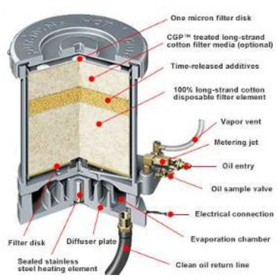
U.S. Department of Energy
Energy Efficiency and Renewable Energy

INL/EXT-06-01355

U.S. Department of Energy
FreedomCAR & Vehicle Technologies Program

Oil Bypass Filter Technology Evaluation Final Report



TECHNICAL REPORT

Larry Zirker
James Francfort
Jordan Fielding

March 2006

Idaho National Laboratory
Operated by Battelle Energy Alliance

INL/EXT-06-01355

U.S. Department of Energy
FreedomCAR & Vehicle Technologies Program

Oil Bypass Filter Technology Evaluation
Final Report

Larry Zirker
James Francfort
Jordan Fielding

March 2006

Idaho National Laboratory
Transportation Technology Department
Idaho Falls, Idaho 83415

Prepared for the
U.S. Department of Energy
Assistant Secretary for Energy Efficiency and Renewable Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ABSTRACT

This Oil Bypass Filter Technology Evaluation final report documents the feasibility of using oil bypass filters on 17 vehicles in the Idaho National Laboratory (INL) fleet during a 3-year test period. Almost 1.3 million test miles were accumulated, with eleven 4-cycle diesel engine buses accumulating 982,548 test miles and six gasoline-engine Chevrolet Tahoes accumulating 303,172 test miles.

Two hundred and forty oil samples, taken at each 12,000-mile bus servicing event and at 3,000 miles for the Tahoes, documented the condition of the engine oils for continued service. Twenty-eight variables were normally tested, including the presence of desired additives and undesired wear metals such as iron and chrome, as well as soot, water, glycol, and fuel.

Depending on the assumptions employed, the INL found that oil bypass filter systems for diesel engine buses have a positive payback between 72,000 and 144,000 miles. For the Tahoes, the positive payback was between 66,000 and 69,000 miles.

SUMMARY

This report is the final of twelve Oil Bypass Filter Technology Evaluation reports that document the feasibility of using oil bypass filter technologies on 17 vehicles in the Idaho National Laboratory (INL) fleet. This evaluation was conducted by INL for the U.S. Department of Energy's FreedomCAR & Vehicle Technologies Program. Almost 1.3 million test miles were accumulated, with the four-cycle diesel engine buses accumulating 982,548 test miles and the gasoline engine Chevrolet Tahoes accumulating 303,172 test miles. PuraDYN oil bypass filter systems were tested onboard eleven of the buses and the six Chevrolet Tahoes for 1,173,552 miles. Refined Global Solutions (RGS) oil bypass filter systems were tested onboard three buses for 112,168 miles. The performance of the puraDYN and RGS oil bypass filter systems are not compared; both were used as test mules to support the goal of reducing petroleum consumption by using oil bypass filter systems in government fleets.

The eight puraDYN systems were installed on the buses during the last 3 months of 2002, and the three RGS systems were installed on the buses during December 2004. The six puraDYN systems were installed on the Tahoes during December 2003. All testing was completed in November 2005. The bypass filters are still being used on the buses, but not the Tahoes.

The buses had regularly scheduled 12,000-mile servicing events, at which the two full-flow filters and one bypass filter on each bus was changed, and three oil analysis samples were taken. One oil sample each was sent to two oil analysis laboratories and the third sample was saved as the archive sample. The two oil analysis reports (one from each laboratory) presented the testing results for 28 variables, including the presence of desired additives and undesired wear metals such as iron and chrome, as well as soot, water, glycol, and fuel.

A total of 15 oil changes on the INL buses occurred during the 3-year evaluation. Seven oil changes were caused by mechanical or human problems: dipstick fitting failure, fuel dilution, mechanic error, injector failure, or intentional engine oil flushing. Eight oil changes were required due to degraded oil quality. Low Total Base Numbers (TBN) alone, or in conjunction with high oxidation/nitration levels, necessitated seven of the eight oil changes. One oil change was required due to high oxidation/nitration levels alone. Seventy-two bus engine oil servicing events occurred during the evaluation, and with eight oil changes required because of degraded oil qualities, 64 oil changes were avoided by using the oil bypass filter systems. The 64 avoided oil changes means 2,164 quarts (541 gallons) of new oil was not consumed nor generated as waste oil. This equates to an 89% reduction in oil changes.

The Tahoes were tested in several test periods. During the first period, the six Tahoes using bypass oil filters achieved a 75% reduction in oil changes and oil use from avoided oil changes. During a middle testing period, various problems, some caused by operations in subzero temperatures and some from human errors, resulted in poor oil-use-avoidance rates. However, during the third testing period, the Tahoes had an 86% reduction in oil changes and oil-change-oil-use when a premium grade of oil was used during the third testing period.

Depending on the assumptions employed, INL found that oil bypass filter systems for diesel engine equipped buses have a positive payback between 72,000 and 144,000 miles. The positive payback period for the gasoline engine Tahoes is between 66,000 and 69,000 miles.

For a complete history of the oil bypass evaluation, see the previous 11 Quarterly Reports and the Test Plan at: http://avt.inl.gov/obp.shtml.

ACKNOWLEDGMENTS

This project was supported by the staff of the Idaho National Laboratory Fleet Operations group. The primary fleet personnel included John Kay, fleet operations point of contact; Aaron Taylor and Alan Palmer, service mechanics; Steve Payne and George Ramirez, installation mechanics; Jim Neff, maintenance scheduling; Aaron Baxter, Tony Rushin, and John Anderson, parts room; and Brett Hobbs, fleet operations manager. The Tahoe vehicle coordinator was Neil Georgeson. The oil analysis was provided by National Tribology Services (NTS) Inc. of Minden, Nevada; CTC Laboratory of Phoenix, Arizona; and ANA Laboratory of Bellmawr, New Jersey. A special thanks to Mike Beateag and Chuck Goudreau of NTS and to Stan Letz of CTC for their constant source of information and assistance with the project.

CONTENTS

FIGURES

TABLES

Oil Bypass Filter Technology Evaluation
Final Report

INTRODUCTION AND BACKGROUND

The oil bypass filter evaluation, performed for the U.S. Department of Energy’s (DOE) FreedomCAR and Vehicle Technologies Program, used 17 vehicles and the maintenance infrastructure at the Idaho National Laboratory (INL) to evaluate oil bypass filtration systems in a DOE fleet situation. The 11 diesel engine buses (from the INL fleet of 99 buses) and the 6 INL Chevrolet Tahoes were selected as test vehicles for this evaluation. The buses travel established routes, carrying workers during their morning and evening trips to and from the INL test site (over 100 miles per round trip). The Tahoes are used to provide security service transportation within the 900-square-mile INL site, or between the INL site and INL facilities in Idaho Falls, Idaho, a distance of 50 miles each way.

This Oil Bypass Filter Technology Evaluation report covers a 38-month evaluation period between October 2002 and November 2005. PuraDYN oil bypass filter systems (Figure 1) were tested on eight (four-cycle) diesel buses and six Chevrolet Tahoes (eight-cylinder gasoline engines), and Refined Global Solutions (RGS) oil bypass filter systems (Figure 2) were tested on three (four-cycle) diesel buses. The puraDYN filter systems were used for 38 months while the RGS filters were in service the last 11 months of the evaluation.

Oil bypass filter vendor data and industry literature suggest that bypass filters extend engine oil life by cleaning solid contaminants as small as one micron out of the engine oil as well as removing harmful liquid contaminants (water, glycol and fuel) from the engine oil. Bypass filters from puraDYN and RGS were used to evaluate the feasibility of reducing engine oil use and minimizing waste oil generation at INL.

Details of the 17 test vehicles include:

- Six buses with Series 50 Detroit diesel engines equipped with three RGS and three puraDYN filters.
- Four buses with Series 60 Detroit diesel engines and six Tahoes with eight-cylinder gasoline engines equipped with puraDYN filters.
- One bus with a Model C10 Caterpillar engine equipped with a puraDYN filter.

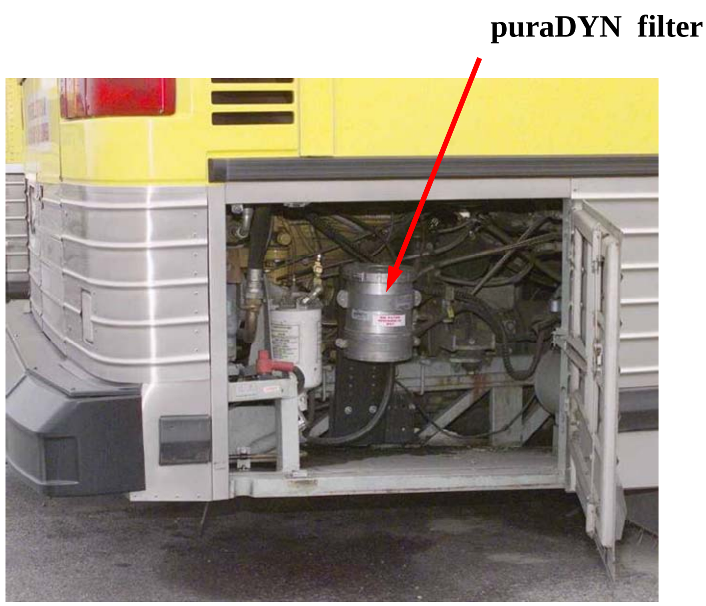


Figure 1. View of a puraDYN oil bypass filter in an INL bus. The single canister unit contains both the oil bypass filter and liquid heating chamber.

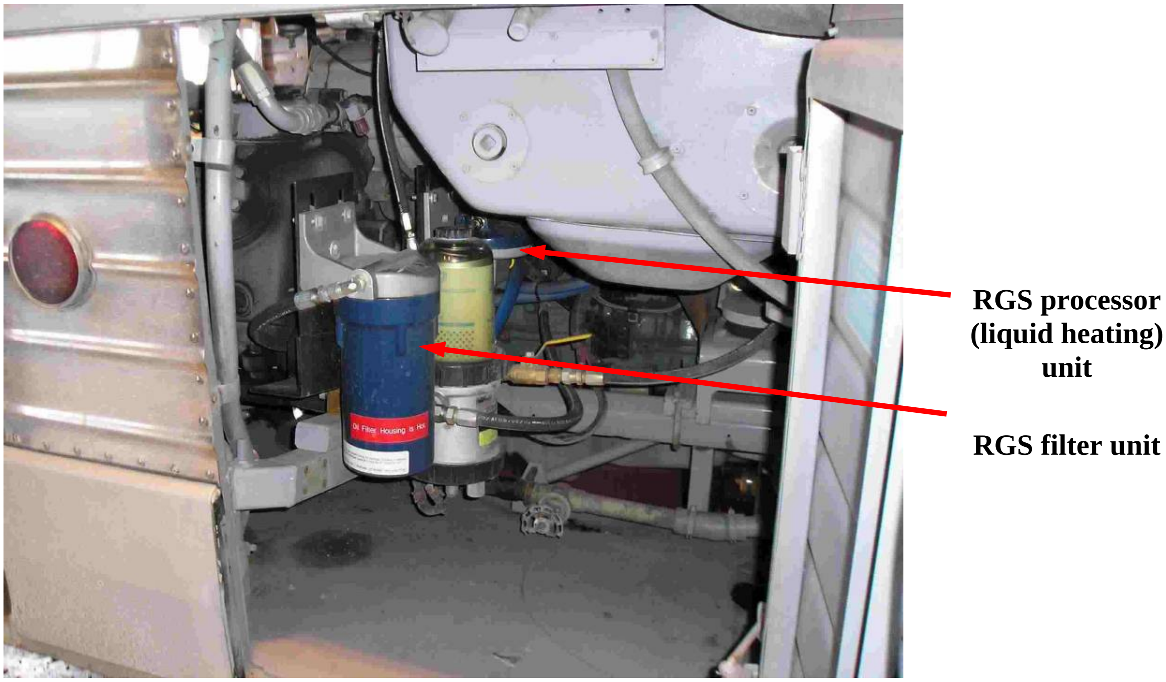


Figure 2. View of an RGS oil bypass system with separate filter and liquid heating units in an INL bus.

Table 1 lists all prior quarterly reports and the major topics presented in them.

Table 1. Major topics of previous quarterly reports, all of which are on line at http://avt.inel.gov/obp.

Reporting Quarter	Report Number	Major Topics
Oct 2–Dec 2 2002	INEEL/EXT-03-00129	• Background on fleet operations, vehicles, filters, and oil selection • Performance evaluation status • Economic analysis • Photographs of installed systems • Bypass Filtration System Evaluation Test Plan
Jan 3–Mar 3 2003	INEEL/EXT-03-00620	• Background on reports • Bus mileage and performance status • Revised filter replacement schedule • Oil-analysis sampling • Light-duty vehicle test status
Apr 3–Jun 3 2003	INEEL/EXT-03-00974	• Background on reports • Bus mileage and performance status • Preliminary trends in oil analysis reports • Revised economic analysis • Ancillary data • Light-duty vehicle test status

Reporting Quarter	Report Number	Major Topics
Jul 3–Sep 3 2003	INEEL/EXT-03-01314	• Background on prior quarterly reports • Bus mileage and performance status • Used engine-oil disposal costs • Unscheduled oil change • Light-duty vehicle test status
Oct 3–Dec 3 2003	INEEL/EXT-04-01618	• Bus mileage and performance status • Bus oil analysis testing and reporting • Light-duty vehicle filter installations • Light-duty vehicle filter installations lessons learned • Light-duty vehicle filter evaluation status
Jan 4–Mar 4 2004	INEEL/EXT-04-02004	• Bus mileage and performance status • Bus oil analysis testing and reporting • Bus engine oil particulate count analysis • Light-duty vehicle mileage and performance status • Light-duty vehicle filter evaluation lessons learned
Apr 4–Jun 2004	INEEL/EXT-04-02194	• Bus mileage and performance status • Bus oil analysis testing and reporting • Lessons learned from the evaluation of heavy-vehicle filters • Light-vehicle mileage and performance status • Lessons learned from the evaluation of light-vehicle filters
Aug–Sept 2004	INEEL/EXT-04-02486	• Bus mileage and performance status • Bus oil analysis testing and reporting • Oil use • Lessons learned on the heavy vehicle • Upcoming INEEL tests • Oil bypass filter system manufactures • Light-vehicle mileage and performance status • Lessons learned from the evaluation of light-vehicle vehicles

Reporting Quarter	Report Number	Major Topics
Oct—Dec 2004	INL/EXT-05-00040	• Status of bus mileage and performance • Analysis and reporting of bus engine oil • Diesel engine idling wear-rate evaluation test • Refined Global Solutions Filter installation • Status of light-duty vehicle mileage and performance
Jan—March 2005	INL/EXT-05-00381	• Status of bus mileage and performance • Analysis and reporting of bus engine oil conditions • Diesel engine idling wear-rate evaluation test • Status of light-duty vehicle mileage and performance. • Lessons learned
April-June 2005	INL/EXT-05-00651	• Status of bus mileage and performance • Analysis and reporting of bus engine oil conditions • Oil saving and quality • Diesel engine idling wear-rate evaluation test results • Status of light-duty vehicle testing • 1,000,000 mile press event.

This final report covers the following topics:

- Bypass filter technology
- Status of bus mileage and performance
- Oil saving
- Analysis and trends of bus engine oil
- Lessons learned from the bus and Tahoe evaluations
- Cost of oil
- Cost of filter systems
- Cost of filter systems installations
- Cost of waste oil disposal
- Cost comparison and oil use savings
- Bypass system payback periods
- Used engine oil disposal costs
- Summary

- Conclusions.

Bypass Filter Technology

The standard oil filters on diesel or gasoline engines are called full flow oil filters because they filter the full oil flow out of the oil pump. The full flow filters trap particles down to the 40 to 60 micron-sized range. The diesel engine oil pumps pump about 35 gallons per minute or 2,100 gallons per hour. If these full flow filters were denser to trap finer particles, they would restrict the flow too much. Size limitations of the full flow filters do not allow them to be large enough to allow higher oil flow rates. A bypass oil filter system:

- Features aftermarket installation
- Is installed as part of the oil supply system but it bypasses the full flow filter
- Filters a partial flow of oil (6 to 8 gallons per hour) in a dense or specialty filter
- Cleans solid contaminants as small as 1 micron
- Does not replace the conventional full flow oil filter system but works in conjunction with it
- Does not negatively affect the engine's oil flow or pressure.

There are roughly a dozen bypass filter systems available from industry. Although they are similar in some aspects, many have unique features such as additive packages and heating chambers. The premise of the bypass filtration industry is that by super-cleaning the solid contaminates out of the oil, the oil stays cleaner, retains it lubricating capability, keeps its acid reducing capacity longer, protects engines (longer engine life), and extends oil drain intervals. Byproducts of longer oil drain intervals include:

- Reduction in foreign oil dependency
- Conservation of new oil use
- Reduction of waste oil generation
- Enhanced return of investment.

BUS TESTING

Status of Bus Mileage and Oil Performance

Before the oil bypass filter evaluation began, the engine oil used by the INL fleet maintenance included 20% recycled products. One of the nuances of the test was to use a premium grade of oil that was in common use by commercial fleets and to reduce any variables due to using recycled oil. The oil selected for the oil bypass evaluation was Shell Rotello-T, 15W-40 oil. The fleet maintenance personnel initially selected this oil, but its widespread use was later confirmed by telephoning six southeast Idaho trucking companies of which four used Shell Rotello-T oil.

The 11 diesel-powered buses traveled 982,548 miles during this evaluation. Figure 3 shows the quarterly and cumulative evaluation test miles for the buses. Figure 4 shows the total evaluation test miles by bus per test quarter. Figure 5 shows the total miles accumulated by bus, the miles achieved per oil change by each test bus, and the number of oil changes each bus would have experienced without the use of oil bypass systems.

