ASSESSMENT OF LUBE OIL MANAGEMENT AND SELF-CLEANING OIL FILTER FEASIBILITY IN WSF VESSELS

PHASES II AND III: PART 1 REPORT

by

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
2013-S-WSU-0044	01497960	

4. Title and Subtitle	5. Report Date
Assessment of Lube Oil Management and Self-Cleaning Oil Filter Feasibility in WSF Vessels Phases II and III: Part 1 Report	10/31/2014
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
Quinn Langfitt and Liv Haselbach	44-739425
9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
PacTrans Pacific Northwest Transportation Consortium University Transportation Center for Region 10 University of Washington More Hall 112 Seattle, WA 98195-2700 Washington State University Department of Civil and Environmental Engineering 405 Spokane Street, Sloan 101 PO Box 642910 Pullman, WA 99164-2910	**11. Contract or Grant No.** DTRT12-UTC10
12. Sponsoring Organization Name and Address	**13. Type of Report and Period Covered**
United States of America, Department of Transportation Research and Innovative Technology Administration and Washington State Department of Transportation	9/1/2012-7/31/2015
	14. Sponsoring Agency Code

15. Supplementary Notes

Report uploaded at www.pacTrans.org

16. Abstract

Washington State Ferries (WSF) has proposed an alternative of the propulsion engine lubricating oil (lube oil) filtration systems on some vessels in their fleet. Currently, WSF uses disposable cartridge filters for oil filtration on most vessels. Self-cleaning oil filters could be installed which would eliminate the need for disposable filter cartridge changes and might raise the particle removal efficiency. WSF began with a pilot installation on one of two engines on the M/V Chetzemoka in early 2014 and is interested in utilizing a three pronged perspective in their decision making on whether to install more of these filters in their fleet, considering operational performance, cost savings, and potential environmental benefits. These three perspectives are the focus of this research endeavor, with operational performance considered through lube oil analysis of samples taken from the M/V Chetzemoka, potential cost savings through a life cycle cost analysis (LCCA), and potential environmental impacts through a life cycle assessment (LCA) methodology. This report covers the first stage of this research effort: a background on lube oil analysis, a rough order of magnitude life cycle cost analysis of lube oil and the filtration alternatives, and an overview of environmental impacts of lube oil and some disposal methods through life cycle assessment methodologies. The preliminary LCCA shows that for a retrofit vessel such as the M/V Chetzemoka, cost savings would likely be achieved by installation of a self-cleaning filtration system, considering a 50 year life cycle. These savings would be even greater for installation on a new vessel. The environmental impact data assembled and modeled herein gives WSF a simple tool for approximating environmental impacts from an LCA perspective separately for acquisition and disposal by distillation. It can be applied directly to the filter problem, or in other capacities when oil use and disposal volume changes are involved. For the acquisition of lube oil, the most significant impact category with respect to US daily normalization per capita is Human Health Non-Cancer. For disposal through distillation to other products, the benefits gained from offsetting these products are always higher than the impacts of the disposal process. Future work is ongoing to gather more information on the oil analyses with the self-cleaning oil filter over extended periods. With this additional information, the work herein will be updated. For the environmental analysis, future work might relate the gallon functional unit to different functional units relevant to WSF operations such as passenger/vehicle capacity, etc. Additional future research could be to expand the analyses to consider other vessels in the fleet.

17. Key Words	18. Distribution Statement
Self-cleaning oil filtration, bypass oil filtration, oil analysis, life cycle cost analysis, life cycle assessment, lubricating oil	No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.		NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AP	Acidification Potential
EP	Eutrophication Potential
ETP	Ecotoxicity Potential
GWP	Global Warming Potential
HHCAP	Human Health Criteria Air Potential
HHCP	Human Health Cancer Potential
HHNCP	Human Health Non Cancer Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment (Environmental)
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory (Environmental)
LCIA	Life Cycle Impact Assessment (Environmental)
LNG	Liquefied Natural Gas
NRC	Non-Recurring Costs
ODP	Stratospheric Ozone Depletion Potential
RC	Recurring Costs
SCP	Smog Creation Potential
TAN	Total Acid Number
TBN	Total Base Number
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts
UPVF	Uniform Present Value Factor
WSDOT	Washington State Department of Transportation
WSF	Washington State Ferries

Acknowledgments

We would like to thank Washington State Ferries and PacTrans for funding. We would also like to thank Sheila Helgath, Shane Kelly, Rhonda Brooks, Greg Hansen, Wes Sweet, Tomi Hume-Pontius, and Mark Gabel for continued support on the project.

Executive Summary

Washington State Ferries (WSF) has proposed an alternative of the propulsion engine lubricating oil (lube oil) filtration systems on some vessels in their fleet. Currently, WSF uses disposable cartridge filters for oil filtration on most vessels. Self-cleaning oil filters could be installed which would eliminate the need for disposable filter cartridge changes and might raise the particle removal efficiency. WSF began with a pilot installation on one of two engines on the M/V Chetzemoka in early 2014 and is interested in utilizing a three pronged perspective in their decision making on whether to install more of these filters in their fleet, considering operational performance, cost savings, and potential environmental benefits. These three perspectives are the focus of this research endeavor, with operational performance considered through lube oil analysis of samples taken from the M/V Chetzemoka, potential cost savings through a life cycle cost analysis (LCCA), and potential environmental impacts through a life cycle assessment (LCA) methodology. This report covers the first stage of this research effort: a background on lube oil analysis, a rough order of magnitude life cycle cost analysis of lube oil and the filtration alternatives, and an overview of environmental impacts of lube oil and some disposal methods through life cycle assessment methodologies.

The preliminary LCCA shows that for a retrofit vessel such as the M/V Chetzemoka, cost savings would likely be achieved by installation of a self-cleaning filtration system, considering a 50 year life cycle. These savings would be even greater for installation on a new vessel.

The environmental impact data assembled and modeled herein gives WSF a simple tool for approximating environmental impacts from an LCA perspective separately for acquisition and disposal by distillation. It can be applied directly to the filter problem, or in other capacities when oil use and disposal volume changes are involved. For the acquisition of lube oil, the most significant impact category with respect to US daily normalization per capita is Human Health

Non-Cancer. For disposal through distillation to other products, the benefits gained from offsetting these products are always higher than the impacts of the disposal process.

Future work is ongoing to gather more information on the oil analyses with the self-cleaning oil filter over extended periods. With this additional information, the work herein will be updated. For the environmental analysis, future work might relate the gallon functional unit to different functional units relevant to WSF operations such as passenger/vehicle capacity, etc. Additional future research could be to expand the analyses to consider other vessels in the fleet.

CHAPTER 1: INTRODUCTION

1.1 Project Background

The Washington State Department of Transportation (WSDOT) has the mission of providing Washingtonians with “safe, reliable and cost effective transportation options” which improve the communities they serve. At the same time, they value innovation, leadership, and sustainability (WSDOT 2014). Washington State Ferries (WSF) is a ferry system operated by WSDOT in Puget Sound in the Seattle-Tacoma metropolitan area. As innovators, leaders, stewards of the environment, and an organization committed to serving their communities, WSF actively pursues novel options to reduce costs and environmental impacts of their operations. WSF has proposed an alternative of the propulsion engine lubricating oil filtration systems on some vessels in their fleet. Currently, WSF uses disposable cartridge filters for oil filtration on most vessels. Self-cleaning oil filters could be installed which would eliminate the need for disposable filter cartridge changes. Additionally, the self-cleaning oil filtration systems are fitted with centrifugal bypass filters which might raise the particle removal efficiency, resulting in improved oil cleanliness, in turn increasing the oil service life (Alfa Laval 2013). Based on this information, the effect of using a self-cleaning filtration system with centrifugal bypass could be to eliminate disposable filter cartridge use and reduce oil use. However, this type of filtration system is not commonly used on marine vessels and limited information is available on its efficacy in this application, with most available data developed from locomotive engines.

Due to the potential of this system to reduce disposal and oil use, Washington State Ferries is investigating their potential use in a marine application, which began with a pilot installation on one of two engines on the M/V Chetzemoka in early 2014. Washington State Ferries is utilizing a three pronged perspective in their decision making on whether to install more of these filters in their fleet, considering operational performance, cost savings, and potential environmental impacts; that is, ‘How well does it work?’, ‘Could it save money?’, and ‘How might it affect the environment?’. These three perspectives are the focus of this research endeavor, with operational performance considered through oil analysis of samples taken from the M/V Chetzemoka, potential cost savings through a life cycle cost analysis, and potential environmental impacts through a life cycle assessment (LCA) methodology. This report covers the first stage of this research effort. The data for these assessments contained herein are particular to the M/V Chetzemoka. Future work should provide information to support the possible decision to install a second self-cleaning filtration system on the M/V Chetzemoka and include more detailed costs as well as environmental impacts of other parts of the oil system.

The information presented herein does not provide definitive answers on whether or not the alternative systems should be installed and does not attempt to address every possible consideration. Additionally, it became clear that at this time the pilot filtration system has not been installed long enough to provide clear indication of filter performance. Accordingly, the oil analysis portion of this report consists of information on oil analysis procedures and interpretation, and the development of tools that may be useful to assess the filtration performance once enough data has been collected. Because filtration performance has not yet been determined, the cost assessment considers a range of possible oil change intervals that might be achieved, and the environmental assessment presented is initial, based around a unit of oil, rather than operational considerations such as a unit of time or engine hours.

1.2 What is a Self-Cleaning Filter?

Self-cleaning oil filtration systems filter oil without the need for disposable filter cartridges. At least one arrangement for accomplishing this is to filter oil with a stack of stainless steel mesh discs which can be backwashed for cleaning. In this type of system, full flow oil filtration is accomplished by the majority of the disc area while the rest has oil flowing back in the opposite direction, which is then diverted to a centrifuge rather than directly to the oil sump. This flushing removes the accumulated solids on the discs and the backflushed oil, now richer with solids, is cleaned in a centrifuge (Alfa Laval 2012). This is accomplished through movement of a distributer as shown in figure 1.1. The centrifugal filter usually obtains a higher removal efficiency than the full flow discs or a standard cartridge style filter. Because the system does not use disposable filters, there are no filter changes. The centrifuge does have a liner (similar to a coffee filter) on which the solids removed in the centrifuge accumulate. According to product literature the typical time period for replacement of this liner is roughly every six months. Figure 1.2 is a schematic of the full system (less the centrifuge) that shows how the discs are stacked and where the oil moves through the system.

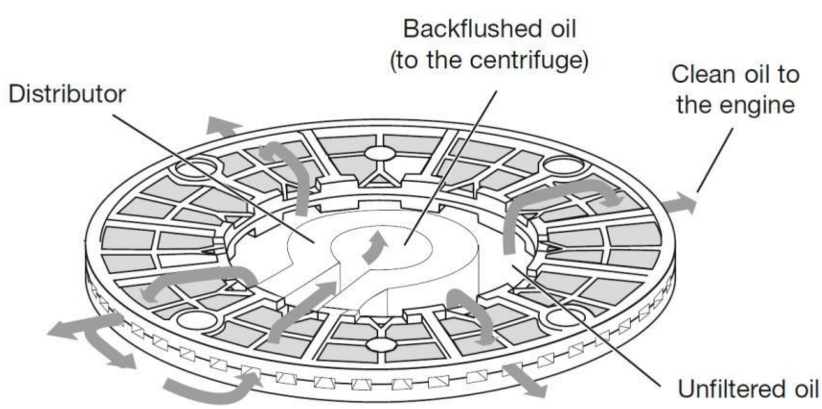

Figure 1.1 Full flow self-cleaning filter disc schematic (Alfa Laval 2012)

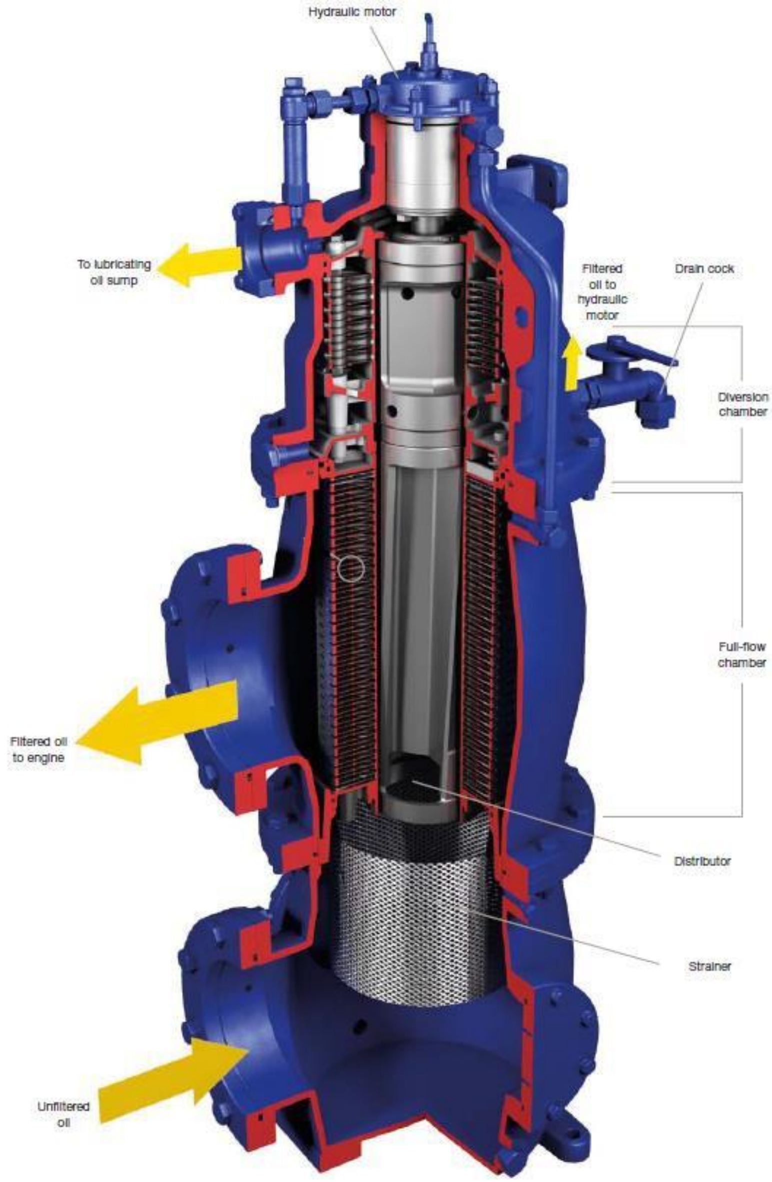

Figure 1.2 Eliminator self-cleaning filtration system schematic (Alfa Laval 2012)

Alfa Laval produces a filter of this type called the Eliminator, which is the filter installed on the M/V Chetzemoka (fig. 1.3). The particle removal size of this filter is approximately 10 μm (micrometers) through the full flow discs and 2 μm in the centrifuge. Oil cleanliness comparisons were studied by Alfa Laval and Norfolk Southern Corporation which suggested through analysis data that the Eliminator filter outperformed a standard paper filter canister, particularly later in oil life, on locomotives (Mattey and Haley 2009). Alfa Laval estimates that oil life is typically doubled (Alfa Laval 2013), and at least one customer testimonial has claimed much longer oil life extensions were achieved in their Boston Harbor Cruises fleet (Schmelz 2001). In addition to oil life extension and filter cartridge elimination benefits, the system also requires less space in the engine room than a typical canister filtration system.

Figure 1.3 Self-cleaning filter installed on M/V Chetzemoka

<u>1.3</u> <u>What is Lubricating Oil?</u>

Lubricating (lube) oil is a widely used fluid with a variety of industrial, commercial, and home applications. One major application is as engine oil and it is this type of lubricating oil that is the subject of this study. The main purposes of engine oils are to prevent metal to metal contact, reduce friction, and transfer heat. As a necessary component in nearly all engines, and with the need for frequent replacement as oil properties degrade with use, lube oil is continually needed for engine operation. The majority of lubricating oils in use today are petroleum based, as are the oils used by Washington State Ferries. Following production of base oil, additives are blended into the oil to give it better lubricating properties.

Lubricating oil must be changed on a regular basis due to oxidation, viscosity change, wear metals and dirt entering the oil, and necessary additives being used up (Livingstone 2013). Manufacturer oil change intervals are generally based on miles in passenger vehicles or hours in marine vessels or large equipment (Pirro and Wessol 2001). Often, the oil has not yet reached the point where it needs to be changed and recommended change intervals are typically very conservative. Oil analysis can be done to test actual oil properties, rather than relying on a miles or hours estimate. This is done by taking small periodic samples of oil and sending them to a laboratory. Then, based on the results of laboratory tests, a change interval is determined. This approach to oil changes only makes economic sense in a fleet of vehicles or ships that use large quantities of oil. This not only ensures that the oil is being changed often enough, but in most cases extends the oil change intervals (Hojat and Mollazade 2009).

1.4 What is in This Report?

In this report, Chapter 2 overviews what an oil analysis program is and what some important factors are in their development. It also contains a summary of a WSF Oil Analysis Database developed specifically for this project. Chapter 3 contains the preliminary life cycle cost analysis. Chapter 4 contains a compilation of environmental life cycle assessment information related to lube oil. Finally, Chapter 5 recaps the project information in the preceding chapters and depicts a methodology for combining both oil analysis (performance) information and cost information as an aid in decision-making, particularly with respect to also qualitatively considering risk.

CHAPTER 2: REVIEW OF AN OIL ANALYSIS PROGRAM

2.1 Introduction to Oil Analysis

Lube oil keeps moving metal parts within an engine from scraping together by providing a thin layer of protection between those parts. Without oil, an engine could not function. Along the same lines, oil of poor quality may lead to poor engine performance and, in the long run, degradation of the engine itself. Therefore, it is important that engine oil remain in proper condition to effectively lubricate an engine at all times during operation.

Likely, the most effective method for ensuring continual oil quality is through oil analysis. Condition of the oil including wear metals levels, contaminant levels, additive levels, and physical and chemical properties can be determined through oil analysis. These properties can reveal how well the oil is able to lubricate and how quickly the engine is wearing. These are the two main purposes of oil analysis: determination of oil quality and detection of excessive engine wear (indicative of a problem within the engine). While excessive wear can cause oil to degrade, these two are unique conclusions that can be determined from similar tests. Both are important and can often individually justify the costs of an oil analysis program through extending oil and filter change intervals, and by extending the lifetime and increasing the reliability of expensive machinery through detection of maintenance needs. This portion of the report focuses on oil health interpretation because the main goal of the oil analyses for the WSF self-cleaning oil filter project is to explore how well the filtration system is filtering oil, and how this might translate to extended oil drain intervals.

The terms operational oil analysis, research oil analysis, and condition-based oil analysis will be used throughout this report. Operational oil analysis is a program which is used to monitor the properties of the oil to reveal if the oil is currently degraded or if there are potential wear or contamination problems in the engine. In this approach, oil changes are occurring in a scheduled fashion based on conservative metrics such as operating hours or time.

Research oil analysis is used to investigate whether or not oil can be left in service for an extended period of time. This approach leaves the oil in service for longer periods of time, and tracks the oil properties to monitor how quickly degradation is occurring and how much the oil change interval could be extended. Research oil analysis will be the approach taken to determine the effectiveness of self-cleaning oil filtration in future studies, once enough data is available.

Condition-based oil changes are basically the result of research oil analysis. In this case, oil changes occur when the properties of the oil have reached benchmark levels signaling poor oil health, rather than when a time/hours based schedule dictates changes occur, typically extending oil drain intervals. Throughout this process operational oil analysis is also continued to track anomalies that might indicate future issues. It is being considered by WSF for this vessel.

2.2 Designing an Oil Analysis Program for Condition-Based Oil Changes

The success of an oil analysis program, with the goal to extend oil change intervals and prolong equipment life, depends largely on the design of the program and the effort put in to ensure proper procedures, laboratory communication, and results interpretation. This section serves as an outline for the preliminary design of such a program that may be helpful to WSF going forward with condition-based oil changes for the self-cleaning filters.

The first question to ask when designing an oil analysis program might be "Is condition-based oil analysis right for our operation?" While analyzing oil is almost surely beneficial to interpreting the needs of equipment and oil change intervals, the cost and effort involved means that oil analysis is not the right decision for every machinery user. Fitch (2001) has developed a checklist (fig. 2.1) to serve as a rough guide for deciding if a company should undertake condition-based oil analysis. A score of over 100 on this checklist indicates a good fit for condition-based oil analysis and over 200 means it is almost sure to positively impact the operation (from a cost perspective).

Condition-Based Oil Change Scorecard

Machine I.D.:

This scorecard is used to assess whether oil changes should be performed on a "scheduled basis" (for example, once per year) or "on condition" using oil analysis. Place a number one (1) in only one box for each of the nine questions below. The red numbers below each box are the assigned weighed score. Once all nine questions have been scored, the Total Score is registered at the bottom. A "condition-based" oil change is generally recommended for machines that score 100 or more.

1. What is the volume of fluid contained in machine compartment, including circulating lines?				
< 5 gallons	6 - 20 gallons	21 - 100 gallons	> 100 gallons	
0	10	40	100	
2. How much makeup fluid as a percent of total volume is added per year or between oil changes?				
< 1% per year	1 - 5% per year	6 - 15% per year	> 15% per year	
0	5	15	25	
3. What is the cost of the lubricant or hydraulic fluid?				
< $2 per gallon	$2 - 4 per gallon	$5 - 10 per gallon	> $10 per gallon	
0	5	25	50	
4. What is the cost of performing an oil change (not including the lubricant cost)?				
Insignificant	Moderate	High	Very High	
0	10	20	50	
5. How accessible is the machine for changing the oil?				
Very accessible	Moderately	Difficult or machine is infrequently available	Not accessible or available	
0	10	20	30	
6. What is the OEM recommended oil change interval?				
1 month or less	1 - 3 months	4 - 12 months	> 12 months	
0	5	10	20	
7. What is the availability of oil analysis (based on turnaround time)?				
> 10 days turnaround	5 - 10 days turnaround	2 - 4 days turnaround	Onsite or < 2 days turnaround	
0	10	20	30	
8. What is the general cost/penalty of machine failure if oil is not changed on time?				
Extremely high	High	Moderate	Very low	
-50	-20	0	30	
9. What is the quality of filtration?				
No filtration provided	Periodic and/or coarse filtration (> 15 microns)	Continuous filtration (6 - 15 microns)	Continuous filtration (< 6 microns)	
0	5	20	40	
				Total Score

Figure 2.1 Oil analysis viability checklist (Fitch 2001)

Risk should also be considered in any oil analysis program. There is always a chance of extra inconvenience when maintenance needs to be done based on test results, which are more unpredictable than scheduled maintenance. This can put a piece of machinery at risk of needing to be pulled out of service for an oil change if critical results are received. However, warning signs usually come on gradually and a situation like this would be rare. With increased oil change intervals there is also some risk of increased wear on the engine. While properties are being monitored, the oil is running in the engine longer meaning that some of the time the oil is running it may be lower quality than before (Fitch 2001). Usually, instituting condition-based oil analysis for extended drain intervals would also include operational oil analysis which may catch these events and overall reduce engine wear.

In selecting an oil analysis laboratory for this program, consider the questions posed in figure 2.2, taken directly from Van Rensselar (2014). Then, choose a test slate in accordance with program goals and equipment characteristics.

CONSIDERATIONS FOR CHOOSING A LAB

Following are a few considerations for selecting an oil analysis lab:

- What are the costs per test and what is/is not included?
- How easy is it to read and interpret reports? (Ask to see a sample report.)
- What guarantees does the lab offer?
- What are the lab's hours of operation?
- How much technical support is available?
- How quickly can the sample get to the lab?
- What are report delivery and format options? Can users sort data?
- What is the turnaround time for sample results?
- What kind of customer training programs does the lab offer?
- Does the lab have proper ISO accreditation?
- Do tests conform to ASTM standards?
- Are lab employees' skills kept up to date and/or are they regularly certified?

Figure 2.2 Laboratory choice considerations (Van Rensselar 2014)

In addition, the frequency of oil testing, sampling locations, and responsive actions needed in case of each warning level should be established (Noria Corp. 2004, Van Rensselar

2014). The frequency of oil testing is an important parameter and one that depends on the type of engine, engine age, expected oil life and more. Testing frequency is sometimes a moving target, such as more frequent testing in very new or old engines and near the end of expected fluid life (Williamson 2001). However, in most situations this approach is too complicated and a set time interval between samples is sinpler. It is common to review previous data to help determine how quickly the oil in a system typically deteriorates from the first sign of a problem to a serious situation, and setting sampling intervals with respect to that metric (Toms 1998). Additionally, some recommend that new oil be tested every time a shipment is received because the properties listed from the manufacturer may vary and an accurate starting point is needed to monitor changes in oil properties (Cat 1998). This initial oil testing can be limited to only a few tests for the most important parameters and does not need to include any tests that would normally be used to detect engine wear, such as wear metals (Toms 1998). Of course, critical to the oil sampling frequency are the timeliness of test results and their interpretation.

Oil sampling procedures aid in obtaining useful results. Many authors identify poor sampling procedures as a major cause of poor oil analysis program results (Fitch and Troyer 2004, Potteiger 2011, Van Rensselar 2012a). If samples are not taken correctly, consistently, and in the right location, the results of analysis on those samples may not be accurate. This can lead to false positives or false negatives resulting in unneeded corrective actions or no action when corrections are needed, respectively (Potteiger 2011).

Sampling location is important for getting a representative sample of oil. Different types of machines, oils, and program goals may require different sampling locations. However, for general oil sampling in a diesel engine the following guidelines might apply although sometimes these guidelines cannot be met due to physical limitations (Fitch and Troyer 2004).

- Collect the oil sample between the pump and the filter.
- Attempt to set up a sampling point in a location where oil is flowing turbulently so that it is well mixed (rather than having settled material).
- Avoid using sampling ports perpendicular to the direction of oil flow as particles can “fly-by”, resulting in a sample with reduced particle count. Instead try to position sampling ports on a 90 degree bend in the oil piping system.

Sampling procedures are equally as important as sampling location. They need to be clear, documented in writing, and followed by all samplers to ensure uniform, high-quality data. Bottles for collection must be clean and well labeled. They must also be large enough to allow the lab to shake and remix any settled particles in the bottle. A general guideline for high viscosity oil is to choose a sampling bottle that is twice as large as the volume of oil needed. The machine should be operating in normal conditions when the sample is taken. Open the sampling port and allow some flushing to occur into a waste oil bottle before taking the sample. Finish taking the sample and move the waste oil bottle back in place under the sampling port before closing the valve. This ensures that the sample taken does not include any irregularities due to opening and closing the sampling port. Send the samples to the lab as soon as feasible because properties can change while sitting in the sample bottle (Fitch and Troyer 2004). It is also important to include information about the engine and oil along with every sample such as the oil type, hours on the oil, hours on the filter, and makeup oil added. This information may aid in subsequent interpretation (Noria Corp. 2004).

Figure 2.3 (directly from Noria Corp. 2004) is a general guide to who is usually responsible for each task in an oil analysis program, although it can vary from program to program.

	Responsibility	
	End User	Laboratory
Step No. 1. Oil Analysis Program Design		
Select components to be sampled	X	
Select the correct tests based on component type	X	X[1]
Select the correct tests based on failure history, RCM and FMEA	X	
Select the correct tests for reliability goals (condition-based oil changes, extend MTBF, etc.)	X	
Select the correct test methods based on desired limits	X	X
Step No. 2. Sampling Strategy		
Select appropriate sampling location(s)	X	
Select sampling frequency	X	
Deploy correct sampling procedures	X	
Use appropriate sampling tools and hardware	X	
Ensure sample bottles are clean	X	X[2]
Provide appropriate sample information (lube type, hours on oil and/or machine, component manufacturer, etc.) for data logging and interpretation	X	
Ensure samples are sent to the lab in a timely fashion	X	
Step No. 3. Data Logging and Analysis		
Log sample information into lab computer database correctly		X
Provide up-to-date new oil sample for accurate base lining of data	X	
Ensure lab is using correct procedures (ASTM, ISO, etc.)	X	
Ensure test instruments are appropriately calibrated		X
Ensure test procedures are accurate, documented and followed		X
Ensure appropriate QC samples are run for all tests and appropriate action taken for all nonconforming QC samples		X
Ensure correct exception tests are deployed when necessary	X	X
Ensure samples are analyzed with 24 to 48 hours		X
Step No. 4. Data Diagnosis and Prognosis		
Compare fluid properties (viscosity, acid number, etc.) with new oil reference and apply appropriate limits based on industry standards		X
Evaluate wear debris data and flag according to OEM limits, statistical limits, trends, etc.		X
Provide reliability goal-based limits for contamination control	X	
Evaluate fluid cleanliness/dryness data relative to goal-based limits		X
Review all sample data and make initial interpretative assessment		X
Carefully review data in combination with maintenance activities and data from other CBM technologies (vibration, thermography, etc.)	X	
Make appropriate CBM decision based on data, experience, reliability goals and objectives	X	
Step No. 5. Performance Tracking and Cost Benefit Analysis		
Use oil analysis to ensure oil condition targets are being met	X	
Use oil analysis to track compliance with contamination control targets	X	
Use oil analysis data in conjunction with asset management information to evaluate cost benefit of oil analysis	X	
Continually review and improve oil analysis program to reflect reliability goals and to optimize oil analysis CBA	X	

1 Many labs provide packaged tests, which should be tailored to component type.
2 If lab provides sample bottles, lab should ensure bottles are certified according to ISO 3722.

Figure 2.3 Standard task delegation in an oil analysis program (Noria Corp. 2004)

The laboratory usually handles the initial interpretation tasks. It is valuable to communicate with the laboratory to determine what actions to take for each level of warning and each parameter (or group of similar parameters) and to document the plan for easy reference. Also, it is useful to document past oil analysis indicators that have resulted in corrective actions as well as those actions which were taken and how this affected the equipment or the next oil sample to help in refining the plan for maintenance actions due to out of limit oil properties.

2.3 Test Report and Property Interpretation for Both Operational and Research Based Programs

Figure 2.4 is an example of an oil analysis report. The main headings are Metals, Contaminants, Additives, Physical Tests, and Physical/chemical Tests.

DATE SAMPLED							
DATE RECEIVED							
DATE REPORTED							
LAB NO.							
SIF NO.							
TIME ON UNIT	Hrs	16469	15922	15355	14809	14241	13472
TIME ON OIL	Hrs	2948	2431	1865	1318	750	3124
OIL BRAND		Chevron	Chevron	Chevron	Chevron	Chevron	Chevron
OIL TYPE		Delo 710 LE	Delo 710 LE	Delo 710 LE	Delo 710 LE	Delo 710 LE	Delo 710 LE
OIL GRADE		SAE 20W40	SAE 20W40	SAE 20W40	SAE 20W40	SAE 20W40	SAE 20W40
OIL ADDED		40.0		0.0			
FILTER	Hrs	400	2141			750	1389
OIL CHANGED							
WO NUMBER							
Metals (ppm)							
Iron (Fe)		6	5	4	7	3	6
Chromium (Cr)		<1	<1	<1	<1	<1	<1
Lead (Pb)		5	5	3	4	1	4
Copper (Cu)		15	12	9	12	6	14
Tin (Sn)		2	2	<1	<1	<1	<1
Aluminium (Al)		2	2	2	2	2	2
Nickel (Ni)		<1	<1	<1	<1	<1	<1
Silver (Ag)		<1	<1	<1	<1	<1	<1
Titanium (Ti)		<1	<1	<1	<1	<1	<1
Vanadium (V)		<1	<1	<1	<1	<1	<1
Contaminants (ppm)							
Silicon (Si)		4	3	2	3	2	2
Sodium (Na)		1	<1	<1	<1	<1	<1
Potassium (K)		<5	<5	<5	<5	<5	<5
Water (%)		<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Coolant		No	No	No	No	No	No
Additives (ppm)							
Magnesium (Mg)		9	<1	<1	<1	3	<1
Calcium (Ca)		3300	3100	2870	3270	3330	2930
Barium (Ba)		5	<1	<1	1	<1	<1
Phosphorus (P)		65	41	37	80	42	43
Zinc (Zn)		6	1	5	2	2	<1
Molybdenum (Mo)		71	64	60	66	68	60
Boron (B)		<5	<5	<5	7	<5	<5
Physical Tests							
PQ Index		<10	<10	<10	<10	<10	<10
Viscosity (cSt 100C)		14.5	14.3	14.7	14.5	14.5	14.5
Viscosity (cSt 40C)		133.9	135.7	129.4	128.7	140.1	135.8
Viscosity Index (D2270)		108	104	115	123	102	106
Soot (%) Infrared		0.2	0.2	0.1	0.1	0.1	0.1
SAE Rating Determination		40	40	40	40	40	40
Fuel (%)		<1	<1	<1	<1	<1	<1
Physical / Chemical							
Oxidation (Abs) E2412/D7414		3	2	2	1	<1	4
Acid Number (mgKOH/g)		2.85	1.62	1.68	1.09	1.46	1.95
Base Number (mgKOH/g)		6.9	7.3	7.4	7.8	8.6	7.3

Figure 2.4 Example oil analysis test report

Wear metals (titled "Metals" in fig. 4) are those metals which are commonly used as materials of engine components. These metals enter the oil through wearing of engine components. Their levels tend to increase the longer an oil is run as some wear is inevitable, but sharp increases in wear metals levels is usually indicative of a problem that needs to addressed. Contaminants are materials that enter the oil primarily through poor seals and during oil changes and top-ups (addition of oil such as after a filter change). Contaminant levels tend to stay steady around a low or zero value, and any kind of sharp increase would probably be indicative of a problem. Additives are materials intentionally put in the oil by the oil manufacturer which are designed to increase lubrication, resist oil degradation, and more. These materials are typically depleted during operation. Depending on the situation, however, this decrease can happen very gradually and often the information gleaned from additive levels is generally limited because in many cases when additive compounds are consumed they change at the molecular level, but the elemental metal concentrations (what is measured for additive levels) remain the same (Toms 1998). Physical and physical/chemical tests are those which typically determine how well the oil is able to lubricate and how much longer it can be left in service.

The bulleted listing of tested parameters that follows this paragraph was taken directly from ALS Tribology's document entitled "Interpreting Your Analysis Results" and as such are italicized (ALS 2010). A few additional pieces of information were added to this list and are referenced where applicable. The "Spectrochemical Analysis for Wear Metals" section lists major sources of wear metals (particular engine components) that may need to be inspected upon high test results, although there may be other sources in addition to those listed. "Spectrochemical Analysis for Contaminants" lists possible sources of each contaminant (both internal to the engine and external). "Spectrochemical Analysis for Additives" lists the role that each additive plays in the oil. "Physical and Chemical Tests for Lubricant Condition" discusses the effects of each contaminant listed on the oil's health. "Physical and Chemical Tests for

Lubricant Service Life" discusses the meaning of each parameter in terms of effects on the engine and oil health, reasons for changes in those properties, and typical trends over oil life. This information is intended to be a short summary.

<u>*Spectrochemical Analysis for Wear Metals*</u>

- ***Iron (Fe):*** *Major component material in equipment manufacturing. Housing/Blocks, Cylinders, Pistons, Gears, Bushings, Bearing, Shafts, Valves, Rings, Rust*
- ***Chromium (Cr):*** *Cylinders Liners and Guides, Bushings, Bearing, Shafts, Valve, Rods, Rings, Hydraulic Cylinders*
- ***Lead (Pb):*** *Bearings/Bushings, Thrust Plates, Washers*
- ***Copper (Cu):*** *Bearings/Bushings, Thrust Plates, Washers, Oil Cooler, Pumps, Disc/Disc Lining*
- ***Tin (Sn):*** *Bearings/Bushings, Pumps, Motors, Compressor Piston, Piston skirt overlay*
- ***Aluminum (Al):*** *Pistons, Bearings/Bushings, Thrust Washers, Rings, Housing/Blocks, Oil Cooler, Cylinders and Cylinders Guides, Engine Aftercooler*
- ***Nickel (Ni):*** *Gears, Shafts, Rings, Valve Trains, Bearings/Bushings, Pumps*
- ***Silver (Ag):*** *Bearings/Bushings, Oil Cooler, Some Gears and Shafts, Disc/Disc Lining*
- ***Titanium (Ti):*** *Bearings/Bushings, Some Gears and Shafts, Turbine Blades, Valve Trains, Gear Trains, Some Shafts (additive in some heavy duty motor oils - HDMOs)*
- ***Vanadium (V):*** *Turbine Blades, Some Bearings and Bushings*

<u>*Spectrochemical Analysis for Additives*</u>

- ***Antimony (Sb):*** *Antiwear and Extreme Pressure, Antioxidant*
- ***Barium (Ba):*** *Rust inhibitor, Water Separability*
- ***Boron (B):*** *Extreme Pressure Additive, Detergency*
- ***Calcium (Ca):*** *Detergency, Alkalinity Reserve (contributes to base number)*
- ***Magnesium (Mg):*** *Detergency, Alkalinity Reserve (contributes to base number)*
- ***Molybdenum (Mo):*** *Extreme Pressure Additive, Lubricity Additive*
- ***Phosphorus (P):*** *Antiwear when present with Zinc, Extreme Pressure Additive, Friction Modifier*
- ***Sodium (Na):*** *Corrosion Inhibitor*
- ***Silicon (Si):*** *Anti-Foam Additive*
- ***Zinc (Zn):*** *Antiwear when present with Phosphorus, Antioxidant, Anticorrosive*

<u>*Spectrochemical Analysis for Contaminants*</u>

- ***Aluminum (Al):*** *Aftercooler Brazing Flux, Dirt if in combination with Silicon*
- ***Boron (B):*** *Engine Coolant*
- ***Magnesium (Mg):*** *Seawater if present with sodium*
- ***Potassium (K):*** *Engine Coolant, Aftercooler Brazing Flux*
- ***Silicon (Si):*** *Dirt, Gasket/Sealant Material, Engine Coolant*
- ***Sodium (Na):*** *Engine Coolant, Seawater, by product from Natural gas (wet gas) transferring*

  (Note that boron, silicon and sodium are in both the additive and contaminant lists.)

Physical and Chemical Tests for Lubricant Contaminants

- ***Water:*** *Water as a contaminant will generally lead to increased corrosion, depletion of proper lubricating film, decreased lubricant performance life and increased acid formation.*
- ***Coolant:*** *Coolant contamination will degrade lubricant service life and performance, create sludge and block lubricant passageways.*
- ***Fuel Dilution:*** *Fuel dilution will decrease fluids viscosity, therefore affecting its lubricity properties. Fuel dilution also promotes degradation of lubricant service life and additive properties.*
- ***Soot:*** *Excessive soot increases viscosity, creates excessive wear, and will tie up active additives needed for lubricant performance.*
- ***Particle Count:*** *"Clean Systems" require a minimum level of cleanliness in order to operate reliably. This is especially true for circulating systems with high pressure and close tolerance components. The ISO Cleanliness Rating is a convenient way to communicate the level of particulate contamination within a system based on the particle count for micrometers sizes greater than 4, 6, and 14.*

Physical and Chemical Tests for Lubricant Condition and Service Life

- ***Viscosity:*** *Improper viscosity can affect a lubricant's performance.*
  - *Too low of a viscosity will not create sufficient surface film to keep moving parts separated and prevent rubbing on opposing metal surfaces.*
  - *Too high of a viscosity will create excessive heat and reduced fluid flow within circulating systems.*
  - *A change in viscosity will indicate a change in the fluid performance integrity. A drop in viscosity generally indicates contamination with a lighter product, addition of an incorrect viscosity grade, and in some cases thermal cracking. An increase in viscosity can indicate oxidation and reduced service life due to age, addition of an incorrect viscosity grade, or excessive soot or insolubles content.*
- ***Base Number:*** *Base number represents the level of alkalinity reserve available for neutralizing acids formed during the combustion process which may be introduced through recirculated exhaust gases. As the lubricant ages and the additive package depletes, the base number will decrease from its initial fresh oil value.* Base number is a measure of the alkalinity present in the oil and is measured in milligram of potassium hydroxide per gram of lubricating oil (Peng 2009).
- ***Acid Number:*** *Acid number in a new lubricant represents a certain level of additive compounding. This can come from antirust, antiwear or other additives. The acid number can drop a bit after a lubricant has been in service for a certain period, which indicates some initial additive depletion. After a time the acid number will start to increase, which indicates the creation of acidic degradation products related to oxidation. The acid number is a means of monitoring fluid service life.* Acid number is a measure of the amount of acid present and is defined as the milligrams of potassium hydroxide needed to neutralize the acid present in one gram of lubricating oil (Peng 2009).
- ***Oxidation Number:*** *The oxidation number is a relative number that monitors increase in the overall oxidation of the lubricant by infrared spectroscopy. This test parameter generally compliments other tests for fluid service life, such as viscosity and acid number. Generally this test is not used as a primary indicator when all other tests are*

within normal limits. Accurate oil information is required to get the most valid test results. (Oxidation means that some of the important organic compounds in the oil are being oxidized and therefore changing their characteristics.)

<u>Tests for Wear Debris</u>

- ***Particle Quantification Index (PQI):*** *PQI is a valuable trending tool for monitoring the relative level of ferrous wear material within a lubricant sample.*

<u>2.4 Oil Analysis to Determine Oil Health</u>

It is widely agreed upon in the literature that oxidation is the primary mechanism of oil degradation. As oil oxidizes, its properties change and its ability to effectively lubricate diminishes. Oxidation causes organic compounds to change into different intermediates, sometimes causing long chain molecules to break down into smaller chains and take on a different shape and having different chemical formulas, most notably with additional oxygen make-up. This changes the way the molecules interact with one another and with engine components, reducing the oil's ability to lubricate (Wurzbach 2000).

Some of the negative effects caused by oxidized oil include "viscosity increase, varnish, sludge and sediment formation, additive depletion, base oil breakdown, filter plugging, loss in foam control, acid number (AN) increase, rust formation and corrosion." (Wooton 2007). Oxidation is controlled mostly by the additives in the oil which can convert the oxidation-formed acid compounds into salts, reducing the impact on the oil. Because oxidation forms acidic compounds, a simple and common way to indirectly measure oil oxidation is through acid number, although tests for direct measurement of oxidation, such as FTIR-oxidation, do exist (Wooton 2007). Similarly, base number is a readily measured important indicator of oil health (some sources do list base number as the most important indicator). While oxidation is the primary mechanism of degradation, one of the most important properties of lubricating oil and determinant of oil condition is typically said to be viscosity (Van Rensselar 2012b).

The next most common reason for condemning lubricating oils beyond degradation of these basic physical properties are high levels or rapid increases in wear metals or contaminants which could signal excessive engine wear or a source of contamination. Additive depletion is rarely a point of focus as this is difficult to detect, and the effects of changing additive levels can typically be detected through the base number changes (Thibault 2001).

The most common approach to determining the end of useful oil life is to set benchmark levels for each oil property that signal conditions where the ability of the oil to provide proper lubrication is at varying levels of risk. Many of these benchmarks are time independent – there is a level that once reached, regardless of time the oil has been in service, it is recommended that action should be taken. On the other hand, some benchmarks can also be time dependent meaning that they are defined by rate of change. Time independent benchmarks are almost universally used for the physical and chemical properties of lubricating oil including viscosity, acid number, and base number and usually used for wear metals, contaminants, and additives. On the other hand, time dependent benchmarks can be set for wear metals, contaminants, and additives to watch for rapidly deteriorating oil, because some level of wear, contamination, and additive depletion is expected, but if it is happening rapidly there may be a problem (Mayer 2005). Most of the following discussion is focused on time independent benchmarks.

Different labs use different terminology with regards to benchmark levels or values of the tested oil parameters which may require some type of action. Some use “caution”, “abnormal”, and “critical” while many other laboratories only include two levels. For most of this report, the terminology “alarm” and “limit” will be used. Alarms are values which generally warrant investigation, whether that be retaking a sample to be sure the results are accurate or taking relatively minor maintenance actions. Limits are the upper threshold value which often require much quicker action and signal a condition where damage to the engine or its components may be possible. It is important to have a written plan for course of action when samples are received back from the lab which exceed alarms or limits.

Setting these benchmarks is not always an easy process because every engine type, oil type, and application require different alarms and limits (Van Rensselar 2012b). Many authors provide rough guidelines generally based on change (absolute value or percentage) from a baseline (new oil properties) as a starting point. Table 2.1 has been copied from Marbach and Frame (1999) and shows engine manufacturer recommendation ranges for many properties based on a study which surveyed engine manufacturers. Alarms and limits generally come from the engine manufacturer, with the oil analysis laboratory guiding the adoption of these benchmarks, and setting them for other properties not addressed by the manufacturer, to meet the end user needs (Van Rensselar 2012b). Sometimes, the lubricant manufacturers and end users themselves are involved in setting alarms and limits as well. Benchmarks are determined in a number of ways, but the most common method (especially for wear metals and contaminants) is to test many similar machines and generate a frequency distribution of parameter levels. This shows what levels can be considered normal and then statistical methods (such as deviation by the standard deviation or a factor of it) are used to set limits based on that data (Noria Corp. 2003, Van Rensselar 2012b). Table 2.2 is a recommendation from Toms (1998) for setting benchmarks based on statistical analysis and includes both time dependent and time independent limits, but the data must form a nearly normal distribution for this statistical method to be applicable. For physical properties, limits can sometimes be set by testing the actual performance of oil.

Table 2.1 Summary of Original Equipment Manufacturer (OEM) oil property limits (Marbach and Frame 1999)

Engine Oil Drain Criteria Spread	
Property	**Guideline Limits Range**
Viscosity @ 40°C (100°F)	+40% increase; -15% decrease
Viscosity @ 100°C (210°F)	±1 visc. Grade; 3 or 4 cSt of new oil
Fuel Dilution	2.5% max.; 4%max.; 5% max.
Water Content	0.2% → 0.5% max.
Glycol Content	0 → 1000 ppm
TAN	2.5 increase
TBN ASTM D664 ASTM D2896	1.0 min 2.0 → 2.5 min.; ½ of new oil
Soot Content	0.8 → 1.5% max.
Pentane Insolubles	1.0 → 3.0% max.
Toluene Insolubles	2.0% max
Elements	
Silicon, Over Baseline*	1.5 ppm (+10 ppm/10 hrs) to 101 ppm
Sodium, Over Baseline	20 to 50
Boron, Over Baseline	20 to 25 ppm
Potassium, Over Baseline	0 to 20 ppm
Titanium, Over Baseline	5 ppm (+1 ppm/10 hours)
Iron, over Baseline	21 ppm (+4 ppm/10 hours) to 500 ppm
Copper, Over Baseline	6 ppm (+2 ppm/10 hours) to 400 ppm
Zinc, Over Baseline	20 ppm (+4 ppm/10 hours)
Lead, Over Baseline	6 ppm (+1 ppm/10 hours) to 152 ppm
Aluminum, Over Baseline	6 ppm (+2 ppm/10 hours) to 99 ppm
Chromium, Over Baseline	4 ppm (+2 ppm/10 hours) to 45 ppm
Molybdenum, Over Baseline	8 ppm (+2 ppm/10 hours) to 40 ppm
Silver, Over Baseline	0 to13 ppm
Tin, Over Baseline	15 to 90 ppm
*Baseline=Quantity in new oil	

Table 2.2 Benchmark setting recommendations through statistical analyses typically for wear metals and contaminants (Toms 1998)

Benchmark	**Formula for Determination**	**Interpretation**
Alarm level	Mean + 2 x Standard Deviation	"First warning of developing problem"
Limit level	Mean + 4 x Standard Deviation	"Problem has progressed to a serious stage"
Alarm trend	60% of alarm level	"Problem is progressing, action may be required"
Limit trend	90% of alarm level	"Problem is progressing rapidly, action is required"

As mentioned earlier, viscosity is usually recognized as one of the most important properties of a lubricating oil. If the oil has too high a viscosity (too thick) it can cause high startup and pump wear, decreased fuel efficiency, and high heat buildup. Too low a viscosity, and the protective film between moving parts may become insufficient to prevent engine wear. Increases in viscosity point to contamination, oxidation, or soot buildup, among other things. Decreases in viscosity might imply contamination, shearing, incorrect lubricant additions, and sometimes hydrocracking. Because of this, changes in viscosity often occur hand in hand with changes in contaminant levels, oxidation, and acid number (ALS 2014a).

Viscosity is generally managed through alarms and limits based on a percentage change from the baseline. Viscosity baselines are typically established by sending a sample of the new oil to the lab when oil changes are made (Noria Corp. 2003). As previously mentioned, the other most important properties are total acid number (TAN) and total base number (TBN). These two are closely related and a trend between them is usually well defined, but they represent different physical definitions. TAN is an indirect indicator of how oxidized the oil is by measuring the acidity of the oil. TBN shows how much acid reducing potential (alkalinity) is still contained in the oil. When oil is new, the TBN is high and the TAN is low. While in service, the TBN decreases and the TAN increases as alkalinity reserves are used up and oil is oxidized. TAN initially tends to hold steady, and then begin increasing when TBN reaches about 50% of baseline. More rapid increases in TAN tend to occur when TBN is around 35% of baseline and usually indicates that an oil change is needed (Polaris Labs 2009). If TAN spikes before this point is reached, it may be wise to change the oil earlier (Fitch 2013).

Note that oil change and filter change are two different things. With so much literature addressing oil change interval extension through oil analysis, it seems that there would also be information about how this affects filter change intervals, but none could be found. However, there are some recommendations to monitor the pressure drop across filter units as a means of determining if filters have become saturated with debris (EMD 2008). It is very unfortunate that filter change intervals are not addressed in most of the literature since filter changes may have significant maintenance expenses. It seems to be implied in some of the articles that filter and oil changes always happen simultaneously, but this is not always true. WSF tends to change the filter more often than the oil on the M/V Chetzemoka.

2.5 Insights for WSF

WSF appears to be a good candidate for using oil analysis to extend oil drain intervals. The quantity of oil used fleet-wide is very high and benchmarks levels are rarely triggered, so the potential payback of properly extended oil drain intervals may be significant. According to a preliminary subjective estimate for WSF, the score on the checklist for appropriateness of condition-based oil changes in figure 2.1 is around 150, implying a possible benefit from them.

The oil analysis results initially collected for the Chetzemoka before the new filtration system was installed, have only shown one parameter triggering any kind of alarm or limit. This is the particle quantification index (PQI) – a measure of total iron wear particles in the oil (ALS 2014b). This test is done through magnetic detection, a different method than the wear metal iron test. The PQI test detects all iron particles, whereas the wear metal test only detects those smaller than about 3 or 10 micrometers, depending on whether inductively coupled plasma or rotating disc electrode was used for the wear metal test, respectively (both testing methods are listed on the ALS report). When PQI is high and wear metal iron is low, the wear particles in the oil are larger than that 3 or 10 micrometer size above which the wear metal test does not detect. There is more than one possible reason why this could be occurring. It may be the case that the particles detected by the PQI test are simply larger than the wear metal test can detect, but smaller than the filter can remove. It could also be the case that there is a filter failure. Disposable filters can fail in at least three modes including rupture of the filter media, erosion of filter pores (pores become larger), and filter clogging. All of these possible issues have the potential to allow larger particles than intended to pass through (or around) the filter (Toms 1998). Any of these failure modes could be consistent with the test results which have shown that PQI levels in the oil are typically very low and steady, until spiking suddenly. Using a self-cleaning filter with a centrifugal bypass might solve both of these potential reasons for high PQI results. The higher removal efficiency of the centrifugal filter should remove any particles larger than the wear metal test can detect and would have less chance of ripping or clogging because the full flow filters are made from metal (rather than paper) and are continuously flushed.

With the higher filtration efficiency that should occur with the self-cleaning filters (due to the centrifugal bypass), some factors of oil health would be expected to improve. Removal of debris from the oil not only reduces the abrasion that might occur from those particles directly, but in some cases could limit other chemical effects that those particles impose on the oil, such as increased rate of oxidation. However, a different aspect of better filtration is the possibility that the filtration will be so effective that detecting engine wear problems may become more difficult due to the high removal rates of wear metals. If this is deemed to be of sufficient concern, one solution could be to utilize filter debris analysis testing (Toms 1998). By testing both the filter and oil for wear metals (in the case of the centrifugal filter, the pad would be tested) high removal efficiency may no longer limit engine condition monitoring capability. In addition, current analyses do not specifically address dissolved metals, nor would they be removed by better filtration. Further research coordinating liner metal content and dissolved metals content may indicate an alternative method for possibly detecting engine wear by a specific dissolved metals test on the oil.

According to one source, “proactive maintenance strategies” beyond oil analysis can double or triple lubricant service life (Fitch 2001). There is evidence that high efficiency filtration increases lubricant life through removal of particles that cause oil degradation (California DTSC 2008, Culpepper 2000, Lin 1993). A standard approach to implementing high efficiency filters is to use them as by-pass because full flow high efficiency filtration may restrict flow and build up too much pressure. According to Blackstone Labs (2014), “After having run many tens of thousands of diesel engine oil samples, it is our opinion that a by-pass oil filtration system is one of the most important factors in extending oil drains.” Additionally, engine wear and oil cleanliness have been linked (Lin 1993), meaning that keeping the oil cleaner through by-pass filtration may also extend the life of engine components.

After reading through many literature sources and collecting recommendations for rough oil analysis alarms and limits as well as reviewing technical documentation from the engine manufacturer (EMD), Table 2.3 was assembled as an initial estimation for engines similar to those used in the M/V Chetzemoka. At this time, the recommendations of the oil analysis laboratory are not available, and its input will be added when it becomes available. The technical documentation about oil and engine health from the engine manufacturer includes more information (including possible reasons for out of limits results and recommended corrective actions) than could be reasonably included in table 2.3 and can be reviewed separately (EMD 2008). No recommendations (or very widely varying recommendations) were found for parameters with a recommended value of “?”.

Table 2.3 Benchmark values of tested oil parameters by source.

	Property	Literature Review		Electromotive Diesel	
		Caution	Critical	Caution	Critical
Metals (ppm)	Fe	43[a]	55[a]	75	125
	Cr	17[a]	25[a]	10	20
	Pb	27[a]	38[a]	50	75
	Cu	29[a]	37[a]	75	150
	Sn	5[a]	9[a]	?	?
	Al	8[a]	12[a]	?	?
	Ni	?	?	?	?
	Ag	?	?	1	2
	Ti	?	?	?	?
	V	?	?	?	?
Contaminants (ppm)	Si	?	?	5	10
	Na	67[a]	106[a]	?	?
	K	?	?	?	?
	Water %	?	?	N/A	Any
	Coolant	?	?	?	?
Additives (ppm)	Mg	2.7[b]	2.25[b,f]	?	?
	Ca	3150[b]	2625[b,f]	?	?
	Ba	0[b]	0[b,f]	?	?
	P	36[b]	30[b,f]	?	?
	Zn	0[b]	0[b,f]	?	?
	Mo	54[b]	45[b,f]	?	?
	B	0[b]	0[b,f]	?	?
Physical Tests	PQI	?	?	?	?
	Viscosity @ 100C max	16.5[b,d]	18[b,c,d,g,h]	?	17
	Viscosity @ 100C min	14[b,d]	12.5[b,c,d,g,h]	?	13
	Viscosity @ 40C max	155[b,d]	170[b,d,g,h]	?	?
	Viscosity @ 40C min	130[b,d]	120[b,d,g,h]	?	?
	Visc. Index	?	?	?	?
	Soot %	?	0.3[c]	?	?
	SAE Rating	?	?	?	?
	Fuel %	1.5[b]	3.5[b,c,g]	?	?
Phys./Chem.	Oxid. (Abs)	?	?	?	?
	Acid Number	1.2[b]	2.2[b,c,g]	?	4.5
	Base Number	4[b]	3[b,c,f,g]	?	2.5

[a]Toms 1998; [b]Noria Corp. 2006; [c]Thibault 2001; [d]Fitch 2013; [e]Polaris Labs 2009; [f]Johnson and Spurlock 2009; [g]Van Rensselar 2012b; [h]Wartsila 2012

In table 2.3, the literature results for metals and some contaminants are listed as "Based on Statistical Analysis of Previous Results." These values can be determined in a number of ways, but one common approach is to collect data from multiple engines (of the same model) over a period of time, find the mean and standard deviation of those test results for each parameter, and set the benchmark as a multiple of standard deviation over the mean (such as mean+2*standard deviation).

Some oil analysis users set both a timed change interval (extended from standard interval) as well as oil property limits and change whenever one is hit first. This provides a second layer of protection and makes the sampling period intervals not as critical and therefore the frequency of testing and expediting of the process probably more economical. It may be possible to make this type of decision using a cost-risk analysis technique.

2.6 Development of a WSF Oil Analysis Database

An online database is maintained by the testing laboratory for all of WSF's oil analysis results from every vessel and piece of equipment for which testing takes place. This research expanded this into a spreadsheet format which includes techniques for historical trending and plotting analysis (Langfitt and Haselbach 2014a). Detailed instructions for modifying or customizing the various sheets in the database are provided on a separate document (Langfitt 2014). An example output that might be obtained using this tool is in figure 2.5. The tool can also be used to visually depict other aspects of the engine. The "Operating Profile" sheet is a plot of the date versus the engine hours on that engine. This plot can quickly show if there has been any periods where the engine was not in use or in use more than usual. Given any unusual oil analysis results, this profile could be used to check if there was an unusual level of operation during those times. Figure 2.6 is a screenshot of an operating profile plot.

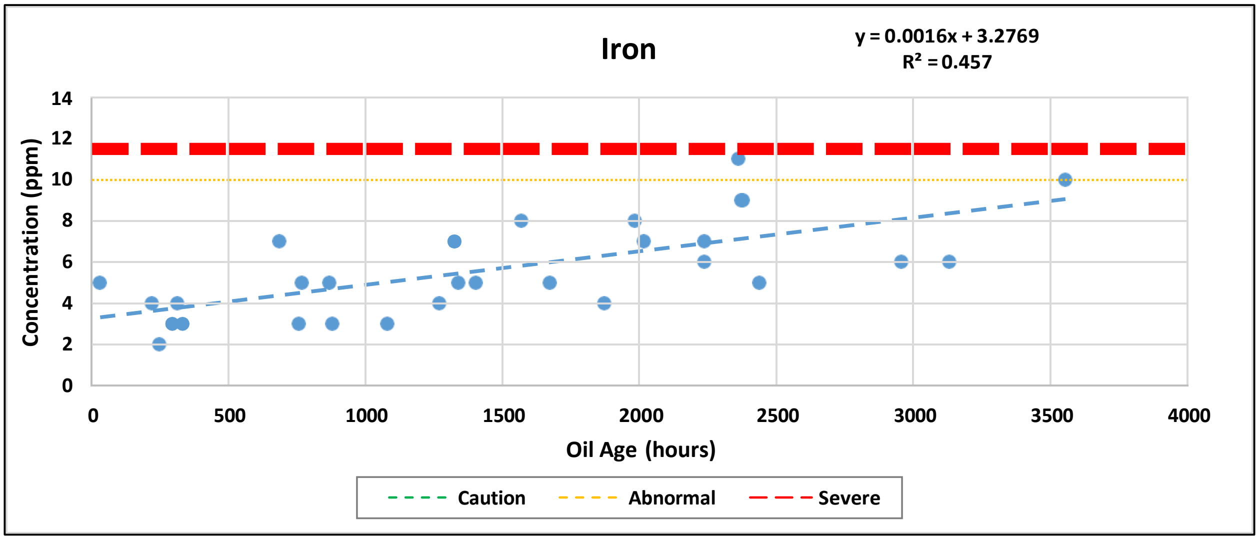

Figure 2.5 Example oil age plot for wear metal iron compiled over many oil change cycles (Limits are not accurate and are shown for depiction only. Typically they are much higher.)

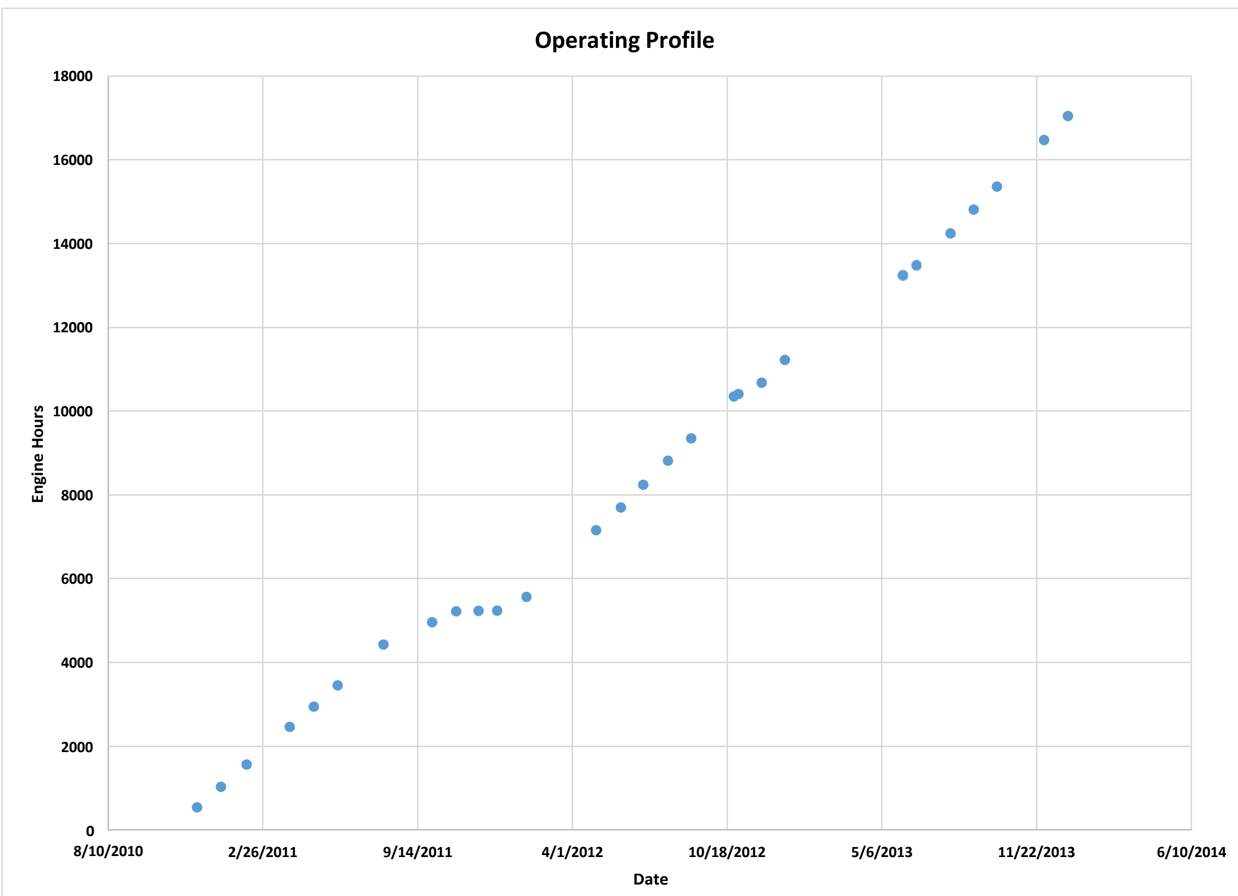

Figure 2.6 Engine operating profile plot

CHAPTER 3: PRELIMINARY LIFE CYCLE COST ANALYSIS

The goal of this preliminary cost study is to determine if installation of this first self-cleaning oil filtration system in the pilot vessel is expected to provide cost savings, taking into consideration applicable costs from the entire life cycle. This was accomplished by comparing costs through a rough order of magnitude LCCA for retrofitting the M/V Chetzemoka from the standard filtration system to the self-cleaning filtration system. Additional preliminary information is provided for these alternatives if initially installed (i.e. in new vessels).

3.1 Background

Life cycle cost analysis is a powerful tool for determining the costs associated with a product, service, or project throughout its full life time. This includes costs (both positive and negative) for design, procurement of materials, construction, use, demolition, disposal, resale, etc. Often, initial costs dominate decision making processes, but studies have shown that for most product systems, operating costs far outweigh up-front costs (Dhillon 2010, King County 2007, Brown and Yanuk 1985). The magnitude of these operating costs is usually not the same between alternative product systems. An LCCA provides detailed information about the expected costs over the lifetime of a product, providing a better tool for decision making than simply comparing up-front costs.

LCCA has been applied to a multitude of applications. Most of the detailed guides and computer programs, however, are focused on building systems (with an ISO standard for building systems) and road transportation applications (USDOT 2002, ISO 2008, Caltrans 2010, Fuller 2010). In fact, free computer tools are available for many applications to guide life cycle cost analysis, such as *RealCost* for transportation applications and *LCCAid* for building applications (FHWA 2014, RMI 2013). A number of articles have been written on general

LCCA methodology for comparing product systems, and they were useful in the development of a Microsoft Excel LCCA tool at WSU specifically for this project

Cost analyses typically involve two entities, the analyst and the decision maker. The analyst collects the information, completes the cost analysis, and writes a report explaining the methods, results, and conclusions of the study. The decision maker is generally a separate entity that uses this report to decide if a project should go forward and in many cases which projects should go forward first from a list of viable projects (Fuguitt and Wilcox 1999). In this self-cleaning filter project, WSU is the analyst and WSF is the decision maker.

The results of an LCCA are only as good as the underlying methodology (Barringer and Weber 1996). First costs are generally well known, but costs that have yet to be incurred are much more uncertain. LCCA is not an exact science and being able to evaluate the data sources, assumptions, and methods before making decisions based on an LCCA is important.

3.2 Oil Filter LCCA Literature Review

No LCCA studies which focused on self-cleaning oil filters could be found, but related cost studies on high efficiency oil filtration systems were (Zirker et al. 2006, Cal. DTSC 2008). Studies in related fields such as gas filtration, diesel engines, and ferries were also reviewed for relevant information (Reenaas 2005, Glosten Associates 2008, Wilcox and Brun 2011).

Zirker et al. (2006) studied bypass filtration in Idaho National Laboratory vehicles. This study installed bypass filters on 17 vehicles (eleven buses and six passenger trucks) and conducted oil analysis testing to determine extended drain intervals. Using bypass filtration and oil analysis resulted in an 89% reduction in oil changes on the buses and about a 75% reduction in oil changes on the trucks. A life cycle cost analysis was performed which determined that converting the vehicles to include bypass filtration had a higher initial cost than keeping the status quo, but lower recurring costs due to reduced oil and full flow filter change needs. Payback in the buses occurred between 72,000 and 144,000 miles (~2-4 years) and in the trucks at 69,000 miles (~2 years). These calculations also omitted costs of oil and filter disposal because they were not well defined, meaning that payback would likely occur even sooner.

The California Department of Toxic Substances Control (California DTSC 2008) examined combining high efficiency full flow oil filters with oil analysis for extended oil drain intervals in numerous types of on-land vehicles. This study replaced standard filters with high efficiency filters in 119 state owned vehicles in a number of fleets, with oil quality being monitored by oil analysis. It found that oil change intervals for the various types of vehicles tested increased by two to five times over the intervals being used previously, saving considerable amounts of oil and labor for oil and filter changes. The cost analysis considered costs of "replacement oil, [high efficiency] and standard filters, oil analysis, waste oil and filter disposal, and labor." The study included benefit-cost analyses, the results of which are presented as payback periods. The cost to convert the vehicles to accommodate high efficiency filters was compared with yearly operational costs to determine this payback period. Payback periods ranged from about 1-7 years with a median of 3.6 years. Considering the lifetime of the vehicles, switching to high efficiency filters would be a sensible investment in the long run.

Glosten Associates (2008) prepared a report for Washington State Ferries which compares the life cycle costs of different propulsion fuels. This study compared three alternatives: continue using diesel engines, install engines that run on liquefied natural gas (LNG), or install engines that utilize a dual fuel hybrid system of diesel and natural gas. The LCCA considered costs for a period of 30 years, ignored those costs that would be incurred by all three systems, and ignored sunk costs for parts already purchased and designs already completed. The study considered capital costs to include purchase, installation labor and design, commissioning, testing, and regulatory approvals (applied mostly to LNG engine as this engine type is atypical). Operating costs included maintenance and repair as well as consumption of fuel and lubricating oils. Disposal costs were ignored since they would likely fall outside of the LCCA timeframe and would likely be similar between the three options. Using a 3% inflation rate and testing cases of both 3% and 5% discount rates, the study found that the LNG engine provided the lowest life cycle costs. The structure and considerations used in the Glosten (2008) study provide a good starting point for those that may be involved in an LCCA concerning the lubricating oil filtration systems and a format/methodology that would be acceptable to WSF.

3.3 Life Cycle Cost Analysis Methodology

An LCCA typically includes several components, including the parts of the 'system' investigated, the cost models used, associated economic concepts, and available information on cost and risk. The methodology for the preliminary LCCA developed for WSF is presented in the following sections.

3.3.1 System

In this study, the oil filtration system includes all components that directly interact with the lubricating oil with the exception of the engine (combustion chamber/pistons). This physically includes any filters, filter holders, piping, oil, disposal containers, draining racks, etc. Maintenance and repairs regarding these physical components are also included in the definition and include labor for cleaning, repairs, and for changing oil and filters (including transportation, handling, ordering, and warehousing) as well as any material needs for maintenance. The following terms will be used throughout the summary:

- Standard filtration system (standard filter)

    - Filter system currently (October 2014) installed on Engine 1 of the Chetzemoka consisting of disposable paper filter cartridges in a canister
- Self-cleaning filtration system (self-cleaning filter)
    - Eliminator filter that is installed on Engine 2 of the Chetzemoka which includes the self-cleaning full flow filters, housing, and bypass centrifugal filter

Only direct economic costs incurred by WSF were considered. As is standard in LCCA, sunk costs (costs already incurred no matter which alternative is chosen) were not considered in the analysis. These include the cost of this analysis, design costs (no new designing needs to be done for second self-cleaning filter installation), and all initial costs of the standard filtration system (including accessories such as drying racks) because it is already in place. Because this LCCA is comparative, costs that are the same for each alternative were also excluded to streamline the data collection and analysis processes. Reenaas (2005) points out that this must be done with care because omitting many large costs can cause the scale of difference between alternatives to become distorted, however, there are few costs of this type in this study and differences should not be significantly distorted. Costs associated with disposing of the filtration systems were also not included because it is assumed that the both filtration systems would last the full life of the ferry and that the standard filtration system would be left in place when it is replaced with the self-cleaning system. Figure 3.1 is a diagram summarizing the life cycle costs for a typical ferry filtration project (the Chetzemoka comparison may not incorporate all of the items as previously discussed). The outermost dashed box is the system boundary, so any items contained within will be included as costs for this study, and any falling outside are not to be considered for the reasons previously stated. Note that some of the costs contained within the system boundary are sunk so their value is zero, however, they are appropriately included in the system boundary because if they were not sunk, their value would have been calculated. (Externalities are items such as social or environmental impacts of a process or system that might have a cost associated with them. They are not included in this LCCA.)

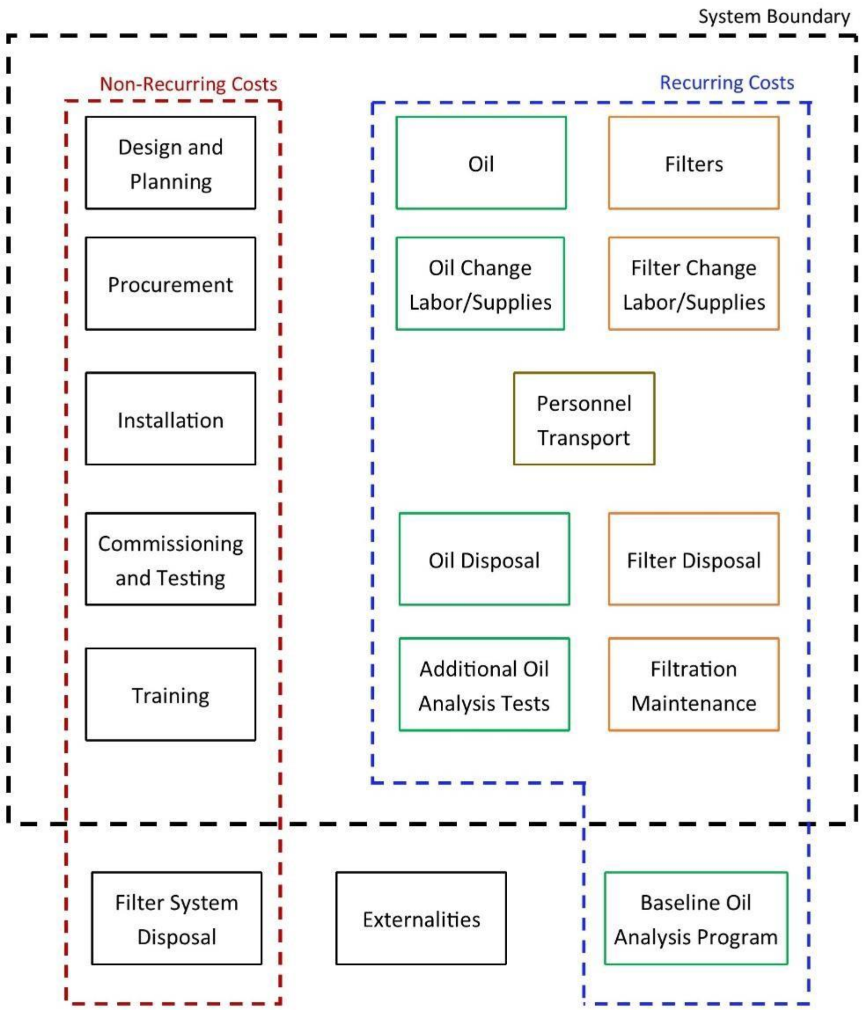

Figure 3.1 Typical ferry filter life cycle cost analysis system diagram

The length of the study period affects the results of an LCCA by changing total life cycle costs of all alternatives. Initial and final costs are one-time costs that are essentially spread out over the study period, so the longer the study, the less weight the initial and final costs carry compared to the recurring costs. This means that the choice of study period can significantly affect results and must be chosen with care. However, this choice is not particularly subjective in the case of the ferry filter project because the lifetime of both filter systems should be limited only by the service length of the vessel. Therefore, it makes sense to set the study period at about the length of time that the vessel is expected to remain in service for WSF. Vessels in the WSF fleet are expected to remain in service for 60 years and the Chetzemoka has already been in service for about five years as of 2014, so the vessel has around 55 years of expected remaining life (WSDOT 2012). For the simplicity of a round number, and because service life is not known with high certainty, the study period considered is 50 years.

3.1.2 LCCA Cost Organization Model

Many possible options exist for organizing costs in an LCCA, and the choice of model can be specific to the situation being assessed. Note that the cost model used should not affect the resulting overall life cycle cost, it simply changes how different costs are organized for computation and presentation. A very simple cost model presented by Dhillon (2010), which splits costs into non-recurring and recurring costs, forms the basis of the cost model used for the self-cleaning filter assessment. In equation form this model is written:

$$LCC = RC + NRC \qquad (3.1)$$

where LCC = life cycle cost,
NRC = non-recurring costs, and
RC = recurring costs.

To make the model more specific to the self-cleaning filtration project, these two types of costs (recurring and non-recurring) are further categorized as follows. The non-recurring costs are the purchase, installation and changeover to a second self-cleaning filter on the Chetzemoka. The non-recurring costs may be summarized in the following equation, although not all may be applied to this analysis because some are sunk:

$$NRC = C_p + C_d + C_i + C_c + C_t \quad (3.2)$$

where C_p = procurement costs,
C_d = design and planning costs,
C_i = installation costs,
C_c = commissioning and testing costs, and
C_t = training costs.

In this report, recurring costs are compounded annually with respect to accounting for the time value of money. The recurring costs that are assumed for these two systems are as presented in the following equation:

$$RC = (C_o + C_f + C_{oc} + C_{fc} + C_{pt} + C_{od} + C_{fd} + C_{oa} + C_m)*(UPVF) \quad (3.3)$$

where C_o=Cost of oil,
C_f = cost of filters or liners,
C_{oc} = oil change labor and supplies cost,
C_{fc} = filter or liner change labor and supplies cost,
C_{pt} = cost of personnel transport for oil or filter change,
C_{od} = cost of oil disposal,
C_{fd} = cost of filter or liner disposal,
C_{oa} = cost of additional oil and liner analyses,
C_m = cost of general filtration system maintenance, and
UPVF = uniform present value factor (discussed later).

The costs and/or formulas to calculate the recurring costs are detailed in Appendix A.

3.1.3 Cost Types and Associated Economic Concepts

As previously mentioned, there are two main types of costs in the LCCA model for this study: recurring and non-recurring. Recurring costs are paid periodically throughout time and must be adjusted to account for the time value of money (in most cases, a sum of money put aside today to pay for a task that will occur in the future is not the amount that the task would cost today). Non-recurring costs that are incurred at the beginning of product life do not need to be adjusted since they are purchased in the present with current dollars. However, those incurred during or at the end of product life need to be adjusted for the time value of money as well. With respect to the time value of money, "present value" is the current worth of a future amount of money. "Present amount" is the current amount of money that would need to be paid for a good to be acquired or a service to be rendered today.

Inflation rate (i) and discount rate (d) are both important parameters for determining the present value of costs that are to be paid in the future. Inflation rate refers to the increase in the nominal price of goods and services over time. Discount rate refers to the money that could be made through alternative investments. These are competing forces – the present value of future costs is increased by higher inflation rate and decreased by higher discount rate. These two rates can be combined into one factor for simplicity (Addison 1999, Eisenberger et al. 1977). While the terminology used for this factor varies, the formula is consistent and will be represented in this study by D and called the "real discount rate", calculated as:

$$D = \frac{1 + d}{1 + i} - 1 \tag{3.4}$$

where D = real discount rate,
d = discount rate, and
i = inflation rate

Discount and inflation rates are estimates for the future and cannot be known exactly. The assumptions used in this report follow those used by Glosten Associates (2008) in the study on alternative fuels for WSF, because this is a similar type of project. Therefore, the inflation rate was set at 3% and the discount rate at 4%.

There are two main types of future costs that can be incurred – those that occur only at a single point in the future and those that recur on a regular and predictable schedule. This study does not include any costs incurred at a single point in the future, so only uniformly incurred costs have to be dealt with. To account for the time value of money of costs that are incurred annually (or can be averaged per year based on a predictable schedule) the present value of the entire series of payments is calculated as the product of the uniform present value factor (UPVF) and the present amount of annual costs, where the UPVF is:

$$UPVF = \frac{(1 + D)^n - 1}{D(1 + D)^n} \tag{3.5}$$

where UPVF= uniform present value factor,
D = real discount rate (equation 3.4), and
n = years between present value year and cost incurred year.

This formula allows costs to be adjusted to present value, no matter when they are incurred. Summing the present value of all costs to be included in the assessment gives the life cycle cost in present value and allows for comparisons on an equal monetary basis.

Besides reporting of life cycle cost, these data are also used to calculate payback periods. A payback period is the amount of time that is required for a system to recover its installation costs by operational savings. It is calculated by leaving the time period of the study as a variable, setting the life cycle cost equations for the standard and self-cleaning oil filters (equation 3.1) equal to one another, and solving for the time period. The result is equation 3.6:

$$Payback\ Period = -\frac{\ln\left(1 - D\,\frac{NRC_{self\ clean} - NRC_{standard}}{ARC_{standard} - ARC_{self\ clean}}\right)}{\ln(1 + D)} \tag{3.6}$$

where payback period is in years and ARC is annual recurring cost (in present amount).

3.1.4 Uncertainty and Risk

Uncertainty and risk are two terms used in economic contexts with related, but distinctly different meanings. Uncertainty refers to a lack of reliable information which may stem from future unknowns or data inaccuracies/exclusions. Risk is when the relative chances of each possible outcome is known, but many outcomes are possible (Fuguitt and Wilcox 1999). This study only considers uncertainty as there has been no study of high efficiency filters in ferries from which to estimate probabilities for risk assessment, such as filtration failure rates. Additionally, other risks are present which do not specifically relate to self-cleaning filters such as the reduced risk of oil spills or injuries to workers from no longer having to transport heavy disposable filter bags, but are difficult to quantify economically at this time.

Potts (2002) identifies four types of uncertainty that could be important in LCCA. These are technical, economic, sociopolitical, and environmental uncertainty. Technical uncertainty deals with unknowns about output performance of the project. Economic uncertainty addresses factors such as future prices and markets. Sociopolitical uncertainty refers to issues of user acceptance and bureaucratic processes that could impede a project. Environmental uncertainty is mostly concerned with environmental impacts that may affect project costs. This study considers only direct costs, ignoring any externalities, and only technical uncertainty is considered with respect to different oil change interval extensions.

3.1.5 LCCA Data Compilation

Valid and complete data are extremely important to an LCCA. It is important for the values and sources of data to be tracked and presented in case a value comes into question at any point during or after the analysis. In the case of the ferry oil filter project there are a number of sources of data including WSDOT technical advisors, project proposals, informal discussions with workers at WSF, and the contract between WSF and the contracted disposal company for oil and filter disposal. Determination of labor time needed to complete oil and filter changes as well as order, warehouse, and any other tasks associated with oil and filters were obtained from informal discussions with workers at WSF. Data sources and values used are listed within the WSU LCCA Tool (Langfitt and Haselbach 2014b).

3.1.6 Major Assumptions

Many assumptions had to be made to complete this rough order of magnitude LCCA. The following listing includes the major assumptions used to generate the results:

- Inflation rate is 3% (chosen to mirror Glosten Associates 2008)
- Discount rate is 4% (average of two rates, 3% and 5%, used in Glosten Associates 2008)
- Time period is 50 years (roughly the lifetime remaining for the Chetzemoka)
- Both filtration systems will last the life of the vessel
- Oil costs used were $8 per gallon (or $9 per gallon if noted on the figures)
- Two (2) oil changes and four (4) filter changes per year for the standard system
- Periodic maintenance costs are the same for both filtration systems
- Additional oil analysis tests needed with self-cleaning filter cost $60 per sample
- No setbacks during installation of second filter
- Costs of drum pickup, including storage drums, removal, and transport are not considered
- Liner testing and disposal are not considered (data not available and disposal likely insignificant)
- Warehousing, ordering, and transport costs of filter and oil are covered by extra labor time for oil and filter change tasks
- Oil pumping for disposal occurs during normal working hours
- Used oil has "marketable value" as defined by the disposal company contract
- The uncertainties considered at this time are:
    - Oil change interval extension
    - Installation costs for standard filtration system (only applicable for new vessels)
- Costs identified in the project proposal, current Emerald Services oil and filter disposal contract, and verbal communication with WSF are sufficiently accurate

3.1.7 Cases Examined and Presented

Three "Scenarios" with three "Cases" each are presented as the results of this rough order of magnitude LCCA. In the Chetzemoka, the standard filtration system is already installed so there are no capital costs associated with it. This condition is represented in Scenario A which is applicable for a single engine in a retrofit vessel. Scenarios B and C are for single engines in new vessels in which there are capital costs associated with installing either filtration system. Scenario B is the condition if the up-front costs of the standard filtration system are half as much as the self-cleaning system and Scenario C is the case if both the self-cleaning and standard filtration systems have the same up-front costs (for all filtration systems we are assuming the same size filtration systems as those on the Chetzemoka).

One particularly unknown variable at this point, which greatly affects cost results, is the degree to which the self-cleaning filtration system could extend oil drain intervals. As a form of sensitivity analysis to account for this uncertainty, there are three modeled cases for oil drain intervals inside of each scenario. Case 1 is when oil drain intervals with the self-cleaning filter are identical to those with the standard filter. Case 2 is when oil drain intervals are doubled by use of the self-cleaning system and Case 3 is when drain intervals are tripled. These scenarios and cases are summarized in table 3.1.

Table 3.1 Scenarios and cases tested for preliminary rough order of magnitude life cycle cost analysis (for one engine on a vessel)

Scenario/Case	Condition
Scenario A	Retrofit – No up-front costs for standard filtration system
Scenario B	New vessel – Up-front cost for standard filtration system half that of self-cleaning
Scenario C	New vessel – Up-front cost for both filtration systems equal
Case 1	No extension of oil drain interval
Case 2	Oil drain interval doubled
Case 3	Oil drain interval tripled

3.4 Life Cycle Cost Analysis Results

Life cycle costs and payback periods were calculated for each scenario and case. The 50 year life cycle cost difference is the amount that could be saved by using self-cleaning filtration on a single engine (in all scenarios and cases self-cleaning filtration was cheaper than standard filtration over 50 years). Results are presented in 2014 dollars in tables 3.2 through 3.4.

Table 3.2 Scenario A – Retrofit vessel – one engine (initial costs of standard filtration is 0)

Case	Oil Change Interval Extension	Payback Time (yr.)	50 Yr. Life Cycle Cost Difference
Case 1	None	22.4(21.6*)	$46,000
Case 2	Double	9.3(8.6*)	$165,000
Case 3	Triple	7.8(7.2*)	$204,000

Note: 50 yr. LCC of standard is $363,000, self-cleaning $159,000-$317,000

* With $9/gallon

Table 3.3 Scenario B – New vessel – one engine, initial costs of standard filtration half of self-cleaning

Case	Oil Change Interval Extension	Payback Time (yr.)	50 Yr. Life Cycle Cost Difference
Case 1	None	10.6	$70,000
Case 2	Double	4.5	$188,000
Case 3	Triple	3.8	$228,000

Note: 50 yr. LCC of standard is $387,000, self-cleaning $159,000-$317,000

Table 3.4 Scenario C – New vessel – one engine, initial costs of standard filtration equal to self-cleaning

Case	Oil Change Interval Extension	Payback Time (yr.)	50 Yr. Life Cycle Cost Difference
Case 1	None	0	$93,000
Case 2	Double	0	$212,000
Case 3	Triple	0	$252,000

Note: 50 yr. LCC of standard is $411,000, self-cleaning $159,000-$317,000

Figure 3.2 represents an analysis of technical uncertainty for oil change interval extension performed only on Scenario A (retrofit). It compares payback period and total life cycle costs at different oil change interval extension factors (e.g. 2=double the oil change interval with self-cleaning than with standard filtration). As can be seen, even increasing the oil life by 50% with the self-cleaning filtration system will have a very significant effect on the cost savings.

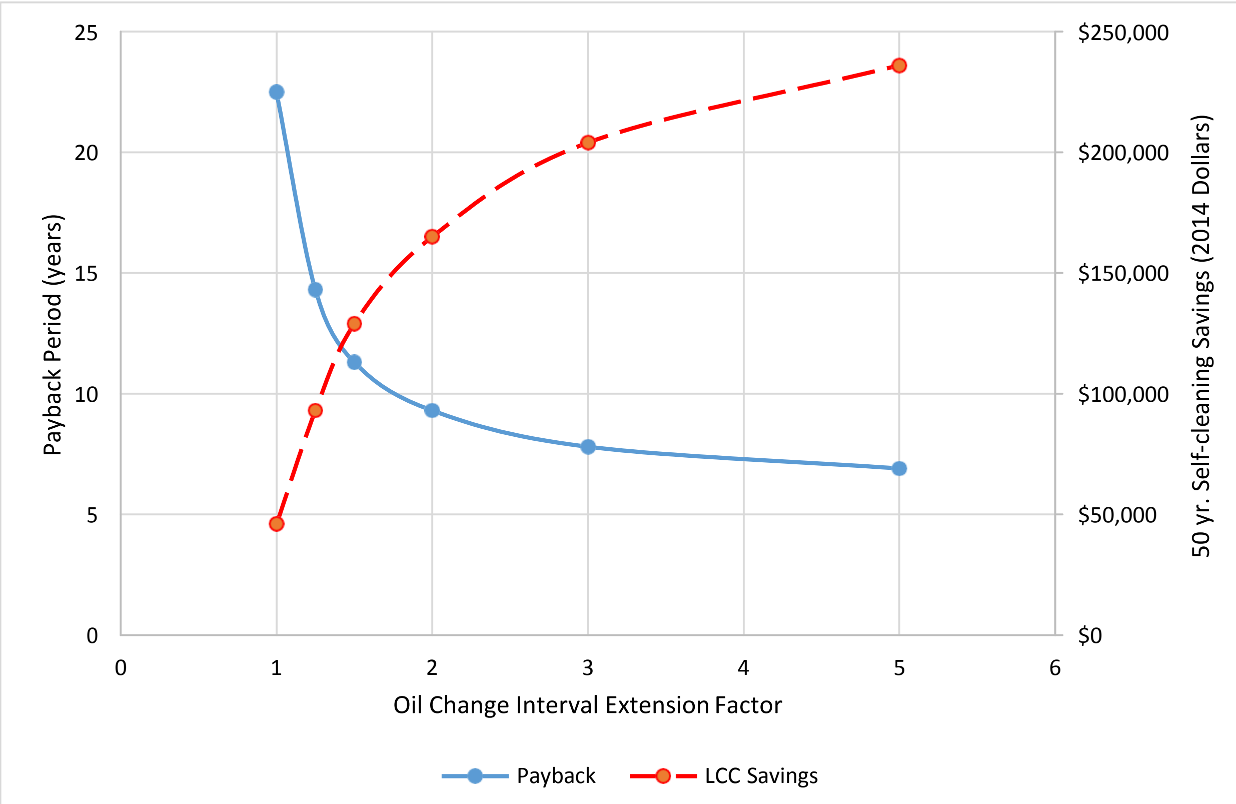

Figure 3.2 Oil change interval extension uncertainty analysis with extension factor applied over currently used oil change interval

Figure 3.3 shows the relative magnitude of three types of costs – installation, oil-related, and filter/liner-related – for Scenario A, Case 2 (retrofit, double oil life) because this is a likely situation to be encountered on the Chetzemoka based on available information. In both cases, oil costs are the majority of overall costs, however, filter costs are also a dominant cost for standard filtration.

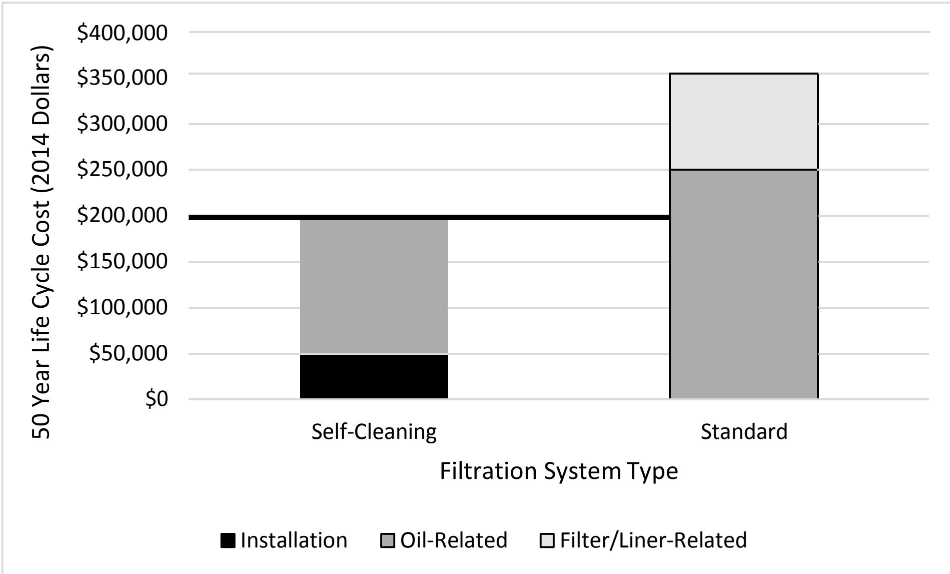

Figure 3.3 Life cycle cost makeup for each filtration system under Scenario A, Case 2 (single system retrofit, double oil life)

3.5 Conclusions

The range of possible payback periods under the previous assumptions is 0-22.4 years. For retrofits like the Chetzemoka, this range is narrowed to 7.8-22.4 years. From figure 3.2, it seems very important to get some oil drain interval extension, and would be unacceptable to get a shorter drain interval from the self-cleaning filtration system. It is important to note that a 50-100% oil change interval extension significantly reduces payback time. Pushing the oil life longer than that may not be necessary, particularly if it is found to not be worth the additional risk. With likely payback at less than a fifth of the vessel's lifespan and average yearly savings of about $3,300 per engine thereafter, this rough order of magnitude LCCA indicates that if a 50 to 100 percent extension of the oil change interval can be achieved through self-cleaning filtration, significant direct economic savings could be achieved, not to mention likely reductions in risk and environmental impacts.

CHAPTER 4: POTENTIAL ENVIRONMENTAL IMPACT ASSESSMENT OF LUBE OIL THROUGH A LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

4.1 Background

As previously discussed, lube oil is a widely used fluid with a variety of industrial, commercial, and home applications. One major application is as engine oil and it is this type of lubricating oil that is the subject of this study. The lubricating oils used by Washington State Ferries are petroleum based and are specifically blended for this application. During use, some of the lube oil is also burned in combustion chambers of two stroke marine engines, with less being burned in upgraded engines. However, the focus of this analysis is to preliminarily quantify environmental impacts in the production, acquisition, and disposal of lube oil. Additionally, it should be clear that this is an assessment of the oil used only, not the filtration system alternatives.

4.1.1 Lubricating Oil Life Cycle and Summary Impacts

The acquisition, processing, and disposal of nearly all natural resources and goods involve inputs and outputs which might affect the environment. These include energy inputs, resource use, air emissions, water discharges, ecosystem disruption, and more. Consideration of inputs and outputs involved in the entire process of making, using, and disposing of a good, and the resulting effects on the environment, is the basis of a life cycle assessment. Life cycle assessments allow researchers to more fully understand product or process impacts in a holistic sense. The procedures and necessary pieces of a life cycle assessment are governed by ISO 14040 and 14044 (ISO 2006a, ISO 2006b). These include the goal and scope definition to convey the reason for carrying out the study and manner in which it will be done, the inventory analysis to compile input and output data, the impact assessment to convert these data into environmental impacts, and interpretation of results. These steps and their iterative nature are illustrated by figure 4.1 (ISO 2006a). There are some quantifiable environmental impacts associated with production, use, and disposal of lubricating oil. Figure 4.2 represents a typical lube oil life cycle.

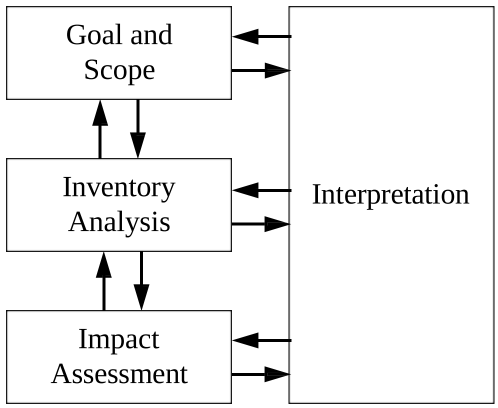

Figure 4.1 Phases of a life cycle assessment (ISO 2006a)

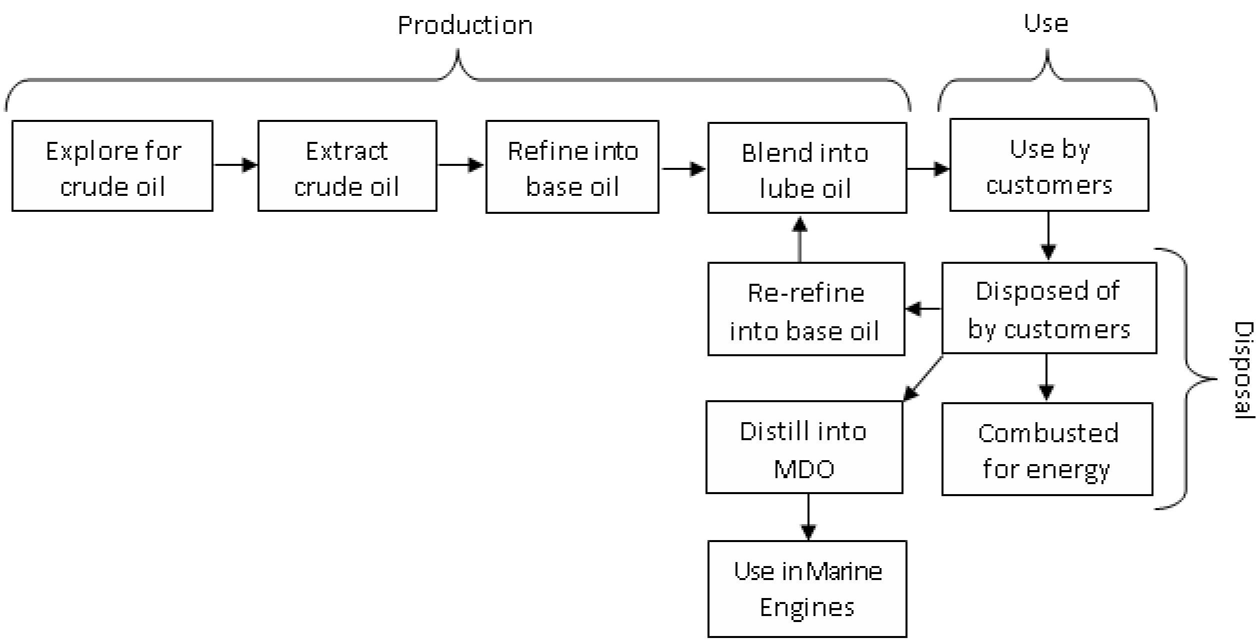

Figure 4.2 Typical lube oil life cycle diagram (MDO is marine diesel/distillate oil)

The manufacture of mineral (petroleum-based) lube oil has many stages, starting with exploration and drilling, and continuing through production of crude, transporting, refining, and blending. Exploration and drilling involve infrastructure additions often in natural areas with undisturbed ecosystems. In order for drilling to occur, machinery must be moved on site. To allow access and placement of this machinery, roads must be built and land must be cleared possibly resulting in deforestation and habitat destruction. Large quantities of water are used during the processes of exploration and drilling. Additionally, contamination of this water is common during these activities. According to Epstien and Selber (2002), produced water (water used during extraction) "generally contains varying quantities of heavy metals, volatile aromatic hydrocarbons (such as benzene, toluene, and xylene) and a vast array of other potentially toxic compounds."

Transporting crude oil from the drilling source to the refinery is accomplished mostly through pipelines, trains, tankers, and trucks. Each of these transportation methods include occasional accidental spills and air emissions. Little data is available on small spills, but air pollution is well quantified. For instance, as a percentage of total marine emissions, crude oil tankers account for over 20% of total CO_2, SO_2, NO_x, and particulate matter emissions as well as 22% of total fuel use (Endresen 2003). Refineries emit releases to air, soil, and water as well as use significant amounts of energy. These releases include criteria air pollutants (NO_x, SO_2, CO, and particulate matter), volatile organic compounds, greenhouse gasses, and hazardous air pollutants (HAPs), such as metals. With about 150 domestic refineries and a throughput of 17 million barrels per day, the quantities of these releases are significant (EPA 2011). However, lube oil represents only a small fraction of the products from crude oil.

4.1.2 Importance of Study and Boundaries of this Compilation

Since Washington State Ferries uses large amounts of lube oil, it is important to understand the environmental benefits of reduced usage by the fleet. This information, together with cost and reduced risk considerations, will be useful supporting decisions between alternative procedures and equipment, such as the proposed self-cleaning filtration upgrade. The main function of lubricating oil to provide the engine with sufficient lubrication to prevent excessive wear. If systems which use oil were being compared, the functional unit would need to be based on some type of comparative measure, such as a number of engine hours of lubrication achieved, since different systems could vary in the amount of lube oil needed to accomplish the function. In addition, full life cycle assessments are very difficult to perform due to the lack of comprehensive data for each aspect of the cycle, especially with respect to proprietary mixes.

Thus, this study is designed to focused solely on the oil life cycle and be general enough to be applied to different systems where the lube oil needs could be quantified in terms of volume for later comparisons. Therefore, given the goal of providing WSF with an effective, simple, and flexible decision-aiding tool, the best choice of functional unit is likely one based on a volume of oil. The intention is to summarize environmental impacts associated with this set quantity of lube oil, both for production and acquisition, and also for disposal, so that WSF decision-makers have the information readily available. In the following sections, available data from other studies and from LCA software databases are compiled. Note that many LCA practitioners use different units for their studies and conglomerate them differently into associated impacts. Therefore, part of the compilation is to try to correlate these various units and impact categories in order to see how they compare. Additional efforts in the compilation include calculations and/or estimates for some of the missing information on lube oil blending and other WSF specific information. Since much of the data used in this study is from literature and databases based on mass of oil, the functional unit is “one gallon of lubricating oil with a density of 0.88 kg/L”. This density was chosen because it is the density of Delo 710 LE lube oil at 15°C (Caltex 2013), which is the particular oil of interest in this study.

Figure 4.2 is the summary process flow diagram containing the flows within the oil system that will be included in this study with the arrows representing transportation processes. Oil processes are assumed to start at the point of exploration for crude oil and follow the oil through its life including transport, refining, use, and disposal. These are separated into two parts in the following sections. First, are the environmental impacts associated with obtaining one gallon of lube oil. The second part relates to the environmental impacts of disposing of one gallon of oil. There are two cases for the first part, one which includes blending of lube oil additives (discussed in more detail later) and one which does not. This methodological choice is due to the uncertainty of the data obtained for the blending stage of lube oil manufacturing. There are also two cases for the second part, disposal by distillation to MDO or by combustion (offset products from oil recycling, i.e. the reformulated MDO, are considered to be within the system boundary and will be accounted for).

Whenever available, United States data was used. This was mostly accomplished by using literature sources from the United States and the GaBi 6 extension database “XVII: Full US”. The main exception to this was for additives blending processes, where only European data could be obtained. For some transport processes and average used oil composition, data for the M/V Chetzemoka (sometimes labeled Chetzy for brevity in tables) were used since it is the main focus of most of this study.

The manufacturing, maintaining, and disposal of equipment/buildings used for lube oil manufacturing, transportation, disposal, and any other processes are not included in the system boundary. This is to limit the complexity of the study and because this equipment typically has long lifespan and high throughput, likely making effects negligible on the scale of the functional unit. Oil technology, disposal technology, etc. changes over time, but since these are not considered in this study since it is intended to represent current impacts. Also, it is assumed that there are no spills of oil in any transfers, such as during oil changes or

4.1.3 Impact Assessment and Impact Categories

Life cycle inventory (LCI) data is the quantity of inputs and outputs to the product or process over the life cycle. These data, such as emissions of NO_2 or use of energy, are the most direct and objective characterization of flows into and out of the system. However, it is nearly impossible to interpret the meaning behind these values because the inventory is generally very large, can include many different units, and the types and severity of environmental impacts resulting from those uses and releases are usually not immediately apparent to the reader. These issues are mostly resolved by including an impact assessment, which converts the quantities of these substances into common units and groups them according to their potential environmental impacts. Classification is the process of assigning each flow to an impact category based on the potential environmental impacts of that flow. Characterization factors are then used to convert each flow within each impact category into common units (e.g. kg CO_2 equivalent for global warming potential) based on the relative impact of the flow to the impact of the equivalent unit. Many frameworks for completing this process have been developed including CML, Eco-indicator, EPS, LIME, LUCAS, Impact, ReCiPe, TRACI, and more (Matthews et al. 2013). Software is generally used to complete these assessments due to the complexity and GaBi 6 has been used in this study.

Impacts can be reported as midpoint or endpoint. Midpoint impacts are the direct effects of the flow, such as an increased CO_2 concentration in the air. Endpoint impacts are the final effects or consequences on people, animal, the environment, etc., such as loss of life years. Endpoints have the advantage of being easier to understand, but midpoints are easier to quantify and require fewer assumptions and reliance on “less-established facts” (Heijungs and Guinée 2012). This study will consider midpoint impacts since TRACI (the impact methodology to be used in this study) only includes midpoint factors (Bare et al. 2002). Possible endpoint indicators for the impact categories considered in TRACI are discussed by Bare et al. (2002).

TRACI 2.0 (The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) was chosen as the impact methodology for this study (Bare 2011). TRACI was chosen as the impact methodology for this study because it was developed specifically for the U.S. (Bare 2011). TRACI 2.0 was chosen instead of the newer TRACI 2.1 because the update removed toxicity characterization for some metals whose toxicity values in USEtox (one basis of TRACI) are considered “interim” (Geyer et al. 2013), some of which are potentially important in this study as lube oil constituents.

In accordance with ISO 14044 (2006b), a comprehensive set of impacts categories that reflect many different potential environmental impacts are considered in this study. Specifically, the chosen impact categories [units] are (see Appendix B for further details):

- Acidification Potential (AP) [H^+ moles-Equiv.]
- Ecotoxicity Potential (ETP) [CTUeco]
- Eutrophication Potential (EP) [kg N-Equiv.]
- Global Warming Potential (GWP) [kg CO_2-Equiv.]
- Human Health Cancer Potential (HHCP) [cases]
- Human Health Criteria Air Potential (HHCAP) [kg PM 10-Equiv.]
- Human Health Non-Cancer Potential (HHNCP) [cases]
- Smog Creation Potential (SCP) [kg O_3-Equiv.]
- Stratospheric Ozone Depletion (ODP) [kg CFC 11-Equiv.]

Normalization and weighting are optional elements of a life cycle assessment according to ISO 14044. Normalization means to relate the equivalent units to some reference that provides meaning, such as the total impacts per capita in the U.S., or per fleet per year, etc. Weighting means to provide some relative value judgment of the importance of an impact category in relation to another impact category. Both have the potential to introduce bias. However, normalization has the key advantage of answering the 'is this a lot?' question. Weighting is usually at the discretion of the decision maker and will not be included herein. The values as characterized for each impact will be presented first, and to aid in interpretation, will also be presented as externally normalized to the US per capita per day baseline (Ryberg et al. 2014).

Primary data availability was very low due to proprietary information, so literature and databases had to be used extensively. Of these literature and database sources, none were developed specifically for marine lubricants, so one of the major limitations of this study is that much of the data used is for lube oil in general. Therefore, the impacts had to be assumed to the same for marine lube oils, which may not always be the case due to different composition than lube oils for other applications. Additionally, the blending stage of lube oil manufacture has not been well studied and that particular portion of the assessment therefore employs significant assumptions. Estimating with assumptions is usually preferable to the alternative of omitting processes that may not be studied, so long as the possible shortcomings are identified, particularly if those processes could be significant in scale of impacts (Klöpffer and Grahl 2014). Using proxy data, such as general lube oil for marine lube oil, where specific data does not exist or is hard to find is further supported by Matthews et al. (2013). Other assumptions in data collection and handling are discussed individually as those data are presented.

4.2 Lubricating Oil Life Cycle Assessment Data Compilation

The LCA compilation is divided into two sections, lube oil acquisition and lube oil disposal. For the lube oil acquisition, this includes base oil, blending, and transport to WSF. For the lube oil disposal, this includes transport from WSF and either distilling into MDO or incineration. Significant information is available for the production of base oil and for some of the disposal processes for used oil. Little or no information is available for the specific lube oil associated with the Chetzemoka for blending or combustion, so those sections of the compilation, and the transport section specific to Washington State Ferries, are all based on calculations and assumptions of the investigators.

4.2.1 Lube Oil Acquisition – Base Oil

Base oil is the main constituent of lubricating oil, the other being additives, which typically make up about 20% of the final product by mass (Raimondi et al. 2012). The production processes for base oil from crude oil have all been modeled by PE International with a base year of 2010 and location of the United States, and the resulting data is available in their GaBi 6 software database. According to the supporting documentation, the included processes are: well drilling, crude oil production, processing, and transportation by pipeline and vessel of the crude oil to the refinery. The dataset takes into account typical distances for crude oil transport, composition of oil, processing technologies, etc. for the United States in particular. The data set is mainly composed of primary data (obtained directly from the source) from industry with secondary data (correlated from other sources) filling in where primary data is not available.

All effects related to the feedstock (crude oil) are allocated on an energy (calorific value) basis to the various refinery products, while all impacts of refinery processes are allocated on a mass percentage of throughput (GaBi 6 2014). This allocation procedure allows each product to be modelled based on the processes actually applied to that product. Table 4.1 presents the LCA results from PE International in the GaBi 6 database for 1 gallon of lubricating oil. In the GaBi 6 database, one can choose from different sets of impact category methodologies. TRACI 2.0 (The

Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) was chosen as the impact methodology for this study, because it is developed specifically for the U.S. (Bare 2011).

Table 4.1 Base oil production impacts from literature and databases for 1 kg of new oil

Impact Category	Unit	Geyer et al. 2013	GaBi 6 Database	GREET	Raimondi et al. 2012
		TRACI 2.0	TRACI 2.0	TRACI 2.0	IMPACT 2002+
Global Warming	kg CO_2 eq	1.14	1.37	0.913	0.985
Acidification	mol H^+ eq	0.336	0.359	2.94×10^{-3}	0.457
Eutrophication	kg N eq	1.63×10^{-4}	2.32×10^{-4}	9.95×10^{-5}	2.38×10^{-3}
Ecotoxicity	CTUeco	0.564	0.543	0	Uncertain
Human Health Cancer	cases	3.2×10^{-10}	1.35×10^{-9}	0	3.3×10^{-8}
Human Health Non-Cancer	cases	5.3×10^{-8}	1.21×10^{-7}	0	1.24×10^{-8}
Human Health Criteria Air	kg PM_{10} eq	1.5×10^{-3}	1.14×10^{-3}	2.52×10^{-4}	1.67×10^{-3}
Smog Creation	kg O_3 eq	0.045	0.075	0.0598	*
Ozone Depletion	kg CFC-11 eq	*	7.45×10^{-11}	0	7.00×10^{-7}

Note: Unit conversions were made to convert IMPACT 2002+ into TRACI 2.0 units and categorization choices were made as well. This may have introduced some additional uncertainty. GWP calculated using TRACI 2.1 methodology in Geyer et al. 2013. GREET data expected to have significant gaps.
*Not reported

Another source of information on base oil production is the study by Geyer et al. (2013) sponsored by the California Department of Resources Recycling and Recovery. Geyer et al. (2013) focused on disposal methods for used oil, but there was information on impacts of displacing primary products (one of which is base oil) with re-refined oil. The differences noted were taken from the report, multiplied by the percentages of the displaced impacts attributed to base oil production, and multiplied by the ratio of total used oil processed to base oil obtained in order to switch the basis to 1 kg of lube oil produced. The result is included in table 4.1.

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) is a tool developed by Argonne National Laboratory to provide energy and emissions data in the transportation sector. Engine oil production is one of the quantified processes within this tool (Argonne National Lab 2013). The emissions data was extracted from GREET and input to a model in GaBi 6, and the results of that model using TRACI 2.0 impact methodology are included in table 4.1. While this tool does provide some great information, it falls short of providing suitable data for a full life cycle assessment because it only considers emissions of greenhouse gases and regulated gases (CO2, CH4, N2O, VOCs, CO, NOx, PM10, PM2.5, and SOx). Therefore, the results are slightly lower than Geyer et al. (2013) and the GaBi 6 database for most impact categories, with some impact categories not being related to greenhouse gas or regulated emissions at all. This shortcoming means that the GREET database may not be the most appropriate source of data for a full life cycle assessment of lubricating oil.

Raimondi et al. (2012) compiled a life cycle assessment of base lube oil impacts which used literature LCA data and Ecoinvent LCI data (database) to compile the life cycle assessment. The impact methodology used was IMPACT 2002+ and as a result, was performed with a different set of impact categories and equivalent units than those listed in table 3.1. Therefore, the impact categories from Raimondi et al. (2012) had to be subjectively categorized to fit into the TRACI 2.0 impact categories and the equivalent units had to be converted. This was accomplished by looking up the impact of the chemical compound used in the equivalent unit for the corresponding impact in units used by TRACI 2.0 as a rough comparison.

4.2.2 Lube Oil Acquisition - Blending

After base oil production, additives are blended in at a blend plant. Additives include detergents, dispersants, viscosity modifiers and antioxidants designed to increase lubrication, resist oil degradation, and inhibit corrosion. The impacts from these additives are typically not considered in LCAs of lube oil, but make up a significant portion of final product, generally around 20% in engine oils (Raimondi et al. 2012). Raimondi et al. (2012) considered the effects of some standard additives and found that the environmental effects of the additives in the specific blend considered in the study were substantial. Environmental impact information for the blending portion of the lube oil used by WSF is not currently available. Therefore, it was assumed that the proportion of impacts from additives on the total blended oil in each impact category in the WSF case are the same as those derived from Raimondi et al. (2012), with the exclusion of any zinc additives because it is known that the WSF lube oil is zinc free. These results are presented in table 4.2 noting the following exceptions:

1. It could not be determined if the additives used in Delo 710 LE oil are similar to those used in the oil from Raimondi et al. 2012.
2. Raimondi et al. 2012 used a different impact methodology than the WSF study.
3. The Raimondi et al. 2012 results were presented as portions of the total impacts, not as characterized values, so these portions are assumed to be the same for the WSF study, however if the base oil production impacts found in Raimondi et al. (2012) were significantly different than in the WSF study, these ratios may not be as valid.
4. Raimondi et al. 2012 was carried out in Europe, not the United States.
5. Raimondi et al. 2012 did not consider energy for blending processes, rather only included the impacts of creating all of the additives.
6. All of the additives that had zinc from Raimondi et al. (2012) were removed, even though other additives may have been used in their place to accomplish the same functions.

Table 4.2 Lubricant blending impacts for 1 kg of new oil (derived from Raimondi et al. 2012)

Impact Category	Unit	Including Zinc-Based Additives	Excluding Zinc-Based Additives
Global Warming	kg CO_2 eq	6.17×10^{-1}	4.97×10^{-1}
Acidification	mol H^+ eq	8.85×10^{-2}	7.83×10^{-2}
Eutrophication	kg N eq	1.40×10^{-5}	3.99×10^{-6}
Ecotoxicity	CTUeco	4.30×10^{-2}	3.34×10^{-2}
Human Health Cancer	cases	2.10×10^{-9}	1.81×10^{-9}
Human Health Non-Cancer	cases	3.40×10^{-8}	2.75×10^{-8}
Human Health Criteria Air	kg PM_{10} eq	2.88×10^{-4}	2.52×10^{-4}
Smog Creation	kg O_3 eq	No Data	No Data
Ozone Depletion	kg CFC-11 eq	7.37×10^{-12}	5.36×10^{-12}

Note: These are estimated and are only intended to convey the possible degree of additional impacts from fully formulating lubricants.

Because the inclusion of additives adds significant impacts, particularly to human health, using the data from Raimondi et al. (2012) and the assumptions previously discussed, this step warrants some further discussion. There are no other studies to support the data on inclusion of additives. This makes it difficult to validate that impacts from additives are similar to what these data suggest. Additionally, due to the uncertainty introduced through our various assumptions, the results including the blended additives are cautiously presented. It should also be noted that if these impacts are considered in the oil acquisition process, the base oil production impacts must be reduced by 20% because only 80% of the 1 kg of lube oil produced is made up of base oil.

4.2.3 Disposal – Distillation to MDO

Proper disposal of lubricating oil can be achieved through a few paths. Combustion for energy recovery, re-refining into fresh base oil, and distillation to marine diesel oil (MDO) are three of the most common disposal approaches. Washington State Ferries contracts with a disposal company to distill its used lube oil into MDO. However, a small portion of the oil is not suitable for distillation to MDO and must be combusted instead. According to the disposal company this makes up about 5% of the oil they receive. The following analysis looks at a unit of used lube oil distilled into MDO.

Inventory data was not available for a life cycle assessment on distillation of lube oil to MDO, so literature data had to be used instead. Few studies address this topic, however there is one that provides a simplified model for the distillation process which includes energy and major chemical inputs (Boughton and Horvath 2004) and another which used more detailed models, but only reported characterized impact results from their LCA, with no detailed data on the inputs and outputs of the processes (Geyer et al. 2013). Since the latter study is more up to date and was significantly more detailed in its modeling, it was determined to provide higher quality data for the WSF study. Moreover, the Geyer et al. 2013 LCA was carried out in TRACI 2.0, the same impact methodology as the WSF study, so the results are readily transferable. Therefore, this section on distillation to MDO relies heavily upon the results presented in Geyer et al. (2013). As a comparative check for at least the same order of magnitude, the inputs for the used oil distillation process from Boughton and Horvath (2004) were modeled in GaBi 6 for the WSF study as well, and those results are also shown in table 4.3.

Table 4.3 Lube oil distillation into MDO impacts from literature for 1 kg used oil

Impact Category	Unit	Boughton and Horvath 2004 as Modeled in GaBi	Geyer et al. 2013
		TRACI 2.0	TRACI 2.0
Global Warming	kg CO_2 eq	0.198	0.14
Acidification	mol H^+ eq	0.0176	0.06
Eutrophication	kg N eq	1.78×10^{-5}	2.6×10^{-5}
Ecotoxicity	CTUeco	0.0204	0.16
Human Health Cancer	cases	3.43×10^{-11}	1.11×10^{-10}
Human Health Non-Cancer	cases	4.45×10^{-9}	7.72×10^{-9}
Human Health Criteria Air	kg PM_{10} eq	4.83×10^{-5}	1.79×10^{-4}
Smog Creation	kg O_3 eq	6.56×10^{-3}	2.24×10^{-3}
Ozone Depletion	kg CFC-11 eq	3.99×10^{-10}	Not reported

Note: Boughton and Horvath impacts were derived from creating a GaBi model with the input process data provided in that source, not taken directly from the source itself. GWP calculated using TRACI 2.1 methodology in Geyer et al. 2013.

The following summarizes some pertinent additional details from the Geyer et al. (2013) study. It followed ISO 14040 guidelines for life cycle assessment, including a critical review. Modeling was based on a 2010 base year and the functional unit was “the management of all used oil generated in California during a calendar year”. The data used in Geyer et al. (2013) came from both primary and secondary sources, most of high quality with scores of 1 or 2 on the Weidema and Wesnaes (1996) Pedigree matrix, made possible by cooperation with industry.

When lube oil is distilled, it produces at least two usable products, marine diesel/distillate fuel and asphalt additive. According to Geyer et al. (2013), when 1 kg of used oil is reprocessed through this method, 0.50 kg of fuel and 0.31 kg of asphalt additive are produced. It is not clear what form the remainder of the products (at least 0.19 kg), however, it is likely from the process diagram in Geyer et al. (2013) that it is "light ends", sludge, and other wastes. Usable products produced in the disposal of used oil displace some needed to produce those products from other sources. Accordingly, it is appropriate to consider that 0.50 kg of fuel and 0.31 kg of asphalt additives do not need to be produced through another method, and the impacts that would have resulted from their production are discounted from the used oil disposal process. Following the same assumptions as Geyer et al. (2013), the displaced fuel is assumed to be no. 2 distillate fuel and the displaced asphalt product to be bitumen. Table 4.4 is a summary of the displaced impacts from distilling 1 kg of used oil into MDO reported in Geyer et al. (2013).

Table 4.4 Displaced impacts from displaced primary product production for 1 kg of used oil disposed of by distillation to MDO (Geyer et al. 2013)

Impact Category	Unit	Geyer et al. 2013
		TRACI 2.0
Global Warming	kg CO_2 eq	0.40
Acidification	mol H^+ eq	0.14
Eutrophication	kg N eq	6.7×10^{-5}
Ecotoxicity	CTUeco	0.16
Human Health Cancer	cases	1.86×10^{-10}
Human Health Non-Cancer	cases	2.09×10^{-8}
Human Health Criteria Air	kg PM_{10} eq	4.95×10^{-4}
Smog Creation	kg O_3 eq	2.67×10^{-2}
Ozone Depletion	kg CFC-11 eq	Not reported

Note: GWP calculated using TRACI 2.1 methodology.

4.2.4 Disposal – Combustion

Combustion is an alternative method of disposing of used lube oil, and is also a process by which some lube oil is used internally in two-stroke marine engines. To be inclusive, some information on the environmental impacts of this method are in this section. However, no offset from combustion or consideration of consumption in the engine are included in our analyses.

Geyer et al. (2013) provided impact category results for a combination of processes that included combustion, and the percentage attributed for each impact category were used to estimate combustion impact information as presented in table 4.5. Audibert (2006) provides emission data for combustion of used oil and many of these emissions were used directly as input to GaBi to calculate impact category equivalents. The notable exception was the metal content, where the actual average metal content from WSF oil analyses were used as input to GaBi, assuming that all of these metals are released into the air . Note that some of the constituents in the emission profile from Audibert (2006) were not characterized in TRACI 2.0 and thus were excluded from the model. The results are reported in table 4.5.

Table 4.5 Impacts for combustion of 1 kg of used oil from literature

Impact Category	Unit	Geyer et al. 2013	Audibert 2006 ("WSF" oil)	Audibert 2006 (typical oil)
		TRACI 2.0	TRACI 2.0	TRACI 2.0
Global Warming	kg CO_2 eq	3.02	2.88	2.88
Acidification	H^+ mol eq	0.53	0.674	0.674
Eutrophication	kg N eq	6.23×10^{-4}	2.31×10^{-4}	1.19×10^{-3}
Ecotoxicity	CTU_e	6.70	0.328	18.9
Human Health Cancer	CTU_h	1.25×10^{-9}	7.27×10^{-11}	5.98×10^{-9}
Human Health Non-Cancer	CTU_h	6.22×10^{-6}	1.56×10^{-7}	1.91×10^{-5}
Human Health Criteria Air	kg PM_{10} eq	5.75×10^{-3}	1.78×10^{-3}	1.78×10^{-3}
Smog Creation	kg O_3 eq	7.66×10^{-2}	0.103	0.103

Note: GWP calculated using TRACI 2.1 methodology in Geyer et al. 2013. Audibert did not complete impact category assessment. Their emission data were converted to LCA impacts using GaBi 6 by the authors. In addition, actual metal composition of WSF oil was separately calculated as labeled. Ozone depletion potential 0 or not characterized in all three datasets.

The impacts from Geyer et al. (2013) and the typical oil from Audibert 2006 do not agree with "WSF" oil impacts within an order of magnitude for ecotoxicity, human health cancer, and human health non-cancer. It is assumed that this is due to the metal concentrations in the WSF used oil which were much lower than most used oil averages reported in the literature (Khawaja and Aban 1996, Boughton and Horvath 2004, Audibert 2006, Geyer et al. 2013).

4.2.5 Lube Oil Transport Processes

Lube oil transport was considered for four stages of the process. These stages are:

- Lube oil from refinery to supplier,
- Lube oil from supplier to WSF (Tacoma dock),
- Used oil from WSF (Tacoma dock) to disposal pre-processing, and
- Used oil disposal pre-processing to distillation.

The transport processes include assumptions about the modes of transport and location of the oil refinery from which the lube oil came. An appropriate blending plant could not be located, so it is assumed that the blending occurs at the Richmond refinery. All distances were obtained from Google Maps and Google Earth, and assumptions are summarized in table 4.6. Using these data, a model was created in GaBi, was applied for 1 kg of cargo, and the resulting impacts using TRACI 2.0 methodology are reported in table 4.7.

Table 4.6 Transportation distance and vehicle type assumptions

Process	Origin	Destination	Distance (mi)	Vehicle Type
Lube oil from refinery to vendor	Chevron Way, Richmond, CA	13th Ave Seattle, WA	965	Ocean Freighter
Lube oil from vendor to vessel	13th Ave Seattle, WA	Point Defiance, Tacoma, WA	40	Class 6 Truck
Used oil to pre-processing	Point Defiance, Tacoma, WA	Airport Way, Seattle, WA	38	Class 6 Truck
Pre-processed used oil to distillation	Airport Way, Seattle, WA	Alexander Ave, Tacoma, WA	31	Class 8b Truck

Table 4.7 Lube oil transport impacts for 1 kg of oil

Impact Category	Unit	Richmond to Rainer Petroleum	Rainier Petroleum to Chetzy	Chetzy to pre-processing	Pre-processing MDO distillation
Global Warming	kg CO_2 eq	1.77×10^{-2}	9.44×10^{-3}	8.97×10^{-3}	4.74×10^{-3}
Acidification	mol H^+ eq	2.05×10^{-2}	2.68×10^{-3}	2.55×10^{-3}	1.49×10^{-3}
Eutrophication	kg N eq	1.98×10^{-5}	2.71×10^{-6}	2.58×10^{-6}	1.52×10^{-6}
Ecotoxicity	CTUeco	9.43×10^{-3}	5.52×10^{-3}	5.25×10^{-3}	2.77×10^{-3}
Human Health Cancer	cases	4.15×10^{-12}	3.89×10^{-12}	2.31×10^{-12}	1.22×10^{-12}
Human Health Non-Cancer	cases	2.31×10^{-9}	1.35×10^{-9}	1.28×10^{-9}	6.78×10^{-10}
Human Health Criteria Air	kg PM_{10} eq	4.14×10^{-5}	7.90×10^{-6}	7.50×10^{-6}	3.88×10^{-6}
Smog Creation	kg O_3 eq	1.07×10^{-2}	1.26×10^{-3}	1.20×10^{-3}	7.26×10^{-4}
Ozone Depletion	kg CFC-11 eq	6.67×10^{-13}	3.90×10^{-13}	3.71×10^{-13}	1.96×10^{-13}

Note: This excludes transport of crude oil to refinery, which is included in base oil production

4.3 Lube Oil Life Cycle Assessment Based Synthesis

The previous section was dedicated to presenting the detailed information obtained from literature, databases, and modeling in GaBi 6 for each portion of the lubricating oil life cycle, as a literature review and discussion of available data on lube oil processes. This section of the report synthesizes this information using the following method:

- Taking data for each life cycle stage from the following sources:
  - Base oil – GaBi 6 Database (Table 4.1)
  - Blending – Raimondi et al. (2012), excluding zinc-based additives (Table 4.2)
  - Transportation – Table 4.7.
  - Disposal by distillation to MDO – Geyer et al. (2013) (Table 4.3)
  - Displaced primary product – Geyer et al. (2013) (Table 4.4)
- Converting the functional unit from 1 kg to 1 gallon of lube oil (0.88 kg/L)
- Segregating into two sections, lube oil acquisition (base oil, blending, associated transportation) and used oil disposal (distillation to MDO, associated transportation, and displaced primary products) so that WSF can analyze the effects of using and disposing of different amounts of lube oil separately, since the quantity of lube oil put into a 2-stroke marine engine system is not the same as the quantity that comes out.

Using the aforementioned method, the estimated impact category results for lube oil acquisition for 1 gallon of new oil is presented in table 4.8. Here there are two totals presented, one with and one without the blending stage. This is to provide decision makers with either option due to the uncertainty of the blending impacts. Figure 4.3 includes external normalization, portraying the ratio of impacts from 1 gallon of oil acquisition to the total US daily per capita impact in each impact category (Total Including Blending).

Table 4.8 Lube oil acquisition impacts for 1 gallon of new oil

Impact Category	Unit	Production of Base Oil[a]	Acquisition Transport	**Total Not Including Blending**	Additive Blending[b]	**Total Including Blending[c]**
Global Warming	kg CO_2 eq	4.56	9.04×10^{-2}	**4.65**	2.05	**5.40**
Acidification	mol H^+ eq	1.20	7.72×10^{-2}	**1.27**	0.295	**1.29**
Eutrophication	kg N eq	7.73×10^{-4}	7.50×10^{-5}	**8.48×10^{-4}**	4.65×10^{-5}	**7.07×10^{-4}**
Ecotoxicity	CTUeco	1.81	4.98×10^{-2}	**1.86**	0.143	**1.61**
Human Health Cancer	cases	4.50×10^{-9}	2.68×10^{-11}	**4.52×10^{-9}**	6.98×10^{-9}	**9.66×10^{-9}**
Human Health Non-Cancer	cases	4.03×10^{-7}	1.22×10^{-8}	**4.15×10^{-7}**	1.13×10^{-7}	**4.26×10^{-7}**
Human Health Criteria Air	kg PM_{10} eq	3.80×10^{-3}	1.64×10^{-4}	**3.96×10^{-3}**	9.59×10^{-4}	**4.04×10^{-3}**
Smog Creation	kg O_3 eq	0.250	3.98×10^{-2}	**0.29**	No Data	**0.24**
Ozone Depletion	kg CFC-11 eq	2.48×10^{-10}	3.52×10^{-12}	**2.52×10^{-10}**	2.45×10^{-11}	**2.20×10^{-10}**

[a]GaBi 6 Database; [b]Raimondi et al. 2012
[c]Uses 0.8*[Production of Base Oil] for base oil impacts since 20% is additives in final lube oil

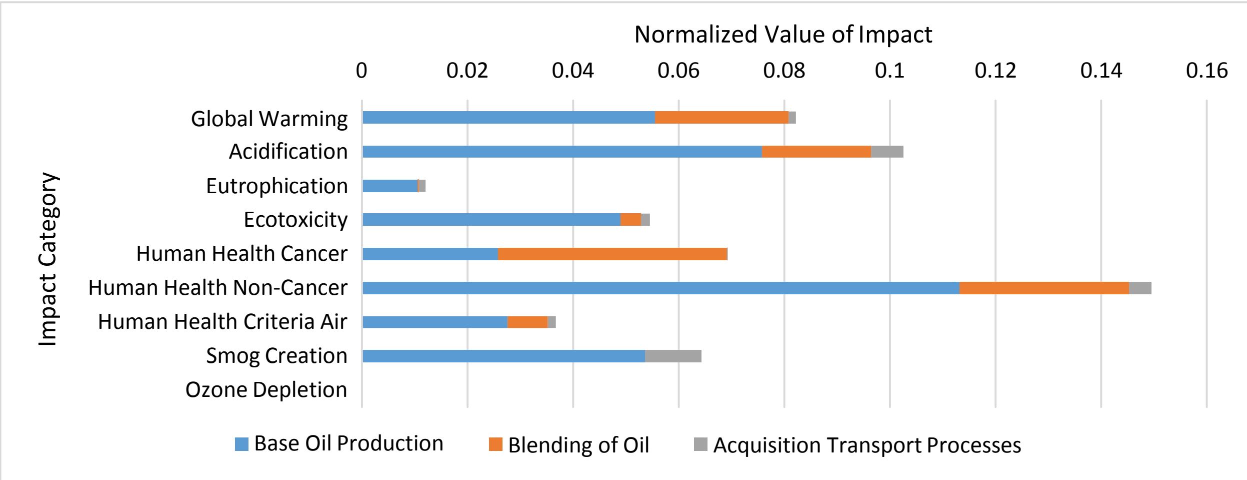

Figure 4.3 Lube oil acquisition impacts for 1 gallon of lube oil externally normalized to total US per capita per day impacts (base oil and transportation from Richmond, CA to WSF locations in Washington from GaBi 6 database, blending ratio impacts from Raimondi et al. 2012, US normalization references from Ryberg et al. 2014 and U.S. population from 2010 census)

The estimated impact category results for lube oil disposal for 1 gallon of used oil is presented in table 4.9. There are two totals presented, one not considering offset primary products from the distillation of used oil and one considering them. For most impact categories, this disposal process is less impactful than creating the same products from crude oil. Figure 4.4 normalizes the impacts to the total US daily per capita impact in each impact category.

Table 4.9 Lube oil disposal impacts for 1 gallon of used oil

Impact Category	Unit	Distillation of Used Oil to MDO[a]	Disposal Transport	**Total Not Including Offset**	Offset Primary Products[a]	**Total Including Offset**
Global Warming	kg CO_2 eq	0.47	0.046	0.512	-1.33	-0.820
Acidification	mol H^+ eq	0.20	0.013	0.213	-0.466	-0.253
Eutrophication	kg N eq	8.66×10^{-5}	1.37×10^{-5}	1.00×10^{-4}	-2.23×10^{-4}	-1.23×10^{-4}
Ecotoxicity	CTUeco	0.53	0.027	0.560	-0.533	0.027
Human Health Cancer	cases	3.70×10^{-10}	1.17×10^{-11}	3.82×10^{-10}	-6.20×10^{-10}	-2.38×10^{-10}
Human Health Non-Cancer	cases	2.57×10^{-8}	6.52×10^{-9}	3.22×10^{-8}	-6.96×10^{-8}	-3.74×10^{-8}
Human Health Criteria Air	kg PM_{10} eq	5.96×10^{-4}	3.79×10^{-5}	6.34×10^{-4}	-1.65×10^{-3}	-1.01×10^{-3}
Smog Creation	kg O_3 eq	0.007	6.40×10^{-3}	0.014	-0.089	-0.075
Ozone Depletion	kg CFC-11 eq	1.33×10^{-9}	1.89×10^{-12}	1.33×10^{-9}	No Data	1.33×10^{-9}

[a]Geyer et al. 2014
Note: Ozone depletion for distillation to MDO derived from Boughton and Horvath (2004).

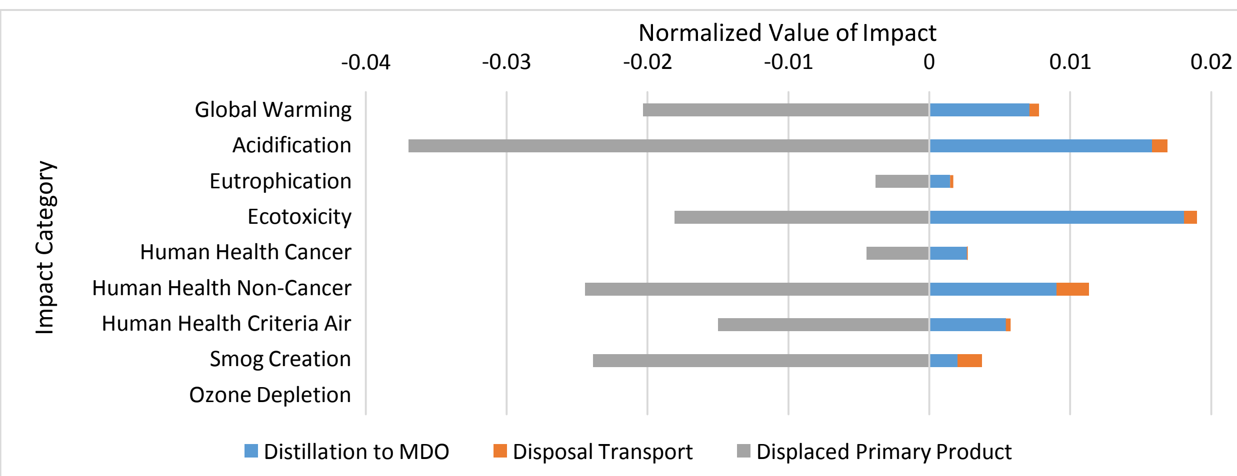

Figure 4.4 Lube oil disposal impacts for 1 gallon of used oil externally normalized to total US per capita per day impacts (distillation and primary product offset impacts from Geyer et al. 2014, transportation from GaBi 6 database using WSF and local disposal service locations, US normalization references from Ryberg et al. 2014 and U.S. population from 2010 census)

CHAPTER 5: SUMMARY

This report covers three major focal areas: oil analysis background, rough order of magnitude life cycle cost analysis, and environmental impacts through life cycle assessment methodologies. The oil analysis portion of the report provides information that might be helpful for making full utility of an oil analysis program. It also develops some of the methodology that will be useful for tracking and analyzing oil properties that will be needed for determining the operational performance of the self-cleaning oil filtration system.

The life cycle cost analysis shows that for a retrofit vessel, cost savings would likely be achieved by installation of a self-cleaning filtration system, considering a 50 year life cycle. These savings would be on the scale of roughly $50,000 to $200,000 (2014 dollars), depending on the oil drain interval, considering oil drain intervals from no extension up to triple the currently used interval. Payback periods for installing a self-cleaning filtration system ranged from 7.8 to 22.4 years under these same circumstances.

The environmental impact data assembled and modeled herein gives WSF a simple tool for approximating environmental impacts from an LCA perspective separately for acquisition and disposal by distillation. It can be applied directly to the filter problem, or in other capacities when oil use and disposal volume changes are involved. For the acquisition of lube oil, the most significant impact category with respect to US daily normalization per capita is Human Health Non-Cancer. For the disposal by MDO distillation, the benefits gained from offset primary MDO production are always higher than the impacts of the disposal process. Note that not included in the synthesis is information on combustion of engine oil which would be applicable to combustion in engines or to disposal by incineration. Future work might consider the relative impacts with relationship to the oil as used by WSF. For instance, other functional units that may be more applicable are impacts per engine hour, people transported, etc.

Using the results of the preliminary work on life cycle cost analysis and oil analysis trending, the authors also developed a tool to aid decisions on oil change interval extension, which has been accepted for presentation at the Transportation Research Board Annual Meeting in January 2015 (Langfitt and Haselbach 2014c). As determined through the cost analysis, there is a diminishing rate of incremental cost savings the longer oil life is extended. At the same time, risk of engine damage from over-extended oil may increase, even if not detected in an oil analysis. Figure 5.1 is the result of the cross cost-risk analysis showing expected trending of the base number, possibly one of the critical oil properties relative to limits for the M/V Chetzemoka, and the cost savings attained for a range of possible oil change intervals. Note that this figure was developed independently of consideration of the self-cleaning filter (only oil change interval extension), but could easily be applied to the self-cleaning filter decision making with inclusion of applicable costs in the LCC Savings curve.

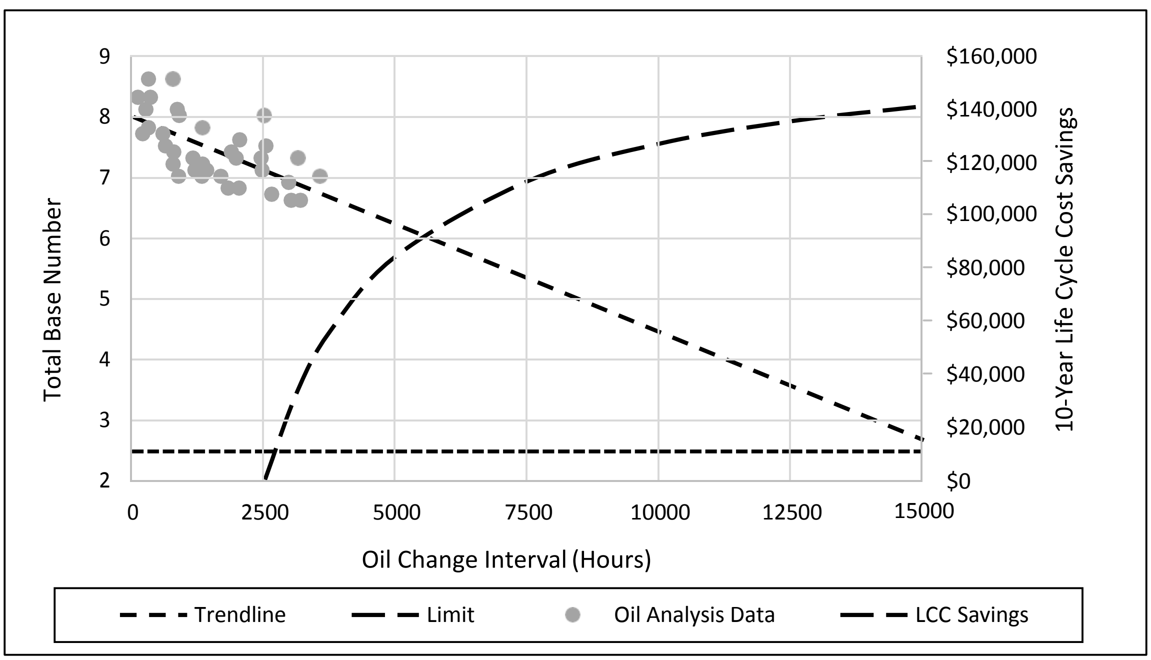

Figure 5.1 Example cross cost-risk tool to help decision-makers choose an extended oil drain interval based on oil analysis and life cycle cost analysis

The tool depicted in figure 5.1 simplifies complex data in a way that can be considered graphically and allows visualization of the benefits or impacts of various extended drain interval options. It is recommended that operational oil analysis continue even under this new change interval in case there is an anomaly in oil degradation.

Future work is ongoing to gather more information on the oil analyses with the self-cleaning oil filter over extended periods. With this additional information, the work herein will be updated. For the environmental analysis, future work might relate the gallon functional unit to different functional units relevant to WSF operations such as passenger/vehicle capacity, etc. Additional future research could be to expand the analyses to consider other vessels in the fleet.

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APPENDIX A: LCCA RECURRING COST MODEL SPECIFICS

RC= (C_o+C_f+C_{oc}+C_{fc}+C_{pt}+C_{od}+C_{fd}+C_{oa}+C_{la}+C_m)*UPV

$$C_o = (\text{Unit oil cost } [\frac{\$}{\text{gal}}])\ (\text{Oil used per change } [\frac{\text{gal}}{\text{change}}])\ (\text{Oil change frequency } [\frac{\text{changes}}{\text{year}}])$$

$$C_f = (\text{Unit filter/liner cost } [\frac{\$}{\text{filter}}])\ (\text{Filters/liners in system } [\frac{\text{filters}}{\text{change}}])\ (\text{Filter /liner change frequency } [\frac{\text{changes}}{\text{year}}])$$

$$C_{oc} = \{(\text{Labor rate } [\frac{\$}{\text{hr}}])\ (\text{Labor hours for oil change } [\frac{\text{hr}}{\text{change}}]) + (\text{Misc. supplies } [\frac{\$}{\text{change}}])\} * (\text{Oil change frequency } [\frac{\text{change}}{\text{year}}])$$

$$C_{fc} = \{(\text{Labor rate } [\frac{\$}{\text{hr}}])\ (\text{Labor hours for filter/liner change } [\frac{\text{hr}}{\text{change}}]) + (\text{Misc. supplies } [\frac{\$}{\text{change}}]) + (\text{Makeup oil per change } [\frac{\text{gal}}{\text{change}}])\ (\text{Unit oil cost } [\frac{\$}{\text{ga}}])\} * (\text{Filter/liner change frequency } [\frac{\text{change}}{\text{year}}])$$

$$C_{pt} = (\text{Personnel transport cost } [\frac{\$}{\text{change}}])\ (\text{Filter and/or oil change frequency } [\frac{\text{change}}{\text{year}}])$$

$$C_{od} = \{(\text{Cost per pickup } [\frac{\$}{\text{change}}]) + (\text{Cost per gallon } [\frac{\$}{\text{gal}}])\ (\text{Gallons per change } [\frac{\text{gal}}{\text{change}}])\}\ (\text{[illegible]} [\frac{\text{[illegible]}}{y\text{[illegible]}}])$$

$$C_{fd} = \{(\text{Cost per pickup } [\frac{\$}{\text{change}}]) + (\text{Cost per filter } [\frac{\$}{\text{gal}}])\ (\text{Filters per change } [\frac{\text{gal}}{\text{change}}])\}(\text{[illegible]} [\frac{\text{[illegible]}}{y\text{[illegible]}}])$$

$$C_{oa} = (\text{Cost per oil analysis } [\frac{\$}{\text{analysis}}])\ (\text{Oil analyses per year } [\frac{\text{analyses}}{\text{year}}]) + (\text{Cost per liner analysis } [\frac{\$}{\text{analysis}}])\ (\text{Liner analyses per year } [\frac{\text{analyses}}{\text{year}}])$$

$$C_m = \sum [(\text{Cost of maintenance action i } [\frac{\$}{\text{act}_i}])\ (\text{Frequency of action i } [\frac{\text{act}_i}{\text{year}}])]$$

APPENDIX B: LCA IMPACT CATEGORY DESCRIPTIONS

Many LCA impact categories express results in "equivalent units", sometimes abbreviated as "equiv." or "eq". This means that the impacts in that impact category are approximately equal to the impacts that would result from release of that quantity of the equivalent compound, but does not mean that all of the releases are actually in the form of that compound. For example, a system may emit a range of greenhouse gases with different radiative forcing values, but those values are known and can be related to the radiative forcing of CO_2 by ratio. This ratio is applied for each output in the inventory and summed to demonstrate that the releases have the same global warming potential that would result from x kg of CO_2 emissions. All of these equivalents are based on scientific studies, but there is much variability in the studies and therefore different interpretations and listings of the equivalents.

The following are explanations of the impact categories included in TRACI. Much of the information is summarized from Bare et al. 2002 and Bare 2011, the descriptions of the original TRACI method and the 2.0 update, respectively.

- Acidification Potential (AP) [H^+ moles-Equiv.]
  - "Acidification is the increasing concentration of hydrogen ion (H+) within a local environment." (Bare 2011). Acidification can occur when substances are introduced to the environmental that increase acidity, either directly or through reactions, and can have effects on man-made structures, lakes, rivers, plants, and animals. A common example of this is acid rain.
- Ecotoxicity Potential (ETP) [CTUeco]
  - Ecotoxicity is the potential of environmental stressing contaminants to damage ecosystems. One example of ecotoxicity is copper inhibiting the reproductive systems of fish. CTUeco is the Comparative Toxicity Unit for ecotoxicity, which is equivalent to the PAF*m^3*day, where PAF is the Potentially Affected Fraction, a measure of stress on the species in the environment.
- Eutrophication Potential (EP) [kg N-Equiv.]
  - Eutrophication is the addition of excessive nutrients, such as nitrates and phosphates, to aquatic ecosystems. This can result in increased accumulation of biomass, such as algae, which can negatively affect aquatic life. Various chemicals are correlated to nitrogen with respect to their eutrophication impact.
- Global Warming Potential (GWP) [kg CO_2-Equiv.]
  - Global warming is the rise in average temperature near Earth's surface. This rise in temperature can also drive changes to Earth's general climate. As with other environmental impacts, sources of global warming can be both anthropogenic and non-anthropogenic.
- Human Health Cancer Potential (HHCP) [cases]
  - Human health cancer potential is the possible increase of cancer risk to human populations exposed to the releases of substances.
- Human Health Criteria Air Potential (HHCAP) [kg PM 10-Equiv.]

        - While criteria air pollutants include a range of emissions types, this impact category specifically deals with particulate matter and precursors to secondary particulate matter formation. Increased particulate matter inhalation can lead to increased risk of respiratory disease, cancer, etc.
    - Human Health Non-Cancer Potential (HHNCP) [cases]
        - Human health non-cancer potential is the possible increase of non-cancer health risks (such as toxicological effects) to human populations exposed to the releases of substances.
    - Smog Creation Potential (SCP) [kg O_3-Equiv.]
        - Smog is another term for tropospheric (near ground level) ozone. It can form from reactions of NO_x and VOCs with sunlight and has the potential to cause health effects on humans and cause damage to ecosystems.
    - Stratospheric Ozone Depletion (ODP) [kg CFC 11-Equiv.]
        - Stratospheric ozone is ozone in the high atmosphere. This ozone protects Earth from radiation. Increased radiation reaching Earth's surface due to ozone depletion can have negative effects on humans, such as increased cancer risk, or on plants and marine life. CFC-11 is a refrigerant that can catalytically decrease ozone in the stratosphere, other ozone depleting chemicals are rated against CFC-11 with respect to this impact.