Assessment of Lube Oil Management and Self-Cleaning Oil Filter Feasibility in WSF Vessels — Final Report

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

FINAL REPORT

by

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16. Abstract
This research examined the feasibility of using self-cleaning oil filtration systems in the Washington State Ferries (WSF) fleet from a three-pronged perspective: (1) filtration effectiveness, (2) environmental impact, and (3) cost impact. A pilot self-cleaning filtration system, which filters oils without using disposable filter cartridges, was installed on one vessel from which to collect data. Filtration effectiveness was analyzed using oil analysis records, by trending the values of oil properties known to be important for lubrication and which indicate oil degradation. Results showed little difference between the standard paper cartridge filtration system currently in wide use and the self-cleaning system. Environmental impact was analyzed with a life cycle assessment methodology which quantifies potential impacts based on expected operation. For the self-cleaning system, there were decreased impacts from oil and filter use, but additional diesel fuel consumed by that system outweighed the benefits in many impact categories. Cost impact was analyzed with life cycle cost analysis, which suggested that the standard system would outperform the self-cleaning system in terms of whole life cost (unless the oil lifetime could be increased by more than three-fold), again mostly due to the additional fuel use of the self-cleaning system. Therefore, if expected costs and environmental impacts are major decision points it appears that a suitable alternative system would need to consume less diesel fuel to be viable. However, the self-cleaning system analyzed in this report would likely decrease risks, such as oil spills during filter handling, and provide operational benefits due to reduced expected maintenance. The pilot system was removed following the data collection period and deployments of self-cleaning filtration systems to other WSF vessels are not expected.

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Self-cleaning oil filtration, bypass oil filtration, oil analysis, life cycle cost analysis, life cycle assessment, lubricating oil, Washington State Ferries	No restrictions.

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EQUATIONS

ABBREVIATIONS

AP	Acidification Potential
BCA	Benefit-Cost Analysis
CFC-11	Cluorofluorocarbon-11 (Freon-11, R11)
CO_2	Carbon Dioxide
CTU	Comparative Toxic Unit
EF	(Oil change interval) Extension Factor
EMD	Electromotive Diesel
EP	Eutrophication Potential
ETP	Ecotoxicity Potential
GWP	Global Warming Potential
H^+	Hydrogen ion
HHCAP	Human Health Criteria Air Potential
HHCP	Human Health Cancer Potential
HHNCP	Human Health Non Cancer Potential
HH	Human Health
hp	Horsepower
ISO	International Organization for Standardization
lb	Pound (weight)
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LNG	Liquefied Natural Gas
NO_x	Nitrogen Oxides
NR	Normalization Reference
NRC	Non-Recurring Costs
NREL	National Renewable Energy Laboratory
O_3	Ozone
OCI	Oil Change Interval
ODP	Stratospheric Ozone Depletion Potential
PM_{10}	Particulate Matter with a diameter less than 10 micrometers
ppm	Parts per million
RC	Recurring Costs
SCP	Smog Creation Potential
SO_2	Sulfur Dioxide
TAN	Total Acid Number
TBN	Total Base Number
TRACI	Tool for the Reduction and Assessment of Chemical and other envir. Impacts
UPV	Uniform Present Value
W	Watt (power)
WSDOT	Washington State Department of Transportation
WSF	Washington State Ferries

EXECUTIVE SUMMARY

Washington State Ferries (WSF), a ferry system operated by the Washington State Department of Transportation (WSDOT), is investigating the use of self-cleaning oil filtration systems. The system analyzed in this report does not use disposable filters and provides a higher particle removal efficiency than standard paper filtration, which suggests the possibility of extended oil lifetime. Therefore, self-cleaning filtration was initially hypothesized to decrease cost and environmental impacts.

This research examined the feasibility of using self-cleaning oil filtration systems in the Washington State Ferries fleet from a three-pronged perspective: (1) filtration effectiveness, (2) environmental impact, and (3) cost impact. A pilot self-cleaning filtration system was installed on one vessel from which to collect data.

Filtration effectiveness was analyzed using oil analysis records, by trending the values of oil properties known to be important for lubrication and which indicate oil degradation. Results showed little difference between the standard paper cartridge filtration system currently in wide use and the self-cleaning system. However, longer data collection periods with both systems at longer oil drain intervals would be needed to solidify those results as effects of extremely long drain intervals were not studied.

Environmental impact was analyzed with a life cycle assessment methodology which quantifies potential impacts based on expected operation. For the self-cleaning system, there were decreased impacts from oil and filter use, but additional diesel fuel consumed by that system outweighed the benefits in many impact categories. For most of the environmental impact types analyzed in both types of filtration systems, diesel fuel consumption for pumping oil dominated total system impacts.