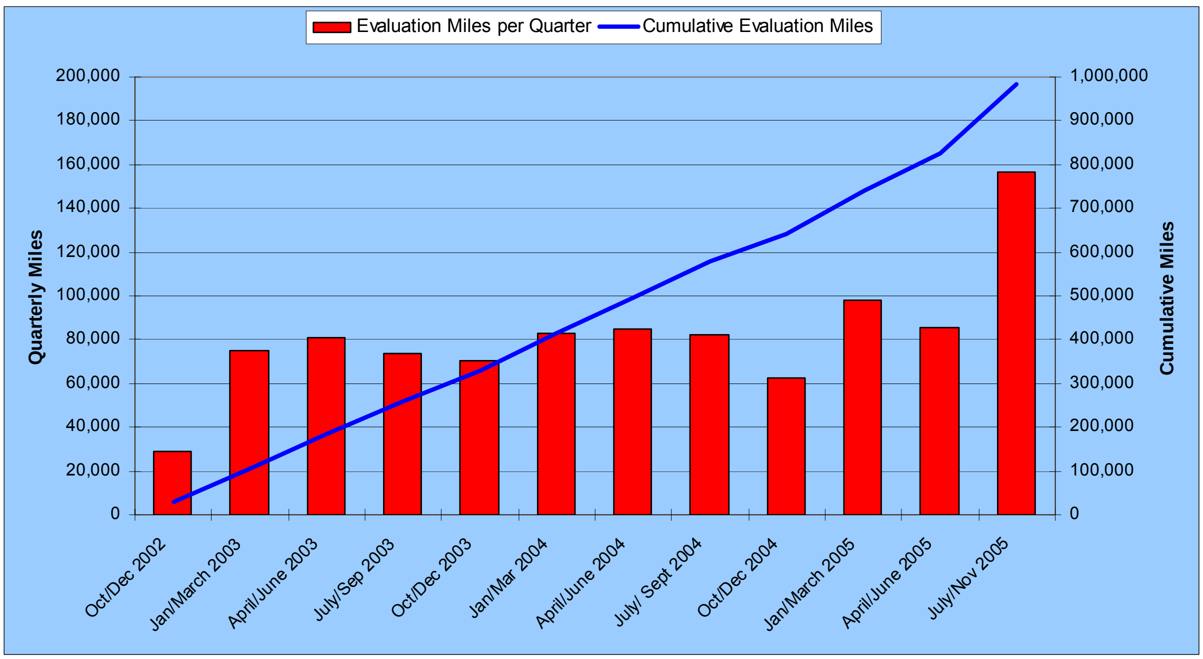


Figure 3. Quarterly and cumulative miles traveled by the test buses.

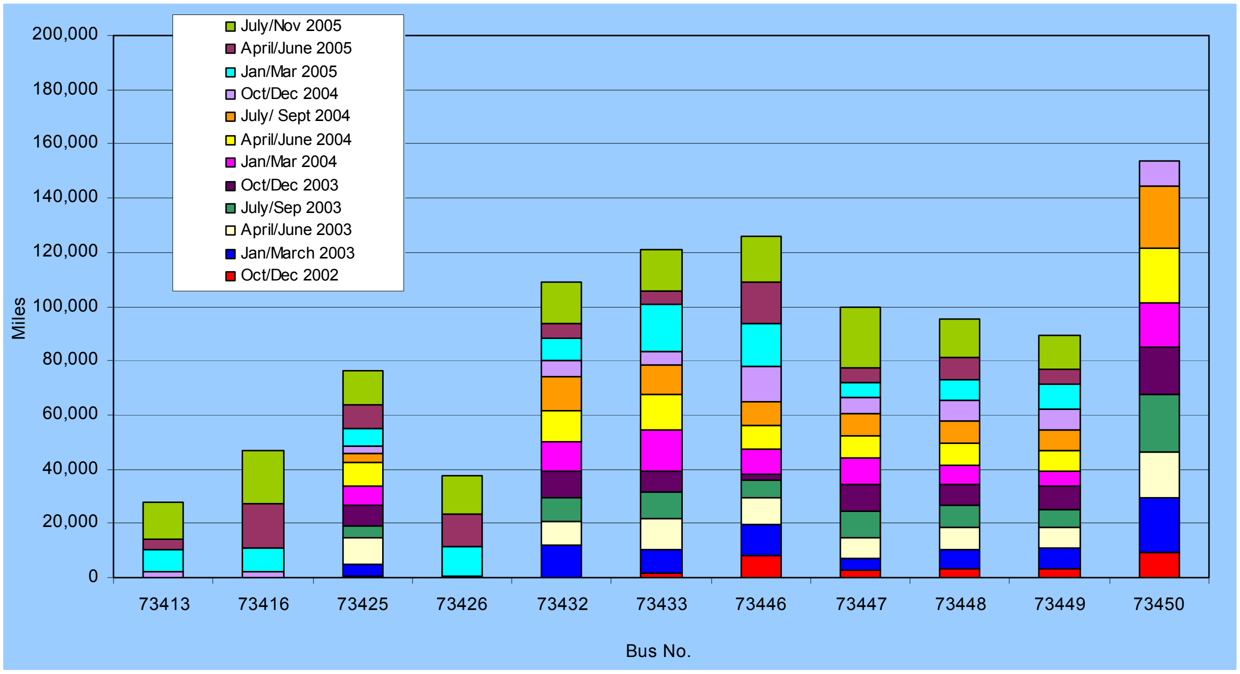


Figure 4. Total evaluation miles by bus and per quarter.

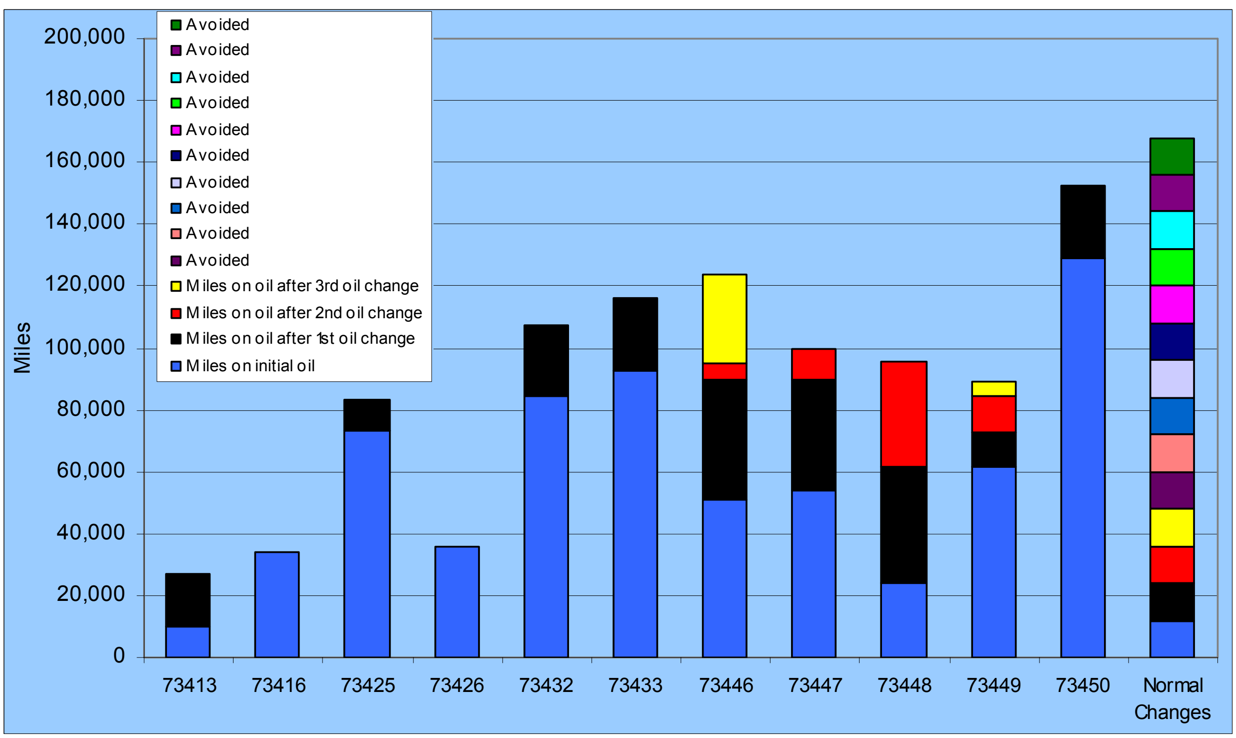


Figure 5. Test miles per oil change by individual bus. The "Normal Changes" bar shows the number of oil changes that would have occurred if the engine oils were changed every 12,000 miles.

Figure 5 does not show whether the 15 oil changes were due to poor oil quality or necessitated by mechanical problems not part of the oil bypass evaluation. Buses 73416 and 73426 never did have an oil change during the test, but the other nine buses did have at least one oil change. Of the first nine oil changes (one per bus), four were the result of mechanical problems not due to poor oil quality issues. The two earliest oil changes, as shown in Figure 5, were early in the evaluation for bus 73413 due to a dipstick fitting failure at 10,250 miles, and for bus 73448 because of an inadvertent oil change by a mechanic at 24,258 miles (the transmission fluid was supposed to be changed). Each engine can be unique in its ability to extend the oil drain intervals. Extended oil drain intervals are also directly related to other intangibles such as operating environment, driver habits, engine age, oil usage, and mechanical problems. The total miles traveled by all the buses up to the first oil changes were 651,143 miles (considering all oil changes due to either mechanical problems or poor oil quality). Dividing 651,143 miles by 11 (the number of test buses) would be 59,195 miles per bus. This average is close to what three buses (buses 73446, 73447, and 73449) actually achieved. Two other buses had fewer miles, but these two buses (73416 and 73426) had not yet had an oil change when the evaluation ended. Four more buses (73425, 73432, 73433, and 73450) had much more miles on their first oil change—between 70,000 and 130,000 miles. Table 2 shows the complete history of oil changes and mileage accrued on the oil.

Table 2. History of oil changes, miles on oil, and the reasons for the oil change.

Bus	1st change date & miles on oil	Reason	2nd change date & miles on oil	Reason	3rd oil change date & miles on oil	Reason	Total test miles
73413	4/13/05 10,250	Dipstick fitting failure					27,856
73416	Not changed						46,796
73425	8/16/2005 73,351	Low TBN					76,487
73426	Not changed						37,516
73432	2/22/2005 84,601	Idling Test					108,907
73433	2/22/2005 92,335	Idling Test					121,125
73446	6/2/2004 51,233	Low TBN	3/22/2005 38,690	Low TBN, high nitration	4/20/2005 5,022	Injector failure	125,870
73447	8/3/2004 54,201	Low TBN	9/21/2005 35,336	High oxidation, high nitration			99,928
73448	9/16/2003 24,258	Inadvertently changed by mechanic	11/17/2004 37,582	Low TBN, high oxidation			95,477
73449	12/20/2004 61,312	Low TBN, high oxidation and nitration	5/17/2005 11,640	Inadvertently changed by mechanic	10/3/2005 11,594	fuel dilution	89,158
73450	8/3/2004 129,140	Low TBN					153,428
Total Miles							982,548

Oil Changes Avoided and Oil Savings

Dividing the 982,548 total bus test miles by 12,000 miles (the "normal" INL bus oil change service interval) suggests that there would have been almost 82 service intervals, but in actuality the buses had 72 service intervals. The buses are typically called into service each time they reach 12,000 miles. The service "tickler" program used by the maintenance personnel is based on the mileage that is recorded by the bus drivers when the buses are fueled. Sometimes the tracking system is less functional, and one bus went as far as 18,987 miles between servicing events. The four other longest intervals were 18,739 miles, 16,835 miles, 16,415 miles, and 15,339 miles. These types of extended service intervals account for the difference between the actual service events (72) and the calculated events (82).

There were eight oil changes because of degraded oil quality and seven oil changes because of mechanical or human problems. The eight oil changes due to degraded oil quality were primarily because of degraded TBN (total base number). The mechanical problems included injector failure and fuel dilution. Once, the oil was inadvertently changed by human error and it was also changed in two buses in preparation for an engine idling test (see: *Diesel Engine Idling Test.* INL/EXT-05-00888 at: http://avt.inl.gov/bus_idle.shtml). Table 2 shows the complete history of the bus oil changes.

Because there were 15 oil changes, 8 from degraded quality and 7 from mechanical or human reasons, there are some assumptions used to calculate the actual oil saved by using bypass filters for this evaluation. For this calculation, none of the mechanical or human problem oil changes were considered. Table 3 shows the calculated oil volume of 541 gallons saved during this evaluation.

Table 3. Oil savings.

Bus Number	Actual Oil Changes Avoided [a]	Quarts oil per change	Quarts of Oil Avoided	Gallons of Oil Avoided
73413	1	28	28	7
73416	3	28	84	21
73425	4	28	112	28
73426	3	28	84	21
73432	8	28	224	56
73433	9	28	252	63
73446	8	40	320	80
73447	5	40	200	50
73448	6	40	240	60
73449	6	40	240	60
73450	10	38	380	95
			Total Gallons	541

a. A calculated value would be to take the total test miles and divide by 12,000 miles, but the actual value would be to count the number of service events and subtract 1 (one) for any change due to oil quality to get the actual oil changes avoided.

When extended oil drain intervals are discussed, practitioners often attempt to increase the service interval mileage, such as going from 12,000 miles to 15,000 miles. The INL researchers in this evaluation did not extend (increase the interval mileage) oil change intervals by a fixed amount, but instead repeatedly avoided (or skipped) the bus service intervals. To have changed the service interval at INL would have caused a major revision or renovation to the INL bus maintenance program. The INL buses are on a regular 12,000-mile service schedule. Each bus gets a regular service inspection, and some components are serviced every 12,000 miles while others are serviced every 24,000, 48,000, or 96,000 miles. Therefore for this evaluation, increasing the interval mileage was never considered.

Another way to measure the success of bypass oil filtration is to look at the number of oil changes avoided and calculate the percentage of oil saved. In calculating the percentage of oil saved, the mechanical oil changes were not used, but the number of avoided oil changes was divided by the total service intervals. In the case of the INL buses used in this evaluation, there was an 89% reduction in oil-change oil use and a concurrent 89% avoidance of waste oil generation. Table 4 shows the number of serving intervals, oil changes, and avoided oil changes.

Table 4. Avoided oil changes.

Bus Number	Test Miles	Actual Service Intervals	Total Oil Changes	Changes for Oil Quality	Changes for Mechanical/Human Reasons [1]	Avoided Changes	Percent Saving
73413	27,856	2	1		1	2	100
73416	46,796	3				3	100
73425	76,487	5	1	1		4	80
73426	37,516	3				3	100
73432	108,907	8	1		1	8	100
73433	121,125	9	1		1	9	100
73446	125,870	10	3	2	1	8	80
73447	99,928	7	2	2		5	71
73448	95,477	7	2	1	1	6	86
73449	89,158	7	3	1	2	6	86
73450	153,428	11	1	1		10	91
Totals	982,548	72	15	8	7	64	89%

a. Oil changes for mechanical reasons were not included in the calculation for the avoided changes and percent savings.

Filter Systems and Test Periods

This oil bypass filter evaluation used two different filter systems. When the evaluation started, all eight INL buses that had 4-stroke diesel engines were equipped with puraDYN filter systems; these buses were tested for approximately 3 years. When three additional INL buses were equipped with 4-stroke diesel engines, it was decided to equip them with bypass filter systems from RGS; these buses were tested for 11 months each. It was always the intent to test the feasibility of oil bypass filter systems, not to compare one commercial product against another. Therefore, both filter systems were used as “mules” to evaluate oil bypass filter systems. Table 5 lists the total months of testing per filter system on each bus.

Highlights of Bus Mileage and Oil Performance

Highlights of the bus mileage and oil performance include:

- Buses traveled a total of 982,548 miles.
- Bus 73450 traveled the most miles (153,428) of all the buses, but in the shortest time interval of the initial eight buses because of engine failure unrelated to the oil bypass filter system.
- The eleven buses traveled a total of 651,143 miles on each of their respective first oil changes or 66% of all test miles.
- Three buses averaged 37,000 miles on the second oil change or three oil drain intervals.
- The bypass filters on the 11 buses had an 86% new oil use avoidance (541 gallons).

- Bypass filters on 11 buses had an 86% reduction in waste oil generation (541 gallons).
- puraDYN filters were tested about 3 years each.
- RGS filters were tested 11 months each.

Table 5. Total months of testing per filter system.

Bus Number	Filter Systems	Start Date	End Date	Total Months[a]
73413	RGS	12/14/2004	11/16/2005	11.2
73416	RGS	12/14/2004	11/16/2005	11.2
73425	puraDYN	12/18/2002	11/16/2005	35.5
73426	RGS	12/7/2004	11/17/2005	11.5
73432	puraDYN	2/11/2003	11/22/2005	33.8
73433	puraDYN	12/4/2002	11/22/2005	35.5
73446	puraDYN	10/23/2002	11/15/2005	37.3
73447	puraDYN	11/14/2002	11/16/2005	36.6
73448	puraDYN	11/14/2002	11/17/2005	36.6
73449	puraDYN	11/13/2002	11/17/2005	36.7
73450	puraDYN	11/20/2002	12/30/2004	25.7

a. 30-day month.

Analysis and Trends of the Bus Engine Oil Evaluation

Oil Analysis Sampling

During the bus engine oil bypass filter evaluation, approximately 180 oil analysis samples were taken. The resulting reports provide the basis for the analysis and trending of the bus engines and oils. At each regular 12,000-mile service interval, three oil analysis samples were taken from each bus. Two of the samples were sent to separate oil analysis laboratories, and one was placed in storage as an archive sample. Periodically, when a report was received, a data point of importance was not consistent with previous trends. It was both handy and valuable to be able to validate the data point with a second laboratory. A few times when TBN or viscosity varied “too much” from the trend established from earlier reports, the testing laboratory was asked to retest the sample. This they readily did when asked, and most often the retested results would fall within the expected trend.

