levels in the drain. GDI camshafts exhibited a higher degree of wear.
5. The Rich cycle was more severe in terms of oxidation and soot formation.
6. Soot-induced wear was proposed as a phenomena responsible for piston bore wear in GDI engines.

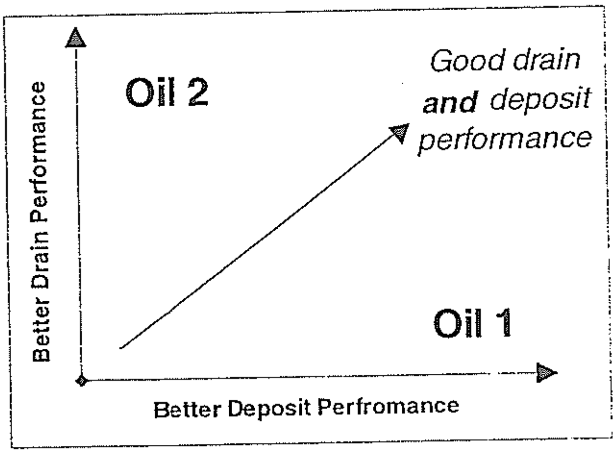


Figure 21. Summary of Oil Performance

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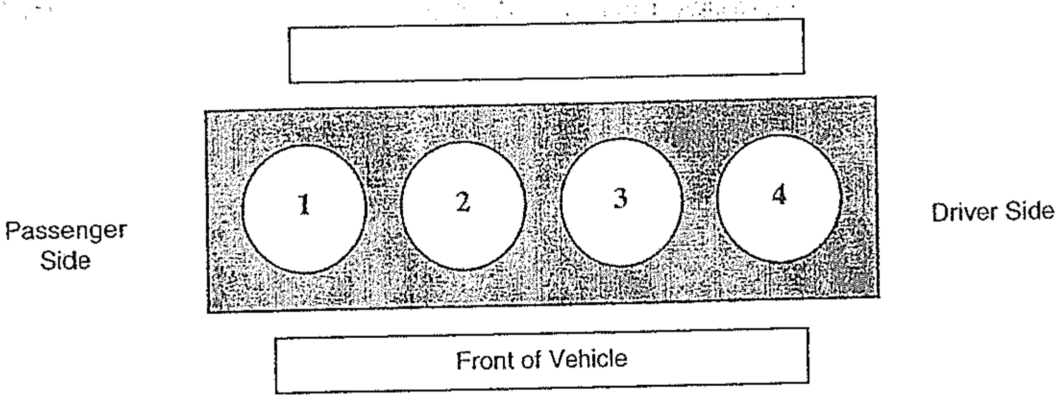
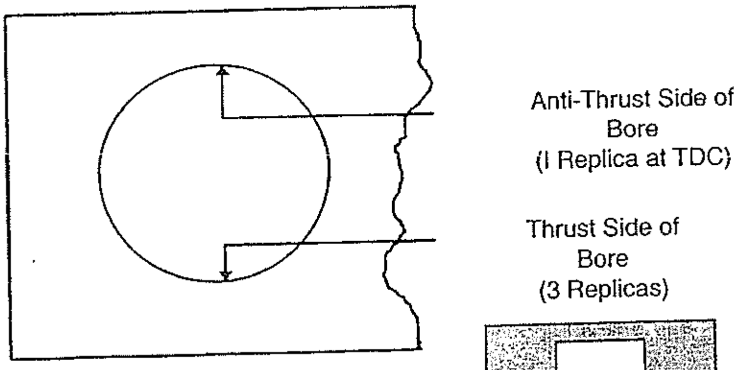
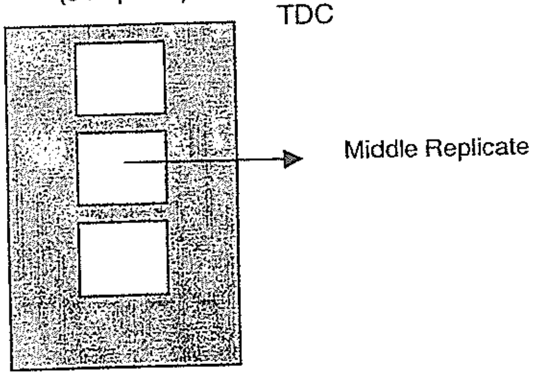
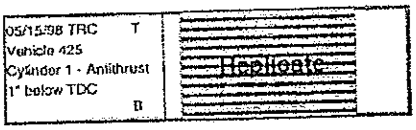
APPENDIX A









Generalized slide with mounted replicate

APPENDIX B

Table B.1: P-values for assessing the significance of the effect of oil, based on 14 total results. Some deconfounding of fuel and oil effects can be done (based on GDI results). Since the performance ranking of the two oils did not depend on engine type, the oil associated with the best performance for both engines is indicated when the difference is significant at the 90% confidence level

Response Significant effects (model fit)	GDI		PFI		Best Oil	Notes
	Rich	Lean	Rich	Lean		
Sludge Oil Engine type Engine type x Oil (R2=45.0, RMSE=.1)	.06		.40		Lowest sludge result was 9.3	An apparent difference in oils in the GDI cars was also correlated with run order, especially in one GDI car (426). No clear chemistry effects could be detected for either sludge or varnish.
Varnish Oil Engine type Engine type x Oil (R2=47.8, RMSE=.06)	.48		.49		Lowest varnish result was 9.7	
% Delta Vis @40 Oil Cycle OilxCycle (R2=53.8, RMSE=4.0)	.04	.12	.04	.12	Both oils were in grade	Oil O2 tended to have less viscosity decrease than O1, but this was evident only at 100C and during the rich cycle. No differences due to engine type.
% Delta Vis @100 Oil Cycle OilxCycle (R2=83.1, RMSE=2.7)	.001	.13	.001	.13		
DC=O Oil Engine type Cycle (R2=89.7, RMSE=105.3)	<.001				O2 (About half the change in O1)	Effect of oil does not depend on engine type or cycle. Engine type and drive cycle were also significant (On average, GDI deltas were about 50% higher than PFI deltas; Rich cycle deltas were 50% higher than Lean cycle deltas).
%DTBN Oil Engine type (R2=87.1, RMSE=4.6)	<.001				O2 (–76% for O2 vs. –97% for O1)	O1 lost all TBN in every run but one. A small difference between engine types was noted.
Fe Engine type 1st run (R2=92.6, RMSE=.001)	.45					Apparent 'Break-in' effect resulted in relatively high iron results on 1st run of each vehicle. The subsequent test results differed only due to engine type with GDI > PFI (GDI levels are about 4 times higher than PFI).

Table B.1: P-values for assessing the significance of the effect of oil, based on 14 total results. Some deconfounding of fuel and oil effects can be done (based on GDI results). Since the performance ranking of the two oils did not depend on engine type, the oil associated with the best performance for both engines is indicated when the difference is significant at the 90% confidence level

Soot Engine type Cycle (R2=91.4, RMSE=.12)	.22					Soot levels were significantly higher during the rich cycle and for GDI vehicles (70% more soot in GDI vehicles on average).
Particle Size Oil Engine type Oil x Engine type R2=84.8, RMSE=16.5)	.87		.004		O2 had larger particles in PFI cars only.	Size was fairly constant across drain intervals with PFI drain particles significantly larger than GDI drain particles. There was no difference among fuels or oils in GDI cars, but O2 had significantly larger particles in the PFI cars (256 vs 205). Recall that O2 is confounded with F2 in the PFI cars.
%DTAN Engine type (R2=36.1, RMSE=51.9)	.97					GDI cars had significantly higher delta TAN than PFI (165% vs 92% on average). However, this may be due to one GDI car with consistently higher deltas and one unusually low result on one of the PFI cars. Cycle and oil did not have a significant effect.
Change in Pentane Insolubles Oil Engine type Cycle Oil x Engine type x Cycle (R2=98.7 RMSE=.06)	.26	.001	.02	<.001	O1 (Insolubles declined or were very small for O1 and increased for O2; this most evident during the lean GDI cycle)	O2 increases were consistently higher, although the magnitude of the increase depends greatly on the engine and cycle.
Al Engine type 1st run (R2=70.8, RMSE =.001)	.45					Apparent 'Break-in' effect especially in PFI cars resulted in high Al levels for 1st run only. Engine type was significant at the p=.11 level, with PFI AL levels twice as high as GDI levels (after adjusting for break-in effect);
Oil Consumption Cycle (R2=35.8, RMSE =.22)	.51					Only drive cycle had a significant impact on oil consumption, with consumption during the Rich cycle about 50% higher.