Cost impact was analyzed with life cycle cost analysis, which suggested that the standard system would outperform the self-cleaning system in terms of 50-year life cost (unless the oil lifetime could be increased by more than three-fold), again mostly due to the additional fuel use of the self-cleaning system. However, the filtration effectiveness analysis did not seem to support the necessary condition of an extension of such length being feasible in the self-cleaning system, while any extension being infeasible in the standard system.

Based on the results of the filtration effectiveness, environmental, and cost analyses, decision-makers at WSF elected to remove the pilot installation of the self-cleaning filtration system (executed in March 2016) and have no immediate plans to implement such systems on other vessels in the fleet. Nevertheless, other similar systems with different operational parameters or characteristics might perform differently, and the conclusions of this report are not to suggest that another self-cleaning or centrifugal filtration system would result in a similar outcome. For example, if a similar system that only filtered oil through a bypass (rather than full flow) were selected, the diesel fuel consumption might be reduced, altering the results of the cost and environmental analyses.

1. INTRODUCTION

1.1 Background on Project

Washington State Ferries (WSF), a ferry system operated by the Washington State Department of Transportation (WSDOT), is investigating alternative oil filtration systems for their fleet. Many of the vessels in service use disposable paper cartridge filters for lube oil filtration. WSF has proposed using a self-cleaning oil filtration system with centrifugal bypass as an alternative. According to product literature (Alfa Laval 2013), use of the new system provides a higher particle removal efficiency than standard paper filtration, and the service life of oil should be able to be increased, reducing oil use. Additionally, such a system does not use disposable filters (except for small centrifugal liners), and therefore, would eliminate filter needs.

Costs related to both systems include at least purchasing, transporting, storing, changing, and disposing of filters and oil. These must be balanced with purchasing, installation, and any additional or reduced operating costs (such as maintenance, additional oil testing, and fuel consumed by the system) incurred by use of the self-cleaning system. Differences in costs between the two systems were examined through life cycle cost analysis (LCCA).

Ongoing (use phase) environmental impacts of oil systems include at least those to produce, transport, use, and dispose of oil, fuel, and filters. The environmental impacts of the self-cleaning system production and transportation must also be considered. The environmental impacts of most components of both systems were examined through life cycle assessment (LCA), and an approximate compilation of environmental data was assembled for each filtration system based on typical or expected usage of each component.

The self-cleaning filtration system was installed on one engine on one vessel (M/V Chetzemoka) as a pilot, and data on its performance and operational needs were collected. This vessel was chosen because it was relatively new and had a supportive crew that was willing to take on the testing. The system was installed in February 2014 and removed in March 2016.

The following terms are used throughout this report as follows:

- Standard filtration system (standard filter)
    - Filter system 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 was installed on Engine 2 of the Chetzemoka from February 2014 to March 2016, which includes the self-cleaning full flow filters, housing, and bypass centrifugal filter

1.2 Background of Self-Cleaning Filtration Systems

The style of self-cleaning oil filtration system studied in this research filters full flow oil through a stack of stainless steel mesh discs, which are periodically backwashed to a bypass centrifuge. A hydraulic “distributor” is used to cycle through the portions of the disc stack for backwashing. Solids are collected on a small liner in the centrifuge which is replaced roughly every six months. The system was small enough to be added as a retrofit without removal of the original filtration system. At least one study (Mattey and Haley 2009) and one customer testimonial (Schmelz 2001) have suggested that such a filtration system can provide better filtration than a paper cartridge system and increase oil life. Product literature states that oil life may be doubled (Alfa Laval 2013). More information about the self-cleaning filtration system (Alfa Laval Eliminator) can be found in the Part 1 Report (Langfitt and Haselbach 2014) or product literature available online.

1.3 Background on Oil Analysis and Extended Drain Intervals

Engine oil provides a layer of protection between moving parts inside an engine, as well as facilitating heat transfer. Because oil degrades over time and with use, it must be periodically changed to ensure it can properly accomplish its intended functions. If oil is allowed to degrade significantly it can affect the performance of the engine and cause damage over time.

Oil is usually changed based on operating-hours intervals, to minimize the risk of an engine running on poor quality oil. However, another approach that may be taken is to periodically monitor essential oil properties through oil analysis and change oil based on its condition. Oil analysis may test wear metals concentrations, contaminant concentrations, additive concentrations, physical properties, and chemical properties, which in turn provide information on the condition of the oil and the engine. Therefore, oil analysis can be used to extend oil drain intervals if oil properties are degrading slowly enough to warrant such an increase. Generally, this is done by setting benchmark (or limit) values for each tested oil property and changing the oil once a benchmark is reached. In some cases, such an approach is augmented with rate-of-change monitoring to detect if any property begins to degrade too rapidly. Another approach that uses a hybrid scheme of oil analysis and time-based oil change intervals is presented by Langfitt and Haselbach (2016a). For detailed background information on oil analysis and extended drain intervals, please refer to the Part 1 Report (Langfitt and Haselbach 2014).