Oil Analysis Reports

An example of an oil analysis report is located in Appendix A. The generic aspects of an oil analysis report include:

- Engine wear metal analysis, such as iron and copper
- Chemical tests for pollutants, such as water, fuel, soot, and coolant in the oil
- Oil condition analysis, such as viscosity and TBN values
- Previous test results
- Judgment/comments on the condition of the engine oil, i.e., normal, abnormal, or critical.

Oil analysis reports provide multiple services to the end user. The spectrochemical or spectrometric analysis of the oil detects and quantifies the parts per million (ppm) of engine wear metals, oil additives, and metal contaminates in oil, and this analysis is the crux of most oil analysis reports. These reports also reveal other data helpful to understanding the condition of the engine and to solving potential problems. For instance, a report showing very high silicon could indicate the air filter could be faulty, high potassium could indicate a coolant leak, and fuel in the oil could indicate injector problems.

The number of items tested in an oil analysis report depends on the level of analysis desired; the more tests desired, the more costly the testing. Oil analysis laboratories can provide a litany of tests for the end user. For this evaluation, particle sizing, rotrode filter spectroscopy, and oxidation/nitration numbers were required beyond the basic suite of tests.

An analysis report is interdependent of many aspects of the condition of the oil, and through consistent reports a trend germane to each engine is established. The reports alert the fleet personnel when an oil or engine wear metal is out of the established range of acceptable values. Other aspects can include:

- Oil degradation from coolant or fuel
- Incorrect grade of lubricant in use
- Air filter failure allowing sand or dirt intake
- Overextended or underutilized drain intervals.

Quantification of PPM Volumes

Values of wear metals are stated in parts per million (ppm) on oil analysis reports. A partial list of wear metals includes iron, copper, lead, and chromium. But when an engine oil analysis reports 50 ppm of iron, what does that mean in terms of the entire volume of engine oil? The volume that 50 ppm of iron displaces in 106 liters (28 quarts or 7 gallons) of engine oil is 1.3 mL of fine iron (less than 10 microns in size), which is equivalent to 0.26 teaspoon. The assumptions and calculation are shown below.

Assumptions:

- 1 liter of oil is equivalent to about 1 kilogram of oil
- A 28-quart oil sump is 26.5 liters, or 26,500 mL
- 1 mL equals 0.2 teaspoons
- 1/1,000,000 is 1 ppm
- 100% is 1,000,000 ppm.

Equation:

$100\% \div 1{,}000{,}000 \text{ ppm} = X\% \div 50 \text{ ppm} = 0.005\%$

$0.00005 \times 26{,}500 \text{ mL} = 1.3 \text{ mL}$

$1.3 \text{ mL} \times 0.2$ (teaspoons) = 0.26 teaspoon of fine iron particles in 28 quarts of oil.

Oil Quality Metrics

Early in this evaluation, oil quality criteria were established as to when the engine oils required changing. These criteria include a list of physical properties and their acceptable value limits. When the physical property values exceeded or fell below the established limits, the oil was changed. These criteria included:

- Oil contaminates: fuel (≥3%), water (>0.25%), and glycol (≥0.25%)
- Oxidation and nitration numbers (≥30 Abs/cm)
- Total base number (≤3.0 mgKOH/mL)
- Soot content (≥3%)
- Viscosity (12.50 to 16.39 centistokes).

For this evaluation, the above listed items were the fitness-for-service limits and were the metrics for determining when to change the oil during this test. For an expanded discussion of oil analysis condemnation limits, see TECHTRAKS (PDF page 43) in the First Quarterly Report, INL/EXT-03-00129, which can be found at http://avt.inl.gov/pdf/oilbypass/oilfilter_bypass1.pdf.

If an oil analysis report indicates a high or higher level of engine wear metals, it does not significantly impact the lubricating value of the oil. Nor will changing the oil solve the wear metal problem. An unusual high wear metal concentration or an extreme negative trend of repeated high wear metals indicates that a bearing or engine part is wearing. To avoid a catastrophic and costly engine failure, appropriate repair/replacement action should be taken.

Water and glycol values were never detected in the oil analysis reports during this evaluation. Soot values were typically below 1.0 Abs (Absorption units), but with a few values in the 1 to 3 Abs range (Figure 6).

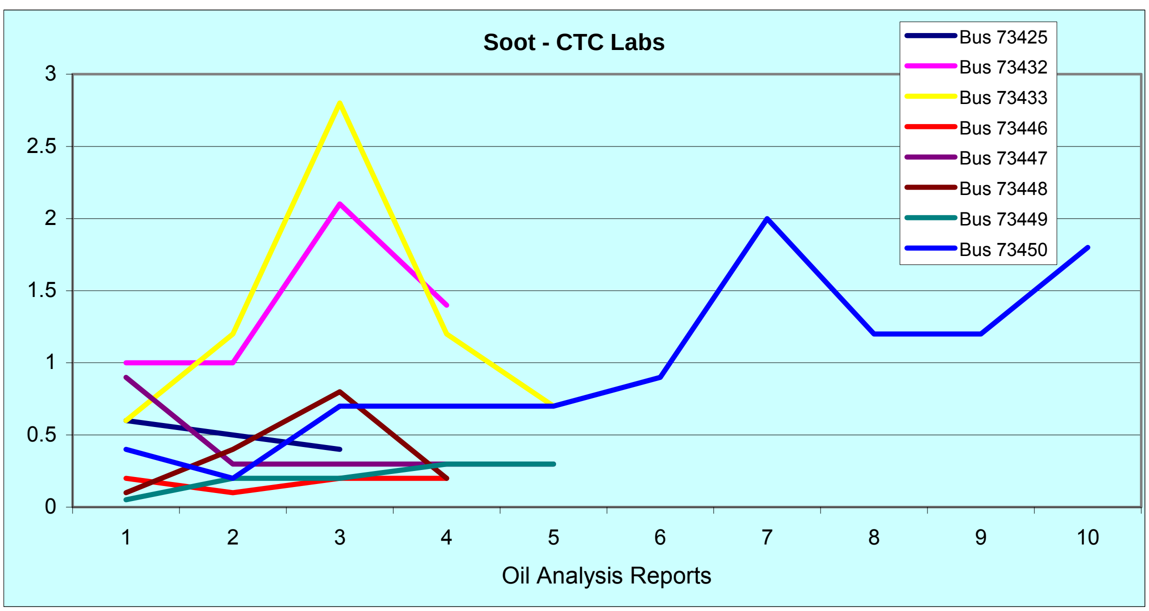


Figure 6. Soot testing measures the presence of solids in the oil from the combustion process. Excessive solids may possibly impair anti-wear benefits and, indirectly, perhaps lead to additional wear above normal for a given engine. Soot levels exceeding 3% indicate the oil should be changed.

Oil Evaluation Trends and Findings

Over the 3-year evaluation period, various trends and findings in the data were observed, details of which are discussed for the following topics:

- Wear metals
- TBN
- Oxidation/nitration numbers
- Viscosity
- Additives
- Fuel dilution
- Oil use.

Wear Metals

There have been three primary wear metals: iron, lead, and copper. Table 6 shows the complete wear metal history of these three metals from one test laboratory for each bus engine. It is important to remember when looking at these data that this is a record of oil tests and that the oil was normally not changed with each service. This means that values tend to increase with each test as the oil ages. Not all bus engines were the same. On some buses, the values would have a distinct increase with each report, and on other buses there would be minor or minimal increases with each report. When the oil in a bus engine was changed, many values at the next service interval would be lower (which is better for iron, copper, and lead). At this point the trend would start over. To highlight this, the first analysis data after each oil change are shaded so the reader can discern when the trends restart.

Table 6. Oil analysis report histories for three bus engine wear metals (iron, lead, and copper).[a]

Bus Number	Test Date	Miles on Oil	Iron (ppm)[b]	Lead (ppm)	Copper (ppm)	Nitration	Oxidation	TBN
73413	2/7/05	5,571	20	4	7	N/G[c]	N/G	7.2
	8/4/05[d]	7,510	14	4	11	N/G	N/G	8.6
	11/16/05	17,597	31	7	15	N/G	N/G	6.7
73416	3/8/05	6,501	24	2	19	N/G	N/G	8.6
	4/7/05	12,174	42	2	83	N/G	N/G	7.9
	5/25/05	20,935	19	1	19	N/G	N/G	10.2
	11/16/05	46,796	101	4	140	6	6	5.6
73426	2/3/05	3,678	16	3	7	N/G	N/G	7.8
	2/16/05	5,243	20	4	10	N/G	N/G	7.8
	5/25/05	18,477	28	5	18	N/G	N/G	6
	9/20/05	30,738	53	10	21	N/G	N/G	5.6
	11/17/05	37,516	75	10	19	N/G	N/G	5.4
73425	4/21/03	6,376	15	2	2	N/G	N/G	10.6
	6/3/03	12,919	33	3	1	N/G	N/G	8
	2/2/04	30,319	128	7	7	N/G	N/G	5

Bus Number	Test Date	Miles on Oil	Iron (ppm)[b]	Lead (ppm)	Copper (ppm)	Nitration	Oxidation	TBN
	8/11/04	46,734	144	11	13	11	5	4.4
	7/28/05	71,331	45	22	9	9	9	2.2
	11/16/05	9,756	18	4	3	7	6	8.4
73432	3/11/03	6,0921	24	4	2	N/G	N/G	8
	4/14/03	12,320	28	3	3	N/G	N/G	9.2
	8/11/03	24,935	60	9	8	N/G	N/G	7
	12/17/03	38,868	76	13	9	N/G	N/G	6.8
	8/5/04	65,730	41	8	6	1	1	7.1
	12/20/04	78,361	39	10	9	8	6	6.5
	2/22/05	84,601	41	8	9	8	5	6.9
	5/5/05	5,704	10	7	2	5	1	4.3
	9/22/05	12,610	24	10	6	10	9	7.4
	11/17/05	23,884	31	9	7	9	8	9.7
73433	2/12/03	6,700	30	4	1	N/G	N/G	8.9
	5/4/03	13,322	49	3	2	N/G	N/G	8.7
	7/29/03	25,617	124	10	4	N/G	N/G	6
	12/18/03	38,487	130	11	5	N/G	N/G	7
	3/4/04	43,443	112	8	4	0	2	7
	6/7/04	56,790	85	0	4	8	4	9.6
	9/22/04	77,067	92	21	5	7	5	8.3
	2/22/05	92,335	17	6	1	8	6	8.6
	4/26/05	4,580	9	11	1	6	1	5
	9/21/05	16,982	28	8	3	8	8	7.4
	11/22/05	23,884	34	7	3	7	7	7.9
73446	1/15/03	9,949	11	2	5	N/G	N/G	10.5
	1/30/03	12,136	8	1	4	N/G	N/G	9.4
	4/30/03	22,648	18	5	9	N/G	N/G	8
	12/16/03	37,827	44	92	16	N/G	N/G	5.6
	5/5/04	51,080	48	83	15	17	12	4.1
	6/2/04	51,233	46	74	16	19	18	1
	9/1/04	8,572	14	13	6	13	12	5.6
	12/21/04	21,274	18	27	9	10	11	4.6
	2/28/05	34,097	38	71	10	24	18	2.6
	5/18/05	4,074	6	3	1	4	5	6.4
	7/20/05	14,371	6	4	7	8	8	8.4
	11/1/05	27,154	24	12	10	12	11	5.1
	11/17/05	28,964	27	10	6	12	11	9.1

Bus Number	Test Date	Miles on Oil	Iron (ppm)[b]	Lead (ppm)	Copper (ppm)	Nitration	Oxidation	TBN
73447	3/11/03	5,908	9	3	3	N/G	N/G	7.9
	6/18/03	13,780	15	5	22	N/G	N/G	7.1
	7/21/03	17,164	15	5	24	N/G	N/G	6.6
	10/13/03	26,089	38	46	33	N/G	N/G	6
	2/4/04	37,939	45	49	37	N/G	N/G	6.4
	6/30/04	52,554	56	57	31	27	21	3
	11/19/04	9,465	15	13	9	9	20	6.2
	6/8/05	21,497	32	62	14	24	20	7.2
	9/6/05	32,550	34	80	14	47	32	3
	9/14/05	34,374	48	85	15	48	37	3.37
	11/16/05	10,391	8	8	6	10	9	8.3
73448	2/4/03	5,713	6	3	1	N/G	N/G	8
	4/22/03	12,509	9	4	2	N/G	N/G	10.4
	9/15/03	24,258	22	19	5	N/G	N/G	7.5
	1/20/04	14,005	12	7	2	N/G	N/G	8
	6/11/04	23,575	19	22	4	14	8	9.2
	11/3/04	35,859	42	107	8	35	28	5.8
	11/30/04	37,582	10	21	2	15	10	6
	4/5/05	11,654	18	26	3	15	4	6.2
	8/15/05	23,255	14	34	7	18	16	4.4
	11/17/05	33,637	37	49	5	8	7	3.3
73449	2/4/03	6,168	5	1	0	N/G	N/G	7.4
	4/28/03	12,572	10	3	2	N/G	N/G	8.6
	9/11/03	24,258	15	14	5	N/G	N/G	5.9
	2/18/04	36,271	38	68	7	5	12	4.2
	7/13/04	47,945	42	97	8	6	10	4.4
	12/1/04	61,312	52	109	9	47	30	1.8
	9/21/05	10,854	9	7	4	9	9	3
	11/17/05	4,612	7	3	1	17	12	8.9
73450	1/8/03	6,934	20	1	4	N/G	N/G	8
	1/21/03	14,545	50	1	6	N/G	N/G	6.4
	3/17/03	25,871	91	4	12	N/G	N/G	5.5
	6/16/03	43,031	206	11	20	N/G	N/G	9
	7/2/03	45,968	162	9	20	N/G	N/G	4.2
	7/23/03	54,812	183	11	20	N/G	N/G	4.5
	8/25/03	65,369	212	15	21	N/G	N/G	7
	10/6/03	68,821	425	18	29	N/G	N/G	3.8

Bus Number	Test Date	Miles on Oil	Iron (ppm)[b]	Lead (ppm)	Copper (ppm)	Nitration	Oxidation	TBN
	1/13/04	89,137	305	17	25	N/G	N/G	4.2
	3/4/04	99,280	370	18	27	6	21	5.8
	5/12/04	110,479	290	13	25	8	20	5.4
	7/15/04	124,136	337	8	21	10	22	4
	9/13/04	9,240	120	3	9	14	15	7.6
	12/2/04	21,512	150	0	13	10	7	6.6

a. Oil analysis reports from CTC laboratory of Phoenix, Arizona.
b. ppm = parts per million.
c. N/G means the information was "Not Given." Early in the evaluation, oxidation/nitration values were not requested.
d. Shaded text shows the first set of oil analysis values after an oil change.

Total Base Number

The TBN indicates the acid reducing value of the oil and is a commonly requested oil analysis test. For this evaluation, when a TBN value was 3.0 mgKOH/mL or below, it served as a flag for requiring an oil change. The TBN of the new oil (Shell Rotello-t 15w-40) used in the bus engines has a TBN of about 10. Degraded TBN was the most prominent value that caused oil change during this evaluation. Table 2 shows that seven of the oil changes were directly related to low TBN. The typical trend for TBN with the bus engines is a gradual decrease over time for used engine oil. Figure 7 shows the trend of several of the engines up to when the oil was changed. There was a direct inverse relationship between TBN and oxidation and nitration levels.

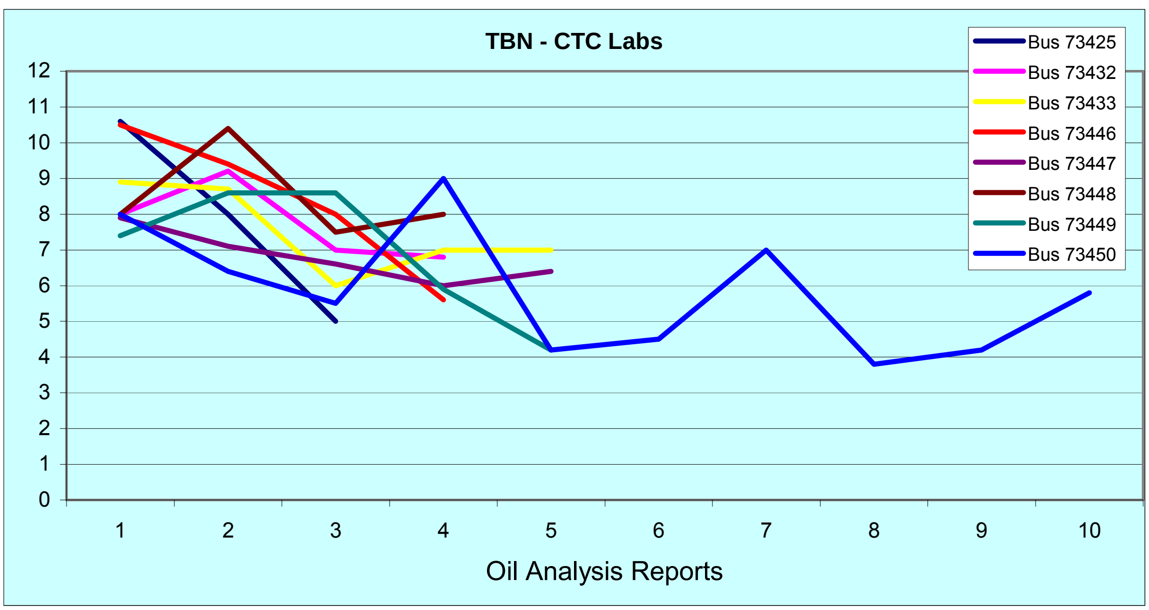


Figure 7. Total base number (TBN) is a measure of the presence of additives that neutralize an acid buildup. A TBN of 3.0 (mgKOH/mL) or below is considered low, and the oil should be changed.

Oxidation and Nitration Analysis

With regular oil changes, harmful oxidation and nitration levels in the oil may never be evident because the motor oil is discarded untested. However, with extended oil-drain intervals, there is a greater possibility for oxidation and nitration of the oil to occur due to the effects of aging, heating, and combustion inefficiencies. Therefore, oxidation and nitration analysis tests were added to the suite of oil analysis tests to measure oil quality.

Fourier Transform Infrared Spectroscopy (FTIR) is used to determine the oxidation and nitration values of oil. ASTM E 168-99 describes the general techniques of infrared quantitative analysis. FTIR identifies types of chemical bonds in an oil molecule by producing a plot of its infrared absorption spectrum. The spectrum for CARBONYL (a suite of oxidation degradation products) has a spectrum value of 1730/cm. The spectrum for organic nitrates (a suite of nitration degradation products) has a wavelength value of 1630/cm. The peak values at these points on the spectrum plot measure the amount of light absorbed and show the relative oxidation and nitration of the oil in Absorption units per centimeter (Abs/cm).

Three samples of new (virgin) test oil were submitted to establish a baseline. These samples had values for both oxidation and nitration of 0.1 Abs/cm. Essentially, there were no oxidation or nitration products (peaks) on the infrared absorption spectrum plots. Oil test laboratory personnel suggested a condemnation value of 30 Abs/cm.

Oxidation and nitration value trends are inversely related to those of TBN. Typically, when TBN values decrease (negative trend), oxidation/nitration values increase (also a negative trend). The only way to definitively reverse these negative trends is to change the oil. Figure 8 shows this relation on one of the buses. Most of the bus oils show this same basic relationship, though some are more dramatic than others. A complete history of oxidation and nitration values from each oil analysis report is shown in Table 7. The oil change dates are very obvious because the next set of values (shaded) will be much lower. Figure 9 shows the general upward (negative) trend of just the oxidation values up to the first oil changing event on each bus. The ANA laboratory was used during the initial stage of the test, but was replaced by the National Tribology Services (NTS).

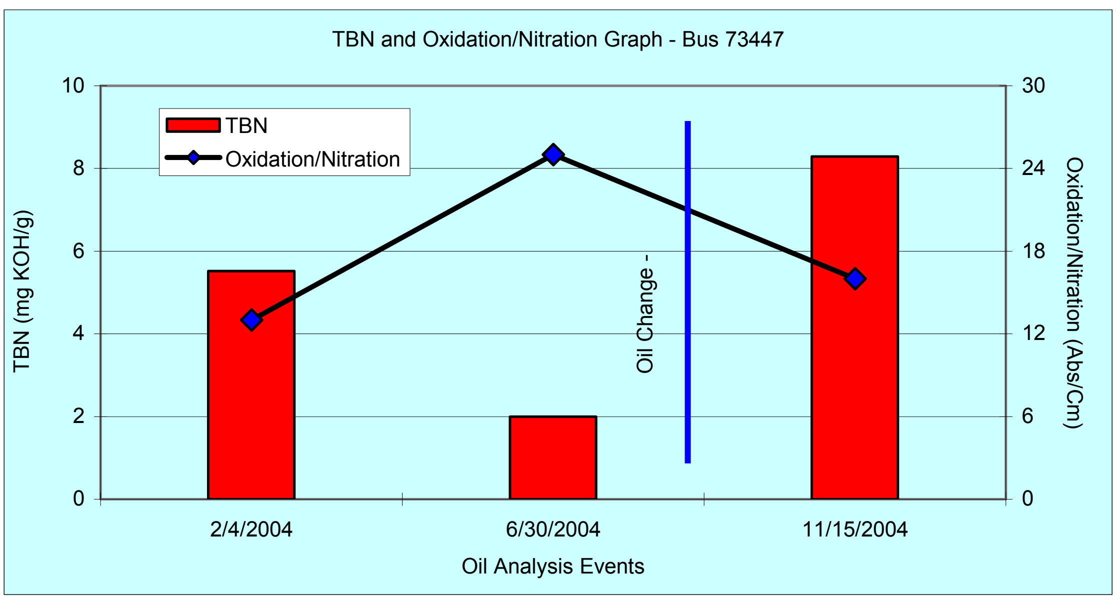


Figure 8. Inverse relationship between TBN and oxidation/nitration levels for three oil testing reports on bus 73447. TBN is graphed on the left axis and oxidation/nitration on the right axis.

Table 7. Oil analysis report histories for oxidation and nitration.[a]

Bus No.	Test Date	Oxidation[b]	Nitration[b]	Notes
73413	None	N/A	N/A	N/A
73416	11/16/05	6	6	CTC Laboratory
73425	11/11/03	8	3	ANA Laboratory
	12/10/03	7	3	ANA Laboratory
	1/2/04	9	4	ANA Laboratory
	2/2/04	11	6	ANA Laboratory
	8/11/04	5	11	CTC Laboratory
	11/16/05[c]	6	7	CTC Laboratory
73426	None	N/A	N/A	N/A
73432	11/4/03	9	1.5	ANA Laboratory
	12/17/03	9	1.7	ANA Laboratory
	8/5/04	1	1	CTC Laboratory
	12/20/04	6	8	CTC Laboratory
	2/2/05	5	8	CTC Laboratory
	5/5/05	1	5	CTC Laboratory
	9/22/05	9	10	CTC Laboratory
	11/17/05	8	9	CTC Laboratory
73433	12/18/03	10.1	2.2	ANA Laboratory
	3/4/04	2	0	CTC Laboratory
	6/7/04	4	8	CTC Laboratory
	9/22/04	5	7	CTC Laboratory
	2/22/05	6	8	CTC Laboratory
	4/26/05	1	6	CTC Laboratory
	9/21/05	8	8	CTC Laboratory
	11/17/05	7	7	CTC Laboratory
73446	11/10/03	10	6	ANA Laboratory
	12/16/03	7	2.9	ANA Laboratory
	5/5/04	12	17	CTC Laboratory
	6/2/04	18	19	CTC Laboratory
	9/1/04	12	13	CTC Laboratory
	12/21/04	11	10	CTC Laboratory
	2/28/05	18	24	CTC Laboratory
	5/18/05	5	4	CTC Laboratory
	7/20/05	8	8	CTC Laboratory
	11/1/05	12	11	CTC Laboratory
	11/17/05	12	11	CTC Laboratory
73447	11/15/03	9	2.5	ANA Laboratory
	2/4/04	11.2	4.1	ANA Laboratory
	6/30/04	21	27	CTC Laboratory
	11/19/04	20	9	CTC Laboratory
	6/8/05	20	24	CTC Laboratory

Bus No.	Test Date	Oxidation[b]	Nitration[b]	Notes
	9/6/05	32	47	CTC Laboratory
	9/14/05	37	48	CTC Laboratory
	11/16/05	9	10	CTC Laboratory
73448	11/4/03	11	3.2	ANA Laboratory
	1/2/04	10	4	ANA Laboratory
	6/11/04	8	14	CTC Laboratory
	11/3/04	28	35	CTC Laboratory
	11/30/04	10	15	CTC Laboratory
	4/5/05	4	15	CTC Laboratory
	8/15/05	16	18	CTC Laboratory
	11/17/05	7	8	CTC Laboratory
73449	11/4/03	9	3.2	ANA Laboratory
	2/8/04	8.5	3	ANA Laboratory
	2/18/04	12	5	CTC Laboratory
	7/13/04	10	6	CTC Laboratory
	12/1/04	30	47	CTC Laboratory
	9/21/05	9	9	CTC Laboratory
	11/17/05	12	17	CTC Laboratory
73450	10/6/03	11	3	ANA Laboratory
	10/28/03	11.3	3.4	ANA Laboratory
	1/13/04	13	5	ANA Laboratory
	3/4/04	21	6	CTC Laboratory
	5/12/04	20	8	CTC Laboratory
	7/15/04	22	10	CTC Laboratory
	9/13/04	15	14	CTC Laboratory
	12/2/04	7	10	CTC Laboratory

a. Oxidation and nitration data compiled from reports from two oil analysis laboratories.
b. Abs/cm = absorption per centimeter.
c. Shaded test results indicate new engine oil was used and tested due to a previous oil change.

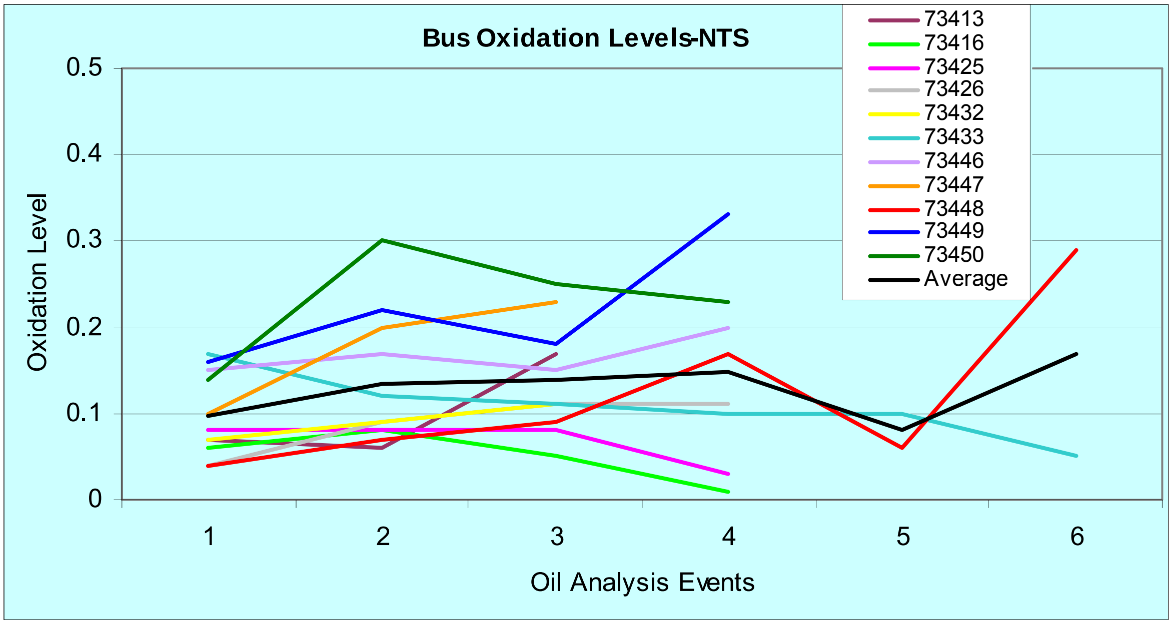


Figure 9. Results from bus-engine-oil oxidation values up to the first oil change.

Viscosity

Figure 10 shows the viscosity for all buses during the evaluation. The low viscosity values are attributed to fuel dilution. Viscosity is the oil's resistance to flow with respect to temperature, as measured in centistokes (cst). The limits for viscosity are based on the SAE grade specified; SAE 40 has a range of 12.50 to 16.29 cst. The test oil used in the bus engines is 15W–40.

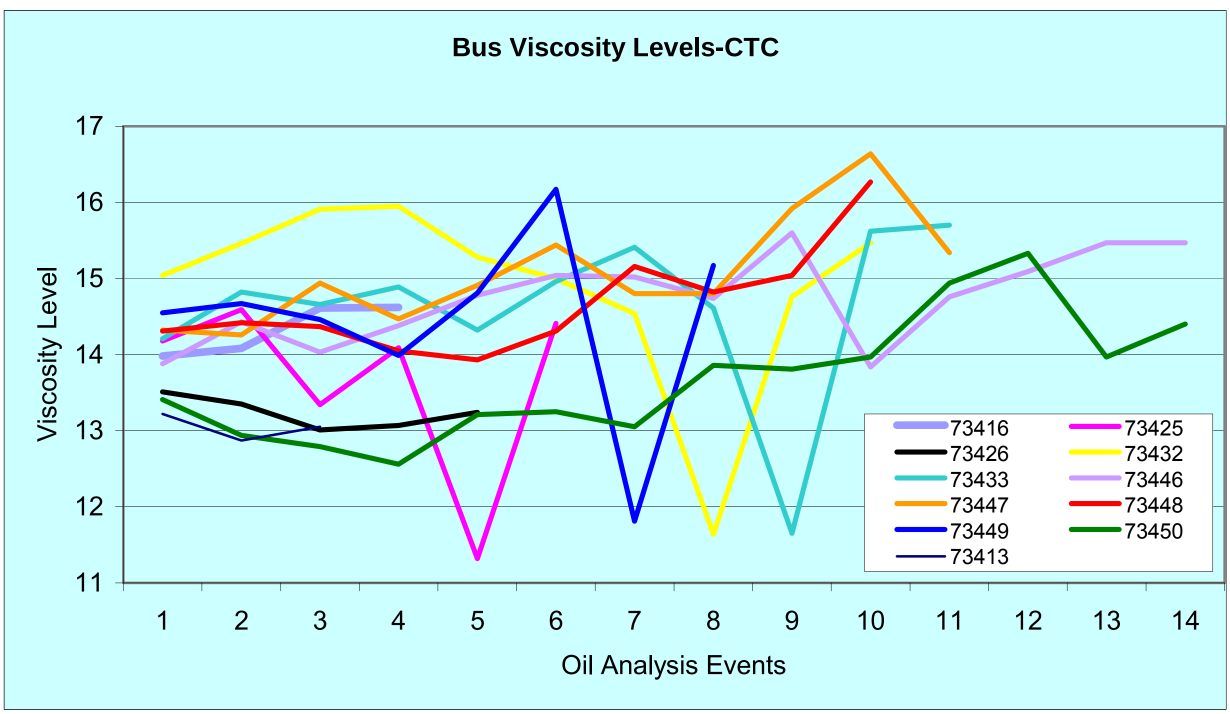


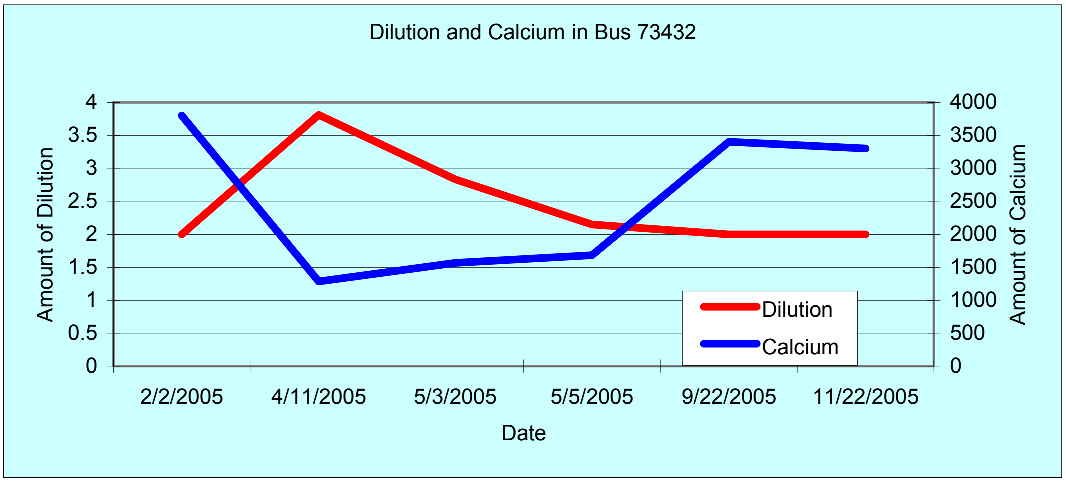
Figure 10. All viscosity testing results for the 11 test buses.

Additives

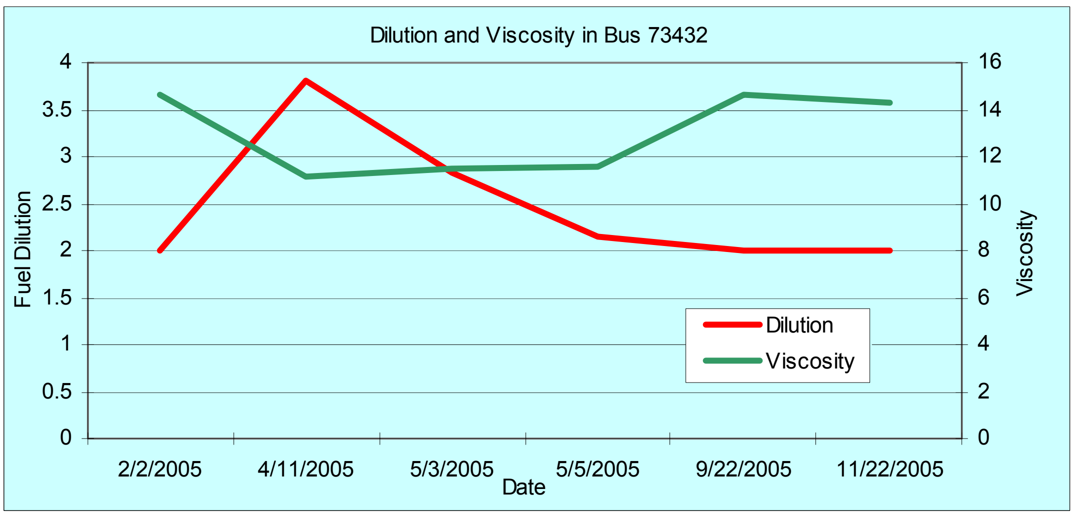
There was no real degradation in the additive values for any of the buses except for when there was fuel dilution.

Fuel Dilution

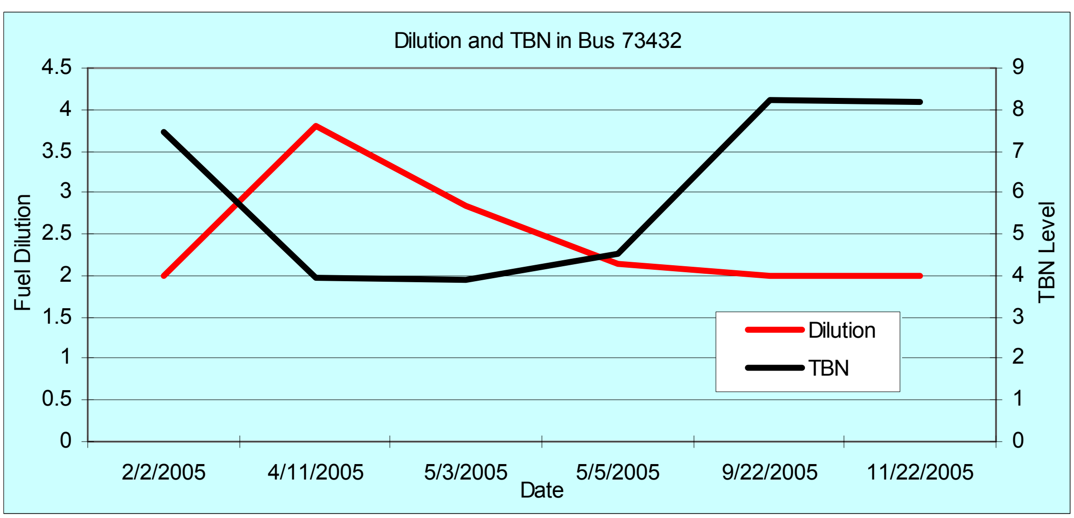
Fuel dilution has an immediate deleterious affect on viscosity, additives, and TBN. Three times during the bypass filter evaluation, the test data showed that when fuel dilution (>2%) occurs, the values of viscosity, calcium, and TBN all decrease. Typically, when the engine oil is changed the oil properties return to normal. This phenomenon also manifested itself during the Diesel Engine Idling Test (see http://avt.inl.gov/bus_idle.shtml) conducted on two of the eleven buses. The three graphics below (Figures 11A-C) show the inverse relationship between fuel dilution and calcium, viscosity, and TBN that occurred during the idling test. Fuel dilution is measured in percent and the baseline (nondetection) value of fuel dilution from the NTS oil analysis reports was <2%. The difference between the bypass filter evaluation and the idle test was that the oil in the idling test "healed" itself as the test proceeded; whereas with the bypass filter evaluation, the oil was changed.



(A)



(B)



(C)

Figures 11A–C. Inverse relationships between fuel dilution, and calcium, viscosity and TBN.

Oil Use

The oil use during the bus evaluation is shown in Table 8.

Table 8. Oil use as of December 1, 2005.

Bus	73413	73416	73425	73426	73432	73433	73446	73447	73448	73449	73450[a]
Test start date[b]	12/14/04	12/14/04	12/7/02	14/14/04	2/11/03	12/4/02	10/23/02	11/14/02	11/14/02	11/13/02	11/20/02
Volume of oil pan[c]	7	7	7	7	7	7	10	10	10	10	9.5
Test miles[d]	27,856	46,796	76,487	37,516	108,907	121,125	125,870	99,928	95,477	89,158	153,428
Status of test[e]	4/13/05	Ongoing	8/16/05	Ongoing	2/22/05	2/22/05	6/2/04	8/3/04	9/16/03	12/20/04	8/31/04
Daily oil check top-off[f]	0	0	32	0	69.5	89	16.75	22	14	15.75	65
Filter service makeup oil[g]	4	6	12	6	18	20	22	16	16	16	24
Oil change volume[h]	7	0	7	0	7	7	30	20	20	30	9.5
Total oil added[i]	11	6	51	6	94.5	116	58.75	58	50	61.75	98.5
Oil replace ment ratio[j]	1.57	0.86	7.29	0.86	13.5	16.57	6.88	5.8	5	6.18	10.37
Oil use per 1,000 miles[k]	0.25	0.13	0.67	0.16	0.87	0.96	0.55	0.58	0.52	0.69	0.64

a. The oil-use log for bus 73450 was incomplete. Only data for 9 months of 2004 are available. The daily top-off and filter makeup oil for the 9 months of 2004 were used to extrapolate the volume of oil used for 2003. No data for 2005 because of engine failure.
b. Date the bypass filter system and the new 15W-40 Shell Rotello-T oil were installed in the bus.
c. Total volume capacity, in gallons, of the diesel engine oil pan.
d. The miles traveled during the test.
e. The status of the test is either ongoing (if the bus is still traveling on the initial charge of oil), or the date the initial test oil was changed.
f. Volume of oil, in gallons, added during the daily oil check up.
g. Volume of oil, in gallons, added to provide the makeup oil when the filters are changed during servicing.
h. Total gallons used during or as the result of oil changes.
i. Total gallons of oil added to the system since the start of the test.
j. The oil replacement ratio is the amount (in gallons) of oil added during the filter evaluation project divided by the volume of the engine oil pan.
k. Divide oil used by test miles divided by 1,000 to get gallons of oil used per thousand miles driven.

During the oil bypass filter evaluation, oil analysis reports document the oil quality as the oil ages. However, the quality of the engine oil in the buses can be enhanced by the regular multi-quart infusions of fresh oil to the oil supply system. The oil quality of a leaking or oil-consuming engine with a premium oil bypass filter system may not degrade significantly because the regularly added oil bolsters the oil values while the filter super cleans the oil. But if an engine is new or otherwise does not consume oil, the oil values may degrade faster, because the oil is not being replenished. The INL buses used in this evaluation are equipped with the newest engines in the fleet and were the only four-cycle diesel engine-powered buses in the fleet.

Some interesting facts are evident in Table 8. Buses 73425, 73432, and 73433 have four-cylinder Detroit Diesel engines. Looking at the oil use as measured by the oil replacement ratio, these four-cylinder engines have greater oil use than the six-cylinder engines. The average volume replacement in respect to the oil pan volume capacity was 12.5 times for the four-cylinder engines, whereas the six-cylinder engine oil volume replacement in respect to the oil pan volume capacity averaged 6.0 times.

The oil use per 1,000 miles driven for the three four-cylinder engines ranged between 0.67 and 0.96 gallons per 1,000 miles driven. The average oil use for the four series 60 engines (six cylinders) was 0.59 gallons per 1,000 miles. The two four-cylinder buses with the highest oil use, 73432 (94.5 gallons) and 73433 (116 gallons), also had consistently high TBN values (high is good).

Buses 73425, 73432, and 73433 have four-cylinder Detroit diesel engines and looking at the oil used for daily top-offs (Table 8), these three buses used 190.5 gallons whereas the four series 60 engines used 68.5 gallons.

Another point of interest is the comparison in average iron parts per million (ppm) test results between the four- and the six-cylinder Detroit diesel engines up to the first oil change (Table 9). Table 9 shows that the parts per million of iron for the four-cylinder engines is generally higher than for the six-cylinder engines.

In discussing the findings of Tables 8 and 9 with the fleet operations personnel, the only explanation is that the four-cylinder engines are working harder and thus getting more wear and consuming more oil.

Table 9. Averaged iron parts per million (ppm) from all oil analysis reports.

Bus	Averaged Iron Values (ppm)
Four cylinder - 73413	22
Four cylinder - 73416	47
Four cylinder - 73425	74
Four cylinder - 73426	38
Four cylinder - 73432	45
Four cylinder - 73433	82
Six cylinder - 73446	27
Six cylinder - 73447	28
Six cylinder - 73448	17
Six cylinder - 73449	24

Bus Testing Lessons Learned

Duplicate Oil Analysis Reports

This evaluation required surety of oil testing and sending duplicate samples to independent laboratories proved valuable. Duplicate samples help in comparing data, in showing trends, and in ensuring oil samples are tested correctly and valid results are obtained. A few times, unexpected results from one test laboratory were confirmed by the second set of results. In addition, one laboratory on occasion had conflicting results when compared to the second laboratory. Requesting retests, either with the sample already sent or with the archived sample, always cleared up any confusion over testing results.

Makeup Oil Affects Oil Quality Values

Makeup oil can affect oil quality values as makeup oil both supplements the additives and dilutes the old oil. The INL fleet mechanic observed that when the bypass filter and the two full flow filters are changed, about 2 gallons of makeup oil is required. Empirical tests were conducted to verify this observed volume of oil. When a bus was serviced, the oil-soaked filters were bagged and placed upright into buckets to avoid losing any filter oil. A set of new filters were borrowed from the parts room along with an empty and full gallon jug of oil. These items were taken to a laboratory with a calibrated scale and weighed. These data and the test methodology are captured in Table 10. This test shows that the mechanic uses about 2 gallons of oil with every servicing of the bus filters. This is about a 20% to 31% influx of new oil into the existing system, depending on the sump capacity; and this has a positive effect on the additives and TBN levels.

Table 10. Makeup oil added to a bus during filter change.[a]

Item	Weight in Grams	Volume in Gallons
Oil and 1-gallon plastic jug	3478.4	
Empty plastic jug	-188.7	
Net weight of 1 gallon of oil[a]	3289.7	1.0
Full flow filter (double bagged)	3249.7	
Bags (7-mil plastic)	-285.3	
Net weight of full flow filter w/oil	2964.4	
New full flow filter	-1272.6	
Oil in full flow filter[b,c]	1691.8	0.51
Used bypass filter (double bagged)	4783.4	
Bags (7 mil plastic)	-285.3	
Net weight of bypass filter w/oil	4498.1	
New bypass filter	-1403.2	
Oil in bypass filter[b]	3094.9	0.94

a. 15W-40 Shell Rotello-T oil
b. Represents new oil volume added to system each time the filter is replaced.
c. There are two full flow filters with on each engine.

Ancillary Intangibles to Not Changing Engine Oil

On May 19, 2003, oil bypass system-equipped bus number 73446, had an alternator failure. The cause of the failure was not reported, but the mechanic who rebuilds the alternators reported that the alternator was unlike any heretofore repaired—the oil-cooled alternator was clean as a new alternator on the inside. There were no deposits of sludge or pockets of dirt on the component parts, typical with previous alternator repairs. There will always be failures of mechanical parts, but reason dictates that if an alternator is cooled with clean oil and no sludge builds up on the parts, the alternator will be cooler and, therefore, less prone to heat-related failures. This is only one data point, but it is a possible value-added benefit of oil bypass filter systems. Changing oil and filters is an intrusive activity. Any time activities, such as putting in the wrong oil, not tightening the oil pan plug or spin-on filter, not filling the oil pan with oil, or having an oil spill, can be reduced or avoided would be additional intangible benefits of bypass oil filter systems.

Extended Oil Drains Standards

There is a lack of definitive national standards to draw from when determining the suitability of engine oil and for determining when it "must" be changed. Each oil analysis laboratory has its own standards or limits that they follow, but these are usually based on oil that is discarded at each service interval. The problem arises when a sample has been sent to a laboratory on a diesel engine that has extended its oil drain a few times. The oil can have high wear metals because very small sized metals tend to accumulate over time. The test laboratory does not know that the oil use has been extended, and they report that the wear metal is too high, but in reality the engine is not in imminent danger of failure.

Wear Rate Analysis

Historical databases of oil analysis laboratories are based on analysis records of oil that has been discarded. Using extended oil change intervals goes against the paradigm of regular oil changes; a negative trend of iron values can, therefore, be somewhat misleading or disconcerting when viewed conventionally. With extended drain intervals, metals can continue to accumulate at a "normal" pace over time, while the oil analysis laboratories think the metal level is too high and comment on the high metals. One technique to evaluate accumulated metal wear levels is to calculate the wear rate ratio to ascertain the seriousness of the wear metal accumulation. Wear rate is determined by dividing the total parts per million of metal in the oil by each 1,000 miles traveled. Table 11 shows ten examples of accumulating iron (Iron ppm column) in the engine oil of bus 73450 and calculated wear rate ratios. With the exception of the 10/6/03 test result, the wear rate ratios are relatively constant until 9/13/04. The oil was changed on 8/31/04, and the iron in ppm did drop with the oil change, as it should. The calculated wear rate ratio on the 9/13/04 sample would have been a "red flag" to the fleet personnel that something was amiss with the engine, as was the case.

Table 11. Bus 73450 wear rate results from CTC Analytical Services.

Test Date	Iron (ppm)	Miles on Oil	Wear Rate
1/8/2003	20	6,934	2.9
1/21/2003	50	13,550	3.7
3/17/2003	91	26,202	2.1
6/16/2003	206	43,037	4.8
10/6/2003	425	68,398	6.2
1/13/2004	305	87,137	3.5
3/4/2004	370	99,280	3.7
5/12/2004	290	110,479	2.6
7/15/2004	337	124,136	2.7
9/13/2004	120	9,246	13.0

ppm = parts per million.
Wear rate = ratio of ppm to each 1,000 miles traveled.

Engine Failure

Bus 73450 experienced engine failure (loss of power and excessive exhaust smoke, according to the service report) during the first workday of 2005. Bus 73450 was towed to the INL maintenance shop for diagnosis, and the engine was eventually removed from the bus and the valve covers removed. The postmortem analysis revealed that the valve train was out of adjustment and several parts were worn out. The mechanic discovered the bolts holding one of the rocker arms had worked loose (unscrewed) about 0.25 inch. With so much play in the rocker arm, the rocker arm and the push rod were severely worn, and eventually the push rod became disconnected from the rocker arm assembly and was bent. This allowed a valve to drop into a cylinder where it was struck and broken into pieces by the piston. With the valve missing, the engine lost power and began to smoke. It was determined that the engine failure was unrelated to the use of the oil bypass filter.

Incorrect Installation

Even the intuitively obvious aspects of the bypass filter systems must be included in the installation handbooks or manuals. The RGS filter systems were installed in December 2004, and the service mechanic installed the system according to the requirements of the factory-furnished installation handbook. In December, both the INL test engineer and the RGS representative inspected one of the buses after their systems were installed. Several weeks later, the INL Fleet Operations point of contact called the INL test engineer and revealed that there was neither a tee fitting nor valve in the system to allow taking of oil analysis samples. The RGS engineers were contacted, and they sent the needed parts for the three buses. Subsequently, the RGS engineer reworked their installation handbook to include installing a tee fitting with a sampling valve.

Regular Service

Having a bypass filter system does not negate conducting regular engine and filter maintenance. It has been reported that when oil bypass filter systems are installed that users sometimes forget or neglect aspects of other engine maintenance. Oil bypass filter systems reduce the use of oil and the disposal of used oil, but the system does not manufacture oil for the engine—it just super cleans it. The engine oil must be topped off as needed, especially when filters are replaced.

TAHOE TESTING

Six INL Chevrolet Tahoe sport utility vehicles were used as light-duty test vehicles for evaluating oil bypass filter systems. The vehicles were part of the security force fleet at INL, and they traveled a total of 303,172 miles during the evaluation. The test vehicles were 2002 models, and when the test began at the end of 2003, the engines already had between 35,000 and 45,000-miles each. To establish a historical baseline of the engine wear metals, before the oil bypass filters were installed, several oil analysis samples were taken prior to the start of testing. This baseline provided a benchmark for each vehicle against which to compare future test results, plus it would not be prudent to start a test on an engine that was failing.

These vehicles were not in the regular motor pool, but the limited-access security vehicle pool. And as such, when something had to be done on the vehicle, it became a security issue to take it out of service. At times the vehicles could be readily accessed, but other times not. To further complicate the issues with the security vehicles was that the vehicles were often on a remote assignment that made it difficult for regular servicing, and sometimes these remote assignments did not promote many miles on the vehicles. This is evident with the 13 baseline oil analysis samples that were taken. When one of the designated vehicles would come in for service, an oil analysis sample was taken. If the vehicle was not driven much, then servicing would not be needed and no sample would or could be taken. To further exacerbate the baseline sampling, sometimes the sample would be forgotten to be taken because the service mechanics were not familiar in taking the sample or a replacement mechanic was on duty when the vehicle came in.

The baseline samples showed that the Tahoe engines tend to generate high copper wear metals. In ten oil analysis reports, the copper values ranged between 10 and 242 ppm, with 30 or less parts per million considered more normal. Table 12 shows the disposition of the oil analysis reports and itemizes the abnormal conditions. Part of an oil analysis report is a subjective observation germane to the condition of the oil by the test laboratory personnel (based on established values). If the values were within the established range, then the disposition is “normal”; if the values are out of an established range, they are “abnormal,” and if the values are much out of the range, they are “severe or critical.” An interesting observation was made at the end of the light vehicle evaluation when it was noticed that the copper values had dropped about 2.6 times with the use of the puraDYN oil bypass filters.

Table 12. Tahoe test vehicles oil analysis baseline reports.

Vehicle	1st Analysis	2nd Analysis	3rd Analysis	4th Analysis
71326	Normal	Normal		
71333	Normal	Abnormal: 58 ppm Cu[a]		
71391	Abnormal: 59 ppm Cu and 1.6 TBN[b]			
71394	Abnormal: 53 ppm Cu	Abnormal: 48 ppm Cu and 100 ppm Na[c]	Normal	Abnormal: 67 ppm Cu
71400	Abnormal: 59 ppm Cu			
71402	Abnormal: 60 ppm Cu	Abnormal: 73 ppm Cu	Abnormal: 242 ppm Cu and 36 ppm Pb[d]	

a. Cu = Copper
b. TBN= Total Base Number (the inverse of Total Acid Number)
c. Na = Sodium
d. Pb = Lead

Installation of six puraDYN PFT-8 filter systems (8-quart capacity) oil bypass filter systems on the Tahoes began during the fourth quarter of 2003. The initial system, on vehicle 71333, took about 6 hours to install, and this initial installation validated the installation procedure. The remaining five systems were installed during the next regular servicing and took about 3 hours for installation. With all the emissions and ancillary equipment required in the engine compartment with light vehicles, finding adequate spaces to install the filters was difficult. With some light vehicles, it would be impossible to find adequate space for a filter to be installed. Because of the tight quarters in the engine compartment, the INL mechanic fabricated a special bracket to hold the filter housing (or canister) in the passenger-side engine compartment at the firewall (Figures 12 and 13). This installation location was excellent because it was readily accessible, and it allowed more than the required 14 inches of gradient between the filter and the oil pan.

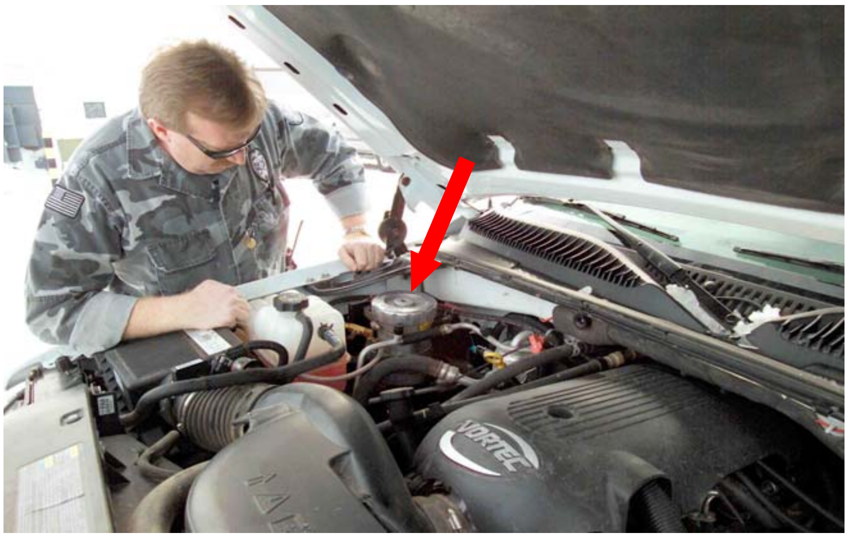


Figure 12. INL personnel viewing the location of the oil bypass filter installation in the engine compartment of an INL Chevrolet Tahoe.

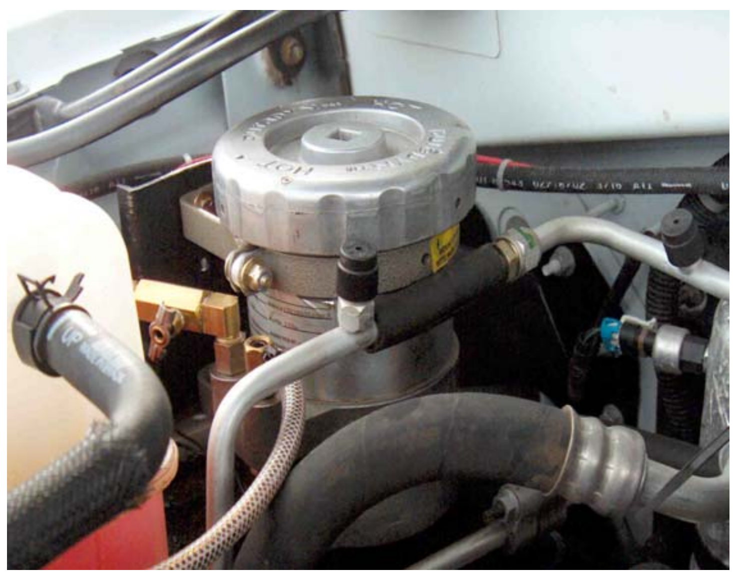


Figure 13. Closeup view of an oil bypass filter in a Chevrolet Tahoe engine compartment.

Status of Tahoe Mileage and Performance

For this light-duty vehicle bypass oil filter evaluation, there were about 60 oil analysis samples taken during the 2-year Tahoe test period. As with the buses, the oil analysis reports provided the data for ascertaining the fitness of the engine oils in the Tahoes for extending the oil drain intervals. The Tahoe evaluation is discussed in four sections:

- First test period
- Middle test period
- Orifice changes
- Last test period.

First Test Period

The oil used in the Tahoes during the first test period was a 20% recycled 30W oil from America's Choice. To avoid operational issues involving the stocking and control of a unique test oil, it was decided to continue using America's Choice oil in the Tahoes as this oil was used in all the light-duty vehicles in the INL fleet. The heavy-duty (including the INL buses) and light-duty vehicle maintenance operations are operated separately at INL, and it was much easier to use a different oil in the buses than the Tahoes for operational and cost reasons.

Because the Tahoes operate as security vehicles 24 hours per day, 7 days per week, have multiple drivers, and often have extended idling times, the Tahoe's are serviced every 3,000-miles. The first testing period covers the start of testing (November 2003) until the initial engine oils in all the Tahoes were changed. The mileage traveled during this first test period totaled 98,266 miles. As with the buses, the oil was not changed on the Tahoes during servicing, but only the filters were changed. As with the buses, when the Tahoes were serviced (oil filters changed), three oil analysis samples were taken; two were sent out to oil analysis laboratories, and one was archived in a fire proof cabinet. When the returned oil reports dictated a degraded oil condition, the Tahoes were called in and the oil changed.

When the vehicles were fueled with gasoline, the drivers would enter the mileage from the odometers into the electronic fueling record. The service scheduler tracks the mileage online and issues service calls when each vehicle reached the 3,000-miles service point. Sometimes the vehicles were unavailable for service calls and would go past the 3,000-miles service point. This is evident by dividing the total miles traveled by the service intervals. The calculated number of service intervals would be 32 (98,266/3,000), but when the actual service intervals were counted, the count was 24. Table 13 shows the history of the oil changes, miles driven, and the cause for changing the oil.

Table 13. History of servicing events during the first Tahoe test period.

Tahoe Number	Start Date	Oil Change Dates	Reason Oil Changed	Starting Mileage	Ending Mileage	Total Miles	Service Intervals	Changes Avoided
71326	12/10/03	4/29/04	Low TBN	45,812	62,048	16,236	4	3
71333	11/12/03	7/1/04	Low TBN	40,825	57,593	16,768	5	4
71391	12/17/03	5/27/04	Low TBN	34,910	54,065	19,155	4	3
71394	12/4/03	4/21/04	Low TBN	43,938	59,199	15,261	3	2
71400	11/24/03	5/26/04	Low TBN	43,966	60,146	16,180	4	3
71402	12/4/03	5/18/04	Low TBN	38,618	53,284	14,666	4	3
					Totals	98,266	24	18

Table 13 shows that 24 service events occurred, but each Tahoe only had one oil change during this period. Therefore, 18 oil changes were avoided. This equates to a 75% savings in new oil use and also a

75% reduction of waste oil generation. Because the engines in the Tahoes have 5-quart oil pans (sump capacity), 90 quarts of oil were saved during this initial testing period. The 75% savings rate may have been higher if the vehicles had been serviced regularly at 3,000-mile intervals. For example, vehicle number 71394 was driven over 15,000 miles but only had three services. This vehicle had a 5,000-mile service interval instead of the regular 3,000-mile interval.

Middle Test Period

After the first oil change occurred on each of the Tahoes, testing naturally continued. Some of the Tahoes accumulated mileage faster than others and several of them would have a servicing event as often as once a month. This corresponded with many oil analysis reports being received, and it became essential to quickly add vehicle servicing directions into the electronic work-order system so the Tahoe mechanic could service the vehicles as needed and help track the use and condition of the oil. Concurrent with this, the mechanic responsible for the Tahoes was changed twice. In addition, a few times the mechanic took days off when the Tahoes would come in for servicing and the backup mechanic didn't know the procedures necessary for the oil bypass filter evaluation. Without going into further detail, from a records point of view, there was significant confusion as to when servicing events actually occurred, and when oil and filters were added or changed. In addition, it appeared that there were oil condition trends in some vehicles but not in others.

As a result, it was decided to change to a premium grade oil in the Tahoes. It was hoped that by restarting with a new oil, the light-duty phase of the project could be brought under control. By consensus of several of the mechanics and fleet personnel, the team picked 10W-30 Castrol oil. A supply of Castrol was stocked, and all the Tahoes were changed over at the next service interval. The new Castrol oil was actually changed a second time to ensure the detergent chemistry of the new oil had time to dissolve any sludge deposits left when using the previous oil.

During this time, a review of the oil analysis reports showed that sometimes the oil values improved and sometimes they declined even with the new oil. The directions in the electronic work orders were changed, and a regular full-time service mechanic took over. It appeared that the Tahoe part of the evaluation was beginning to turn around. However, the TBN values on the vehicles were still lower than what was hoped for. The puraDYN service representative visited INL and reviewed the oil analysis reports and thought that he had a solution for enhancing the longevity of the oil.

Orifice Changes

When the puraDYN bypass filter systems were originally installed in the Tahoes, the standard 1/32-inch orifice (0.0313 inch) was used. However, because of the cold weather in Idaho (-20^{o}F to -40^{o}F is not infrequent), this orifice allowed too much oil into the filter housing early in the mornings when the engines and engine oils were cold. The cold oil was too thick to flow through the dense filter media, and as designed, the oil would back up and overflow through a release valve on the filter housing, resulting in puddles of oil underneath some of the Tahoes. After researching this problem with puraDYN's help, replacement cold weather 1/64-inch (0.0156-inch) orifices were installed on all the Tahoes. This change was made only a couple of weeks into the testing during the first test period. There were no more overflows, and it was with this smaller orifice that the first two phases of the evaluation occurred.

Towards the end of the middle testing period, it was thought that the low TBN values might be caused by insufficient oil flows to the bypass filters due to the use of the small 1/64-inch orifices. Therefore, puraDYN provided new valve assemblies with a 1/40-inch (0.025 inch) orifice (Figure 14) in order to increase the oil flow to the bypass filters. The 1/40-inch orifices were installed in hopes of reducing the rapid decline of TBN values. The 1/40-inch orifices were installed prior to the start of the last test period. This second orifice change occurred at the same time that there were inconsistencies with record keeping and other previously discussed evaluation problems during the middle test period, that were not to be blamed on the puraDYN systems.

Figure 14. New puraDYN orifice assembly with oil analysis sampling valve.

Last Test Period

To bring order to the Tahoe testing, it was decided to restart the testing and change the directions on the electronic work orders. The security manager was able to make all the Tahoes available for servicing (engine oil and filter changes), and the testing was restarted.

Table 14 shows that the Tahoes traveled 99,123 miles during this test period, and that 29 service events occurred. Because the oils in two of the Tahoes were not changed when the last test period evaluation ended on 12/1/05, there were only four oil changes during this period. So this means that 25 changes were avoided. This equates to an 86% savings in new oil use and an 86% reduction of waste oil generation. With the five quart oil pans, 125 quarts of new oil use was avoided during this testing period, and 125 quarts of waste oil were not generated.

Table 14. History of servicing events during the last Tahoe test period.

Tahoe Number	Start Date	Oil Change Dates	Reasons Oil Changed	Starting Mileage	Ending Mileage	Total Miles	Service Intervals	Changes Avoided
71326	2/2/05	6/14/05	Low TBN & Viscosity	77,981	93,761	15,780	5	4
71333	2/2/05	N/A	Not changed	75,682	87,376	11,694	3	3
71391	2/1/05	6/28/05	Low TBN & Viscosity	74,676	89,355	14,679	5	4
71394	2/2/05	N/A	Not changed	75,553	90,630	15,077	4	4
71400	2/2/05	8/29/05	Low TBN	88,363	101,005	12,642	4	3
71402	1/26/05	6/7/05	Low TBN	61,402	90,653	29,251	8	7
					Totals	99,123	29	25

Tahoe Testing Lessons Learned

Metering Jet

To supply oil to the filter system, a flexible oil supply line is used to tap into a pressurized source of oil from the engine. A metering jet is placed inline the oil supply line to reduce the oil flow into the bypass filter system as the bypass filters are too dense for high oil flow rates. The standard or normal metering jet has a 1/32-inch-diameter orifice that flows about 6 gallons of oil per hour into the filter. The standard jet operational pressure is limited to a maximum of 65 pounds per square inch (psi) oil pressure. The mechanic ran the engine after installation to check for leaks and none were found. It was thought that this metering jet was properly matched to the Tahoe engine pressure, however, the vehicle was returned to the mechanic a couple of days later with oil leaking out of the vent hose on the filter housing. It was discovered that oil pressure is significantly higher when the vehicle is started after sitting over night in subfreezing temperatures. When the vehicle was started in the morning, the cold oil had too much backpressure, and the standard size orifice allowed too much oil flow, therefore oil overflowed out of the vent hose. The mechanic referred to the installation manual, which suggests that with higher oil pressures (>65 psi), the high-pressure jet 1/64-inch orifice, should be used. The standard metering jet was replaced, and the high-pressure jet was used for the remaining installations. This reduced the flow rate to the filter (about 4 gallons per hour), and no subsequent overflows occurred. Therefore, for cold climates, use a high-pressure metering jet.

Installation Process and the initial Oil Change

With the first Tahoe bypass filter system installation, the oil was changed and then it was driven to the line mechanic to install the bypass system. However, the system should have been installed first, because the oil had to be changed to hook up the oil return line through the oil pan drain plug opening.

ECONOMIC ANALYSIS

An economic analysis of oil bypass systems for buses was originally conducted in the First Quarterly Report (see: http://avt.inl.gov/pdf/oilbypass/oilfilter_bypass1.pdf) and updated in the Third Quarterly Report (see: http://avt.inl.gov/pdf/oilbypass/oilfilter_qtr3_03.pdf). In this final report, the economic analysis has been updated for the buses, and one has been generated for the Tahoes; both based on the knowledge gained after 1.3 million miles of testing. The major factors or items considered or used in this analysis included:

- Oil cost
- Filter system hardware costs
- Installation labor costs
- Oil sampling and testing costs
- Waste oil disposal costs.

It was never the intent of this evaluation to compare the performance of one manufacturer's system against another manufacturer's system. Therefore, a comparison of the costs of each system has not been performed. The following economic analysis is for a generic oil bypass filter system.

There are myriad of pricing scenarios possible: purchasing a single system for a single vehicle up to purchasing thousands of systems for a large fleet, or getting the "government" rate, which may be higher or lower depending on one's ability to negotiate. Therefore, if the price a reader can obtain is better than those used here, congratulations. The prices quoted below are those encountered by INL at the end of this evaluation, with some assumptions employed and described when appropriate. If more specific cost information is needed, please contact the oil bypass manufacturer of choice directly.

Oil Costs

The cost of oil is a major influence, and it has seen recent increases (which may continue), which only shortens payback periods for oil bypass filter systems. The cost to INL for a 55-gallon drum of Shell Rotello 15W-40 oil when purchased early in the evaluation was $355.67 per drum. More recently, 1 gallon jugs cost $7.26 per gallon. At first, a few drums were used, but it was essential to use jugs because they could be placed in the cargo bays of the buses for makeup oil. The cost of $7.26 per gallon is used in the analysis for the buses.

The cost of the Castrol 15W-30 oil used in the Tahoes was $2.79 per quart when last purchased. The Castrol oil was purchased in quart quantities in order to provide it to the drivers as makeup oil. The $2.79 cost is used for the Tahoe oil change analyses.

Filter System Hardware Costs

The costs of oil bypass filter systems vary by vendor. The costs for a few systems were obtained, and a generic cost of $400.00 for heavy vehicles and $300.00 for light vehicles was used as the baseline for this analysis. (These are the approximate costs for the RGS and puraDYN systems). There may be some hidden costs that can be unique to a particular manufacturer or vehicle, such as costs to fabricate a bracket to hold a filter or heater element, or other costs for unique hoses and fitting for the connections between the system and the engine and oil pan.

The cost to install oil bypass systems as a new-equipment-option on a truck manufacturing line is also known, but such costs would include labor, which is broken out separately here. However, this option is approximately the same as the above $400 hardware cost, excluding installation and the economic utility of having it come with a new truck, as an onboard option, with an OEM warranty.

Installation Labor Costs

The cost for installing a bypass filter system can vary based on the system design and the vehicle it is installed on. Some systems have no heater function or have the heater and filter as a single unit (such as puraDYN); both options mean there would be single piece installation. Other bypass filter systems can have the filter and heater as separate units (such as RGS), which means two pieces must be installed on a vehicle and also connected to each other. In addition, the onboard vehicle access can be complicated or easy. The bottom line is that the installation times could vary significantly. However, based on the INL experience, a value of 2.5 hours of installation time is assumed at a fully burdened labor rate of $60 per hour, or a total of $150 per installation for both the buses and Tahoes in commercial environments.

Oil Sampling and Testing Costs

For the purpose of this analysis, it is assumed that the costs for oil sampling, testing, and reviewing of the testing-generated oil-condition reports would be identical if a fleet used oil bypass filter systems or performed traditional oil changes. It is assumed that a well managed fleet will sample the condition of its engine oils as a diagnostic tool to prevent catastrophic engine failures from occurring. Therefore, the costs associated with oil testing are not included.

Waste Oil Disposal Costs

The authors originally thought a significant factor in the economic life-cycle analysis of oil bypass filter systems would be used engine oil disposal costs. However, INL waste generator services personnel stated that they spend less than 4 hours per year managing the waste oil and generating the paperwork for disposal. In addition, there are no fees to INL for allowing waste oil haulers to pick up the waste oil for resale. Given the volume of oil generated by INL's 99 buses and 1,500 other vehicles, the annual cost per quart or gallon of oil for 4 hours of labor is not a consideration. It appears that when oil is recycled for refining or burnt in applications such as cement kilns or boilers to recover the energy, there is minimal oversight required by the oil generating fleet. It also became apparent that when the cost of crude oil is high, the costs for picking up and disposing of waste oil tends to be at no or minimal cost to the generating fleet.

Various DOE facilities were contacted to determine their waste oil disposal costs, and it was found that many of the facilities also pay no or minimal disposal costs. In addition, the vehicles at several DOE facilities are serviced by local automotive dealerships. Therefore, five automotive dealerships were contacted to ascertain their disposal costs (Table 15).

Table 15. Costs associated with the disposal of waste engine oil.

Location	Waste Oil Pickup Cost
Automotive Dealer 1	None
Automotive Dealer 2	None
Automotive Dealer 3	None

Automotive Dealer 4	$30
Automotive Dealer 5	$20
Idaho National Laboratory	None
Sandia National Laboratory	None
Brookhaven National Laboratory	None
Nevada Test Site	None
Hanford Laboratory	$55
Y-12 Plant at Oak Ridge	None
Argonne National Laboratory-East	$10

Table 15 lists the findings of a limited search of the five automotive dealerships and seven DOE facilities. The search shows that the oil pickup and disposal costs vary from no charge (67% of responses) to $55.00. The pickup charge is the same for 1 gallon of oil or a full tank (of unknown size) of waste oil. While the cost varies between locations, it is either zero or assumed to be relatively minimal on a per quart basis. Also, research shows that with high crude oil costs, the recyclers are more willing to pick up waste oil at no cost. Therefore, the cost of used oil pickup and disposal is considered a nonfactor in the economic life-cycle analysis.

The low waste oil disposal costs discussed here are not the case in every environment that fleets operate in. For instance, the operations of military vehicles, especially in nondomestic locations, introduces very unique environmental and economic issues both for the disposal and transportation of waste oils that may significantly accelerate the positive payback period for oil bypass systems. Domestic locations that could also enhance the payback periods for oil bypass systems would include remote national parks or wilderness areas where oil disposal options can be very limited, distant, and costly.

Buses—Bypass Filter System Economics

Three scenarios were considered for the economic analysis of installing bypass filter systems on the diesel-engine-equipped INL buses. The analyses and results (Figure 15) are discussed below. The costs were computed over 504,000 miles for each of the three bus scenarios (assumes the approximate life of a bus diesel engine at 500,000 miles, and an equal number of 12,000-mile oil service segments). This analysis assumes that a bypass filter system would operate for all 504,000 miles on a diesel bus engine and that 90% of the oil changes would be avoided. This is based on INL being able to avoid on average, 89% of the oil changes in the test buses.

INL Bus Scenario I — Oil Bypass Filter System Costs as Tested

The red line in Figure 15 represents the costs per bus for using oil bypass filter systems on the eleven INL buses. (All the assumptions and the costs for each service event are in listed in detail in Appendix B, Table B-1).

Every 12,000 miles the two full flow filters and the one bypass filter on each bus was changed. This was not performed according to the manufacturers' directions. When the testing started, the INL mechanics struggled with the procedure change of only changing the full flow filters every 48,000 miles. This was a variance from normal operations. It was determined that it was easier to allow this practice to continue than to assign a test engineer to be present at every 12,000-mile service event to ensure the full flow filters were not changed. Changing the full flow oil filters every 12,000 miles added an additional $1,566 in hardware and labor costs compared to Scenario III.

The total 504,000-mile cost for installing and using an oil bypass filter system on the INL buses was $5,452 per bus.

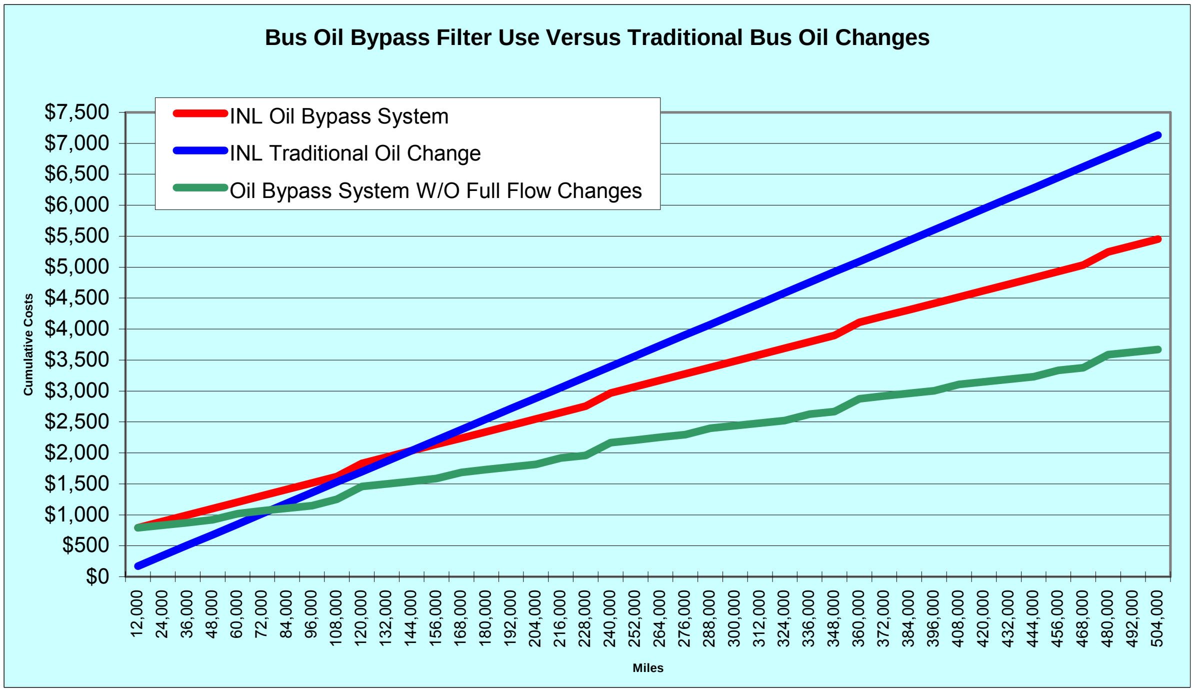


Figure 15. Life-cycle costs of two oil bypass filter system operations and traditional engine oil changes, based on the INL experience with oil bypass filter systems on buses with diesel engines.

INL Bus Scenario II — Traditional Oil Changes

The blue line in Figure 15 represents the traditional costs per vehicle for changing the full flow filters and oil in an INL bus every 12,000 miles. No bypass filter systems are used in this scenario. (All the assumptions and the costs for each service event are in listed in detail in Appendix B, Table B-2).

The total 504,000 mile cost for traditional full flow filter and oil changes every 12,000 miles was $7,131 per bus.

INL Bus Scenario III — Oil Bypass Filter System Costs When Avoiding Full Flow Filter Changes

The green line in Figure 15 represents the costs per vehicle that the INL would have incurred for each oil bypass filter system equipped bus if the INL had only changed the full flow filters per the oil bypass filter manufacturers' instructions for changing the full flow filters every 48,000 miles. This is the only difference between scenarios I and III. (All the assumptions and the costs for each service event are in listed in detail in Appendix B, Table B-3).

The total 504,000-mile cost for installing and using an oil bypass filter system on the INL buses in accordance with the direction to only change the full flow filters every 48,000 miles was $3,689 per bus.

INL Bus Oil Bypass Filter System Payback Periods

Comparing the traditional oil change method (Scenario II) and the way INL operated the oil bypass filter systems (Scenario I), oil bypass filter systems have a positive payback between 132,000 and 144,000 miles for the buses.

Comparing the traditional oil change method (Scenario II) and if INL had operated the oil bypass filter systems as directed (Scenario III), oil bypass filter systems would have a positive payback between 72,000 and 84,000 miles for the buses.

Tahoes—Bypass Filter System Economics

Two scenarios were considered for the economic analysis of installing bypass filter systems on the gasoline engine Tahoes. The analyses and results (Figure 16) are discussed below. The costs were computed over 150,000 miles (assumes a life of 150,000 miles for the Tahoes and an equal number of 3,000-mile oil service segments).

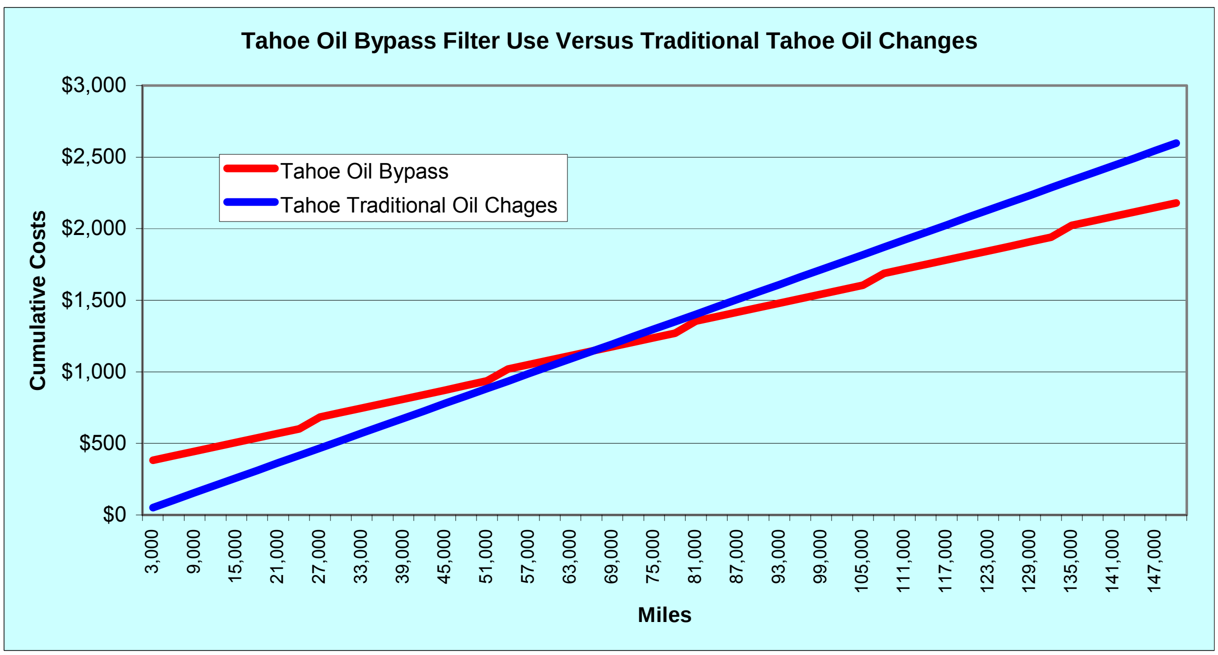


Figure 16. Life-cycle costs of Tahoe oil change options.

This analysis assumes that a bypass filter system would operate for 150,000 miles on a Tahoe and that 80% of the oil changes would be avoided. This is based on INL being able to avoid 75% of the oil changes in the Tahoes during the first testing period and 86% during the third testing period. It was decided not to penalize the economics of oil bypass systems on light-duty vehicles because of the difficulties encountered by INL during the middle testing period.

INL Tahoe Scenario I — Oil Bypass Filter System Costs as Tested

The red line in Figure 16 represents the costs per Tahoe for using oil bypass filter systems on the six Tahoes. (All the assumptions and the costs for each service event are in listed in detail in Appendix B, Table B-4).

The total 150,000 mile cost for installing and using an oil bypass filter system was $2,180 per Tahoe.

INL Tahoe Scenario II — Traditional Oil Changes

The blue line in Figure 16 represents the traditional costs per vehicle for changing the full flow filters and oil in an INL Tahoe every 3,000 miles. No bypass filter systems are used in this scenario. (All the assumptions and the costs for each service event are in listed in detail in Appendix B, Table B-5).

The total 150,000-mile cost for traditional full flow filter and oil changes every 3,000 miles on an INL Tahoe was $2,598 per vehicle.

INL Tahoe Oil Bypass Filter System Payback Period

Comparing the traditional oil change method (Scenario II) and the way INL operated the oil bypass filter systems on the Tahoes (Scenario I), the oil bypass filter systems have a positive payback between 66,000 and 69,000 miles on the Tahoes.

POTENTIAL ENGINE OIL SAVINGS IN INL, DOE COMPLEX, AND FEDERAL FLEETS

The potential engine oil savings in the INL, DOE complex and all federal fleets if oil bypass filter systems were used was originally calculated in the Oil Bypass Filter Technology Seventh Quarterly Report (INEEL/EXT-04-02194, see http://avt.inl.gov/pdf/oilbypass/oilfilter_qtr7_04.pdf). There has not been a significant change (less than 3%) in the number of vehicles and miles driven between 2003 (data originally used) and 2005 (latest available full-year data), so this analysis has not been repeated.

CONCLUSIONS

- Over 982,000 test miles, the 11 buses with oil bypass filter systems avoided on average 89% of oil changes and therefore, reduced by 89% their use of petroleum (engine oil) for oil changes.
- The degradation of the TBN and oxidation/nitration values were the two major oil quality metrics leading to the eight intentional bus oil changes.
- Seven bus oil changes were due to mechanical problems with the bus (injector failure), mechanic error, or from removal of two buses from testing for other uses.
- There were a total of 541 gallons of new oil use avoided by buses during the evaluation.
- PuraDYN oil bypass filter systems were tested on eight buses for over 36 months for 870,380 miles.
- RGS oil bypass filter systems were tested over 11 months on three buses for 112,168 miles.
- There were about 180 oil analysis reports issued for the buses.
- Bus 73450 traveled 153,428 test miles, the most of any individual test bus.
- Eleven buses traveled a total of 651,143 miles before their first oil changes.
- Three buses averaged 37,000 miles on the second oil change.
- If a 28-quart capacity engine has 50 ppm of iron in its oil, this equates to about 0.26 teaspoon of fine iron particles.
- As oil use is extended, the TBN levels generally decrease and the oxidation values increase; both are negative oil quality indicators.
- The three times when fuel dilution occurred in the bus oils, it had a dramatic negative affect on TBN, calcium, and viscosity levels.
- Buses 73432 and 73433 had the most oil use during normal operations, and neither required an oil change because of degraded oil quality. This suggests that when a bus gets regular infusions of new oil, TBN levels tend to stay acceptable.
- The four-cylinder engines had an average of 2.7 times higher iron levels in the engine oils than the six-cylinder engines. It is believed that the four-cylinder engines work harder and, therefore, have more measurable iron wear.
- In the first test period, the six Tahoes traveled 98,266 miles. They avoided 18 oil changes and the use of 90 quarts of oil; an oil change avoidance rate of 75%.
- In the third test period, the six Tahoes traveled 99,123 miles. They avoided 25 oil changes and the use of 125 quarts of oil; an oil change avoidance rate of 86%.
- Degraded TBN followed by out-of-specification viscosity levels were the two predominate failure modes of the Tahoe oil.
- The metering jets in the light-duty sized bypass filter systems had to be changed to a smaller size during very cold weather. The bypass filters in the Tahoes could not process large volumes of thick oil during early-morning startups; oil would overflow from the filter vents.
- The INL economic analysis suggests that the return on investment (payback period) occurs between 72,000 and 144,000 miles for the buses. This can vary with the system costs, oil prices, installation costs, and operational methods.
- The INL economic analysis for the Tahoes suggests a payback period between 66,000 and 69,000 miles. Again, this can vary with the system costs, oil prices, installation costs, and operational methods.

Appendix A

Oil Analysis Report

staveley FLUIDS ANALYSIS

3319 WEST EARLL DRIVE
PHOENIX, AZ 85017-5242
(800) 445-7930, FAX (602) 252-4639

CUSTOMER NO.: 15505
UNIT NO.: 73432
DESCRIPTION: ENGINE
END USER: LARRY ZIRKER
BATTELE ENERGY ALLIANCE
END USER LOCATION: IDAHO FALLS, ID 83415-3830

MAKE: DETROIT DIESEL
MODEL SERIES 50
OIL BRAND: SHELL
OIL TYPE: ROTELLA T 15W40
SERIAL NO.:
FUEL TYPE: DIESEL

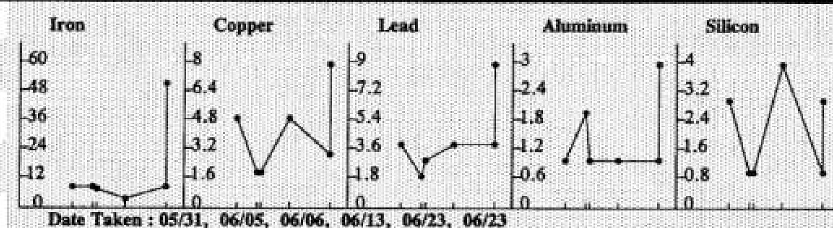
NO. COPIES 1

SAMPLE DATA			SPECTROCHEMICAL ANALYSIS (ppm)																				PHYSICAL PROPERTIES					
LAB#	SAMPLE DATE / RECEIPT DATE	TIME ON OIL / TIME ON UNIT	IRON	CHROMIUM	LEAD	COPPER	TIN	ALUMINUM	NICKEL	SILVER	SILICON	BORON	SODIUM	MAGNESIUM	CALCIUM	BARIUM	PHOSPHORUS	ZINC	MOLYBDENUM	TITANIUM	VANADIUM	POTASSIUM	FUEL (%VOL)	VIS @ 40 C cSt	VIS @ 100 C cSt	WATER (% VOL)	SOOT/SOLIDS (%WT)	GLYCOL
148465 NORMAL	06/23/2005 07/13/2005	800	52	2	9	8	2	3	0	0	3	62	12	16	3779	1	1269	1526	206	0	0	0	<1	N/A	14.25	0	0.1	NEG
136187 NORMAL	06/23/2005 06/23/2005		9	1	4	3	0	1	0	0	1	1	3	16	2521	0	1008	1129	1	0	0	0	<1	N/A	13.57	0	0.2	NEG
119041 NORMAL	06/13/2005 06/14/2005	600	4	0	4	5	3	1	0	0	4	0	0	14	2478	0	1123	1270	0	0	0	0	<1	N/A	13.72	0	0.2	NEG
116193 NORMAL	06/06/2005 06/09/2005		8	0	3	2	0	1	0	0	1	0	3	13	2677	0	1032	1215	1	0	0	0	<1	N/A	13.72	0	0.2	NEG

ADDITIONAL TESTS

LAB#	TAN	TBN	OXID	NITR
148465	2.24	7.8	1	1
136187	2.13	7.9	6	7
119041	2.27	8.9	1	3
116193	2.24	8.8	2	8

GRAPHICAL ANALYSIS



Key
A: Abnormal *C:* Critical

ANALYSIS RECOMMENDATIONS

LAB#	
148465	RESULTS OF TEST PERFORMED INDICATE NO CORRECTIVE ACTION REQUIRED. ANALYST-SAL
136187	RESULTS OF TEST PERFORMED INDICATE NO CORRECTIVE ACTION REQUIRED. ANALYST-PXK
119041	RESULTS OF TEST PERFORMED INDICATE NO CORRECTIVE ACTION REQUIRED. ANALYST-PXK
116193	RESULTS OF TESTS PERFORMED INDICATE NO CORRECTIVE ACTION REQUIRED. ANALYST-A.A

LARRY ZIRKER
BATTELE ENERGY ALLIANCE
P O BOX 1625
IDAHO FALLS, ID 83415-3830

SV 100 Rev. 12/04

Appendix B

Oil Bypass Versus Traditional Oil Change Economics

Table B-1. INL bus oil bypass cost sheet.

INL Buses - Oil Bypass System Costs										
Event Intervals[a]	Bypass Filter Element[b]	Bypass Filter Element Change Labor[c]	Full Flow Filter[d]	Full Flow Filter Change Labor[e]	Makeup oil[f]	Oil Change Labor[g]	Initial Bypass System Parts and Labor[h]	Cost per Event	Cumulative miles	Cumulative Costs
12,000	$50.00	$30.00	$48.00	$60.00	$9.08	$45.00	$550.00	$792.08	12,000	$792.08
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	24,000	$895.16
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	36,000	$998.24
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	48,000	$1,101.32
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	60,000	$1,204.40
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	72,000	$1,307.48
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	84,000	$1,410.56
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	96,000	$1,513.64
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	108,000	$1,616.72
12,000	$25.00	$15.00	$24.00	$30.00	$72.60	$45.00		$211.60	120,000	$1,828.32
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	132,000	$1,931.40
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	144,000	$2,034.48
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	156,000	$2,137.56
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	168,000	$2,240.64
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	180,000	$2,343.72
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	192,000	$2,446.80
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	204,000	$2,549.88
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	216,000	$2,652.96
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	228,000	$2,756.04
12,000	$25.00	$15.00	$24.00	$30.00	$72.60	$45.00		$211.60	240,000	$2,967.64
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	252,000	$3,070.72
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	264,000	$3,173.80
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	276,000	$3,276.88
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	288,000	$3,379.96
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	300,000	$3,483.04
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	312,000	$3,586.12
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	324,000	$3,689.20
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	336,000	$3,792.28
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	348,000	$3,895.36
12,000	$25.00	$15.00	$24.00	$30.00	$72.60	$45.00		$211.60	360,000	$4,106.96
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	372,000	$4,210.04
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	384,000	$4,313.12
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	396,000	$4,416.20
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	408,000	$4,519.28
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	420,000	$4,622.36
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	432,000	$4,725.44
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	444,000	$4,828.52
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	456,000	$4,931.60
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	468,000	$5,034.68
12,000	$25.00	$15.00	$24.00	$30.00	$72.60	$45.00		$211.60	480,000	$5,246.28
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	492,000	$5,349.36
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	504,000	$5,452.44
Totals	$1,075.00	$645.00	$1,032.00	$1,290.00	$635.44	$225.00	$550.00	$5,452.44		

a. Two change outs of all filters during the first 12,000 miles and some action taken every 12,000 miles thereafter.

b. A cost of $25 per heavy-duty, high capacity bypass filter replacement is assumed.

c. A fully burdened hourly labor rate of $60 is assumed. It is assumed that 0.25 hours are required to change out a bypass filter canister.

d. Full flow filter cost $12 with two per bus.

e. Full flow filter change labor cost $60 rate × 0.5 hours per change for both full flow filters.

f. Makeup oil $7.26 per gallon, 2 quarts full flow, 1 quart bypass 35 quart sump. Every tenth 12k service event, oil is changed based on - 90% avoidance.

g. Oil change labor cost of $60 × 0.75 hours.

h. $400 hardware and 2.5 hours × $60.

Table B-2. INL traditional bus oil changes cost sheet.

INL Buses Traditional Oil Changes							
Event Intervals[a]	Full Flow Filter[b]	Full Flow Filter Change Labor[c]	Makeup oil[d]	Oil Change Labor[e]	Cost per Event	Cumulative miles	Cumulative Costs
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	12,000	$169.79
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	24,000	$339.58
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	36,000	$509.37
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	48,000	$679.16
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	60,000	$848.95
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	72,000	$1,018.74
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	84,000	$1,188.53
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	96,000	$1,358.32
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	108,000	$1,528.11
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	120,000	$1,697.90
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	132,000	$1,867.69
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	144,000	$2,037.48
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	156,000	$2,207.27
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	168,000	$2,377.06
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	180,000	$2,546.85
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	192,000	$2,716.64
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	204,000	$2,886.43
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	216,000	$3,056.22
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	228,000	$3,226.01
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	240,000	$3,395.80
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	252,000	$3,565.59
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	264,000	$3,735.38
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	276,000	$3,905.17
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	288,000	$4,074.96
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	300,000	$4,244.75
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	312,000	$4,414.54
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	324,000	$4,584.33
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	336,000	$4,754.12
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	348,000	$4,923.91
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	360,000	$5,093.70
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	372,000	$5,263.49
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	384,000	$5,433.28
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	396,000	$5,603.07
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	408,000	$5,772.86
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	420,000	$5,942.65
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	432,000	$6,112.44
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	444,000	$6,282.23
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	456,000	$6,452.02
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	468,000	$6,621.81
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	480,000	$6,791.60
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	492,000	$6,961.39
12,000	$24.00	$30.00	$70.79	$45.00	$169.79	504,000	$7,131.18
Totals	$1,008.00	$1,260.00	$2,973.18	$1,890.00	$7,131.18		

a. Oil and full flow filter changes every 12,000 miles.
b. Full flow filter cost $12 with two per bus.
c. Full flow filter change labor cost $60 rate × 0.5 hours per change for both full flow filters.
d. Makeup oil $7.26 per gallon, 2 quarts per full flow and 35 quarts for sump.
e. Oil change labor cost of $60 × 0.75 hours.

Table B-3. INL bus oil bypass system avoiding full flow filter changes cost sheet.

INL Bus Oil Bypass System Avoiding Full Flow Filter Changes										
Event Intervals[a]	Bypass Filter Element[b]	Bypass Filter Element Change Labor[c]	Full Flow Filter[d]	Full Flow Filter Change Labor[e]	Makeup oil[f]	Oil Change Labor[g]	Initial Bypass System Parts and Labor[h]	Cost per Event	Cumulative miles	Cumulative Costs
12,000	$50.00	$30.00	$48.00	$60.00	$9.08	$45.00	$550.00	$792.08	12,000	$792.08
12,000	$25.00	$15.00			$1.82			$41.82	24,000	$833.90
12,000	$25.00	$15.00			$1.82			$41.82	36,000	$875.72
12,000	$25.00	$15.00			$1.82			$41.82	48,000	$917.54
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	60,000	$1,020.62
12,000	$25.00	$15.00			$1.82			$41.82	72,000	$1,062.44
12,000	$25.00	$15.00			$1.82			$41.82	84,000	$1,104.26
12,000	$25.00	$15.00			$1.82			$41.82	96,000	$1,146.08
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	108,000	$1,249.16
12,000	$25.00	$15.00	$24.00	$30.00	$70.79	$45.00		$209.79	120,000	$1,458.95
12,000	$25.00	$15.00			$1.82			$41.82	132,000	$1,500.77
12,000	$25.00	$15.00			$1.82			$41.82	144,000	$1,542.59
12,000	$25.00	$15.00			$1.82			$41.82	156,000	$1,584.41
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	168,000	$1,687.49
12,000	$25.00	$15.00			$1.82			$41.82	180,000	$1,729.31
12,000	$25.00	$15.00			$1.82			$41.82	192,000	$1,771.13
12,000	$25.00	$15.00			$1.82			$41.82	204,000	$1,812.95
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	216,000	$1,916.03
12,000	$25.00	$15.00			$1.82			$41.82	228,000	$1,957.85
12,000	$25.00	$15.00	$24.00	$30.00	$70.79	$45.00		$209.79	240,000	$2,167.64
12,000	$25.00	$15.00			$1.82			$41.82	252,000	$2,209.46
12,000	$25.00	$15.00			$1.82			$41.82	264,000	$2,251.28
12,000	$25.00	$15.00			$1.82			$41.82	276,000	$2,293.10
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	288,000	$2,396.18
12,000	$25.00	$15.00			$1.82			$41.82	300,000	$2,438.00
12,000	$25.00	$15.00			$1.82			$41.82	312,000	$2,479.82
12,000	$25.00	$15.00			$1.82			$41.82	324,000	$2,521.64
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	336,000	$2,624.72
12,000	$25.00	$15.00			$1.82			$41.82	348,000	$2,666.54
12,000	$25.00	$15.00	$24.00	$30.00	$70.79	$45.00		$209.79	360,000	$2,876.33
12,000	$25.00	$15.00			$1.82			$41.82	372,000	$2,918.15
12,000	$25.00	$15.00			$1.82			$41.82	384,000	$2,959.97
12,000	$25.00	$15.00			$1.82			$41.82	396,000	$3,001.79
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	408,000	$3,104.87
12,000	$25.00	$15.00			$1.82			$41.82	420,000	$3,146.69
12,000	$25.00	$15.00			$1.82			$41.82	432,000	$3,188.51
12,000	$25.00	$15.00			$1.82			$41.82	444,000	$3,230.33
12,000	$25.00	$15.00	$24.00	$30.00	$9.08			$103.08	456,000	$3,333.41
12,000	$25.00	$15.00			$1.82			$41.82	468,000	$3,375.23
12,000	$25.00	$15.00	$24.00	$30.00	$70.79	$45.00		$209.79	480,000	$3,585.02
12,000	$25.00	$15.00			$1.82			$41.82	492,000	$3,626.84
12,000	$25.00	$15.00			$1.82			$41.82	504,000	$3,668.66
Totals	$1,075.00	$645.00	$336.00	$420.00	$417.66	$225.00	$550.00	$3,668.66		

a. Two change outs of all filters during the first 12,000 miles and some action taken every 12,000 miles thereafter.

b. A cost of $25 per heavy-duty, high capacity bypass filter replacement is assumed.

c. A fully burdened hourly labor rate of $60 is assumed. It is assumed that 0.25 hours are required to change out a bypass filter canister.

d. Full flow filter cost $12 with two per bus changed every 48,000 miles or during oil change.

e. Full flow filter change labor cost $60 rate × 0.5 hours per change for both full flow filters.

f. Makeup oil $7.26 per gallon, 2 quarts per full flow and 1 quart bypass. Every tenth 12k service event, oil is changed based on - 90% avoidance.

g. Oil change labor cost of $60 × 0.75 hours.

h. $400 hardware and 2.5 hours × $60 labor installation.

Table B-4. INL Tahoe oil bypass system cost sheet.

INL Tahoe Oil Bypass System										
Event Intervals[a]	Bypass Filter Element[b]	Bypass Filter Element Change Labor[c]	Full Flow Filter[d]	Full Flow Filter Change Labor[e]	Makeup oil[f]	Oil Change Labor[g]	Initial Bypass System Parts and Labor[h]	Cost per Event	Cumulative miles	Cumulative Costs
3,000	$15.00	$15.00			$1.40		$350.00	$381.40	3,000	$381.40
3,000	$15.00	$15.00			$1.40			$31.40	6,000	$412.80
3,000	$15.00	$15.00			$1.40			$31.40	9,000	$444.20
3,000	$15.00	$15.00			$1.40			$31.40	12,000	$475.60
3,000	$15.00	$15.00			$1.40			$31.40	15,000	$507.00
3,000	$15.00	$15.00			$1.40			$31.40	18,000	$538.40
3,000	$15.00	$15.00			$1.40			$31.40	21,000	$569.80
3,000	$15.00	$15.00			$1.40			$31.40	24,000	$601.20
3,000	$15.00	$15.00	$8.00	$15.00	$15.35	$15.00		$83.35	27,000	$684.55
3,000	$15.00	$15.00			$1.40			$31.40	30,000	$715.95
3,000	$15.00	$15.00			$1.40			$31.40	33,000	$747.35
3,000	$15.00	$15.00			$1.40			$31.40	36,000	$778.75
3,000	$15.00	$15.00			$1.40			$31.40	39,000	$810.15
3,000	$15.00	$15.00			$1.40			$31.40	42,000	$841.55
3,000	$15.00	$15.00			$1.40			$31.40	45,000	$872.95
3,000	$15.00	$15.00			$1.40			$31.40	48,000	$904.35
3,000	$15.00	$15.00			$1.40			$31.40	51,000	$935.75
3,000	$15.00	$15.00	$8.00	$15.00	$15.35	$15.00		$83.35	54,000	$1,019.10
3,000	$15.00	$15.00			$1.40			$31.40	57,000	$1,050.50
3,000	$15.00	$15.00			$1.40			$31.40	60,000	$1,081.90
3,000	$15.00	$15.00			$1.40			$31.40	63,000	$1,113.30
3,000	$15.00	$15.00			$1.40			$31.40	66,000	$1,144.70
3,000	$15.00	$15.00			$1.40			$31.40	69,000	$1,176.10
3,000	$15.00	$15.00			$1.40			$31.40	72,000	$1,207.50
3,000	$15.00	$15.00			$1.40			$31.40	75,000	$1,238.90
3,000	$15.00	$15.00			$1.40			$31.40	78,000	$1,270.30
3,000	$15.00	$15.00	$8.00	$15.00	$15.35	$15.00		$83.35	81,000	$1,353.65
3,000	$15.00	$15.00			$1.40			$31.40	84,000	$1,385.05
3,000	$15.00	$15.00			$1.40			$31.40	87,000	$1,416.45
3,000	$15.00	$15.00			$1.40			$31.40	90,000	$1,447.85
3,000	$15.00	$15.00			$1.40			$31.40	93,000	$1,479.25
3,000	$15.00	$15.00			$1.40			$31.40	96,000	$1,510.65
3,000	$15.00	$15.00			$1.40			$31.40	99,000	$1,542.05
3,000	$15.00	$15.00			$1.40			$31.40	102,000	$1,573.45
3,000	$15.00	$15.00			$1.40			$31.40	105,000	$1,604.85
3,000	$15.00	$15.00	$8.00	$15.00	$15.35	$15.00		$83.35	108,000	$1,688.20
3,000	$15.00	$15.00			$1.40			$31.40	111,000	$1,719.60
3,000	$15.00	$15.00			$1.40			$31.40	114,000	$1,751.00
3,000	$15.00	$15.00			$1.40			$31.40	117,000	$1,782.40
3,000	$15.00	$15.00			$1.40			$31.40	120,000	$1,813.80
3,000	$15.00	$15.00			$1.40			$31.40	123,000	$1,845.20
3,000	$15.00	$15.00			$1.40			$31.40	126,000	$1,876.60
3,000	$15.00	$15.00			$1.40			$31.40	129,000	$1,908.00
3,000	$15.00	$15.00			$1.40			$31.40	132,000	$1,939.40
3,000	$15.00	$15.00	$8.00	$15.00	$15.35	$15.00		$83.35	135,000	$2,022.75
3,000	$15.00	$15.00			$1.40			$31.40	138,000	$2,054.15
3,000	$15.00	$15.00			$1.40			$31.40	141,000	$2,085.55
3,000	$15.00	$15.00			$1.40			$31.40	144,000	$2,116.95
3,000	$15.00	$15.00			$1.40			$31.40	147,000	$2,148.35
3,000	$15.00	$15.00			$1.40			$31.40	150,000	$2,179.75
Totals	$750.00	$750.00	$40.00	$75.00	$139.75	$75.00	$350.00	$2,179.75		

a. Bypass filter element each 3,000 miles.
b. A cost of $15 per light-duty bypass filter element replacement is assumed.
c. A fully burdened hourly labor rate of $60 is assumed. It is assumed that 0.25 hours are required to change out a bypass filter canister.
d. Full flow filter cost $8 changed every ninth 3,000 mile service event - 80% Tahoe oil change avoidance.
e. Full flow filter change labor cost $60 rate × 0.25 hours per change for full flow filter.
f. Makeup oil $2.79 per quart, 0 quarts full flow, 5 quarts sump, 0.5 quart bypass. Oil change ninth 3k service event 80% avoidance.
g. Oil change labor cost of $60 × 0.25 hours.
h. $200 hardware and 2.5 hours × $60 labor installation

Table B-5. INL Tahoe traditional oil change sheet.

INL Tahoe Traditional Oil Change							
Event Intervals[a]	Full Flow Filter[b]	Full Flow Filter Change Labor[c]	Makeup oil[d]	Oil Change Labor[e]	Cost per Event	Cumulative miles	Cumulative Costs
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	3,000	$51.95
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	6,000	$103.90
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	9,000	$155.85
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	12,000	$207.80
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	15,000	$259.75
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	18,000	$311.70
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	21,000	$363.65
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	24,000	$415.60
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	27,000	$467.55
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	30,000	$519.50
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	33,000	$571.45
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	36,000	$623.40
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	39,000	$675.35
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	42,000	$727.30
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	45,000	$779.25
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	48,000	$831.20
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	51,000	$883.15
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	54,000	$935.10
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	57,000	$987.05
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	60,000	$1,039.00
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	63,000	$1,090.95
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	66,000	$1,142.90
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	69,000	$1,194.85
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	72,000	$1,246.80
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	75,000	$1,298.75
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	78,000	$1,350.70
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	81,000	$1,402.65
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	84,000	$1,454.60
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	87,000	$1,506.55
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	90,000	$1,558.50
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	93,000	$1,610.45
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	96,000	$1,662.40
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	99,000	$1,714.35
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	102,000	$1,766.30
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	105,000	$1,818.25
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	108,000	$1,870.20
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	111,000	$1,922.15
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	114,000	$1,974.10
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	117,000	$2,026.05
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	120,000	$2,078.00
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	123,000	$2,129.95
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	126,000	$2,181.90
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	129,000	$2,233.85
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	132,000	$2,285.80
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	135,000	$2,337.75
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	138,000	$2,389.70
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	141,000	$2,441.65
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	144,000	$2,493.60
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	147,000	$2,545.55
3,000	$8.00	$15.00	$13.95	$15.00	$51.95	150,000	$2,597.50
Totals	$400.00	$750.00	$697.50	$750.00	$2,597.50		

a. Oil change every 3,000 miles.
b. Full flow filter cost of $8.
c. Full flow filter change labor cost $60 rate × 0.25 hours per change for single filter.
d. Makeup oil $2.79 per quart, 5 quart capacity.
e. Oil change labor cost of $60 × 0.25 hours.