In this report, oil analysis results are presented for the main engines on the M/V Chetzemoka to compare oil being filtered by the standard and self-cleaning systems. The properties listing in Table 1.1 are those for which data was available for the analyses.

Table 1.1 Properties Tested by WSF through Oil Analysis

Wear Metals	*Additives*	*Contaminants*	*Physical & Chemical/Physical*
Iron	Antimony	Water	Viscosity @ 40°C
Chromium	Barium	Coolant	Viscosity @ 100°C
Lead	Boron	Fuel Dilution	Viscosity Index
Copper	Calcium	Soot	Base Number
Tin	Magnesium	Potassium	Acid Number
Aluminum	Molybdenum	Silicon	Oxidation Number
Nickel	Phosphorus	Sodium	SAE Rating
Silver	Silicon		Particle Quantification Index
Titanium	Sodium		
Vanadium	Zinc		

Note: Silicon and sodium are in both the additive and contaminant lists.

1.4 Background on Life Cycle Cost Analysis (LCCA)

Life cycle cost analysis (LCCA) is a methodology for determining the costs of a product or project over its entire life cycle. Typically, that includes at least costs of design, acquisition of raw materials, manufacture/construction, use, disposal/demolition, and transportation. Therefore, LCCA captures expected costs in a more holistic perspective than simply considering first costs, which are often much lower than operating costs for many product systems (Dhillon 2010, King County 2007, Brown and Yanuk 1985).

As with any assessment, LCCA is only as accurate as the underlying data, assumptions, and cost models (Barringer and Weber 1996). Particularly uncertain are costs occurring in the future, due to significant assumptions about the time value of money, price escalation of goods and services (or lack thereof), and future operating procedures. However, all major assumptions in an LCCA are outlined for transparency so that they may be taken into account when interpreting results. More background on life cycle cost analysis can be found in the Part I Report (Langfitt and Haselbach 2014).

1.5 Background on Life Cycle Assessment (LCA)

Life cycle assessment is a procedure to consider the environmental impacts of a product or process over its entire life time. The term “cradle-to-grave” is often attached to life cycle assessment to put this in perspective, and represents that all process from the extraction of resources from Earth until those resources are returned to Earth should be considered (SAIC 2006). Relevant stages of the product’s or process’s life generally includes at least material extraction, processing, manufacture, distribution, use, and disposal (or recycling). Inputs and outputs occur in many of these life stages that have consequences on the environment. Inputs are typically energy (such as electricity or fuels) and resources (such as ores, minerals, and water). Outputs are typically emissions to air, water, and soil including at least conventional air pollutants, greenhouse gases, chemicals, solid wastes, and even products themselves (Matthews et al. 2015). These stages are summarized in Figure 1.1 (EPA 1993). Environmental effects of products and processes are of interest because those products and processes with fewer/smaller negative environmental impacts contribute to sustainability and from this viewpoint could be considered preferable.

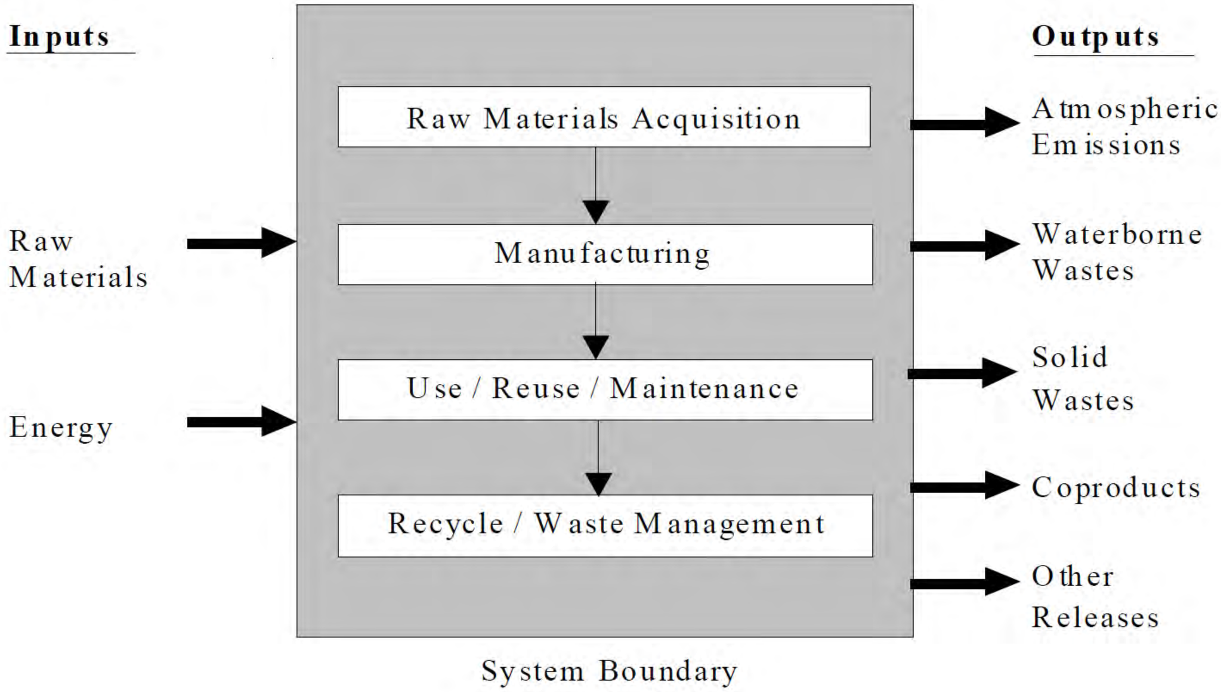

Figure 1.1 Typical life cycle stages for a product system (EPA 1993).

Life cycle assessment is useful for comparing products or processes and bringing to light environmental tradeoffs between them. LCA also helps avoid the shifting of environmental issues from one source to another when deciding between multiple options for a product or process, which is easy to do when only considering one part of the life cycle. For instance, one fuel might release more air emissions during its use than another, but require more energy and inputs to create. If only focusing on one stage or the other, the choice would be clear. However, LCA could reveal the different types and magnitudes of possible environmental impacts from each fuel over the entire life cycle, giving the decision-maker a more robust tool (SAIC 2006).

The methodology for completing an LCA can be generalized into four basic steps. First, the goal and scope of the study must be defined. This step gives the reader a clear understanding of what the LCA is trying to accomplish, how it will be carried out, where boundaries will be drawn, what environmental impacts will be considered, etc. Next, an inventory of inputs and outputs, such as those described above, must be compiled in a processed called the life cycle inventory (LCI). Then, the potential environmental effects of those inputs and outputs must be assessed in a process called life cycle impact assessment (LCIA). Finally, the results must be interpreted, in the context of the goal and scope including limitations and assumptions, to aid in a decision-making process. This is an iterative process whereby all of these phases can be updated throughout the assessment as new information becomes available (SAIC 2006). Figure 1.2 is a diagram signifying the general outline of a life cycle assessment.

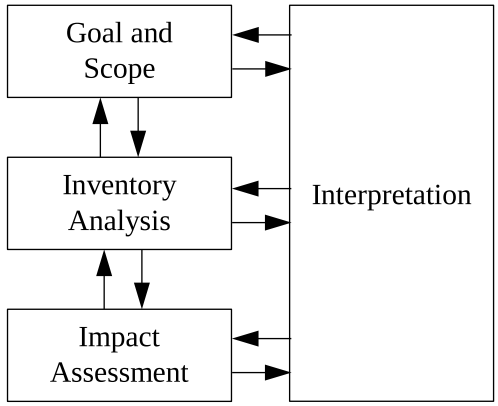

Figure 1.2 Phases of a life cycle assessment (Adapted from ISO 2006a).

The main results of an LCA are impact category indicators for each of the chosen environmental impact categories. These results are presented in a relevant unit for each category. For instance, global warming impacts are often presented in kg CO_2-equivalent because CO_2 is a common greenhouse gas that contributes to global warming. The physical meaning of this result is that the product or system contributes additional radiative forcing equal to the amount that would be expected from the emission of that mass of CO_2.

The International Organization for Standardization (ISO) maintains standards which govern how a life cycle assessment should be carried out, which are specifically ISO 14040:2006 (Environmental management – Life cycle assessment – Principles and framework) and ISO 14044:2006 (Environmental management – Life cycle assessment – Principles and framework) (ISO 2006a, ISO 2006b). These standards use the general phases just identified and describe in detail how they can be carried out and what must be included in each. This study is designed to be compliant with these standards.

While LCA is a highly developed tool for environmental decision-making, there are many limitations that must be understood before making decisions based on the results of an LCA. Data quality is extremely important to an LCA and often data cannot be obtained for all processes, and even for those which data is available, there will always be uncertainty pertaining to their accuracy. An LCA cannot consider every possible environmental impact and is hence limited by the decision of which environmental impacts are included in the study. Methodological choices such as spatial and temporal issues, allocation procedures, and characterization factor sources also affect study results. There is no way to objectively weight the importance of different environmental impacts, so no overall, aggregated impact can be determined to base a judgment of one product or process over another in a comparative assessment (Finnveden 2000). Additionally, social and economic concerns are not considered in an LCA. One way to mitigate this issue is to use other assessments in combination with LCA as a suite of decision-making tools (Haes et al. 2004).

1.6 Project Objectives

This report covers a portion of the Assessment of Lube Oil Management and Self-Cleaning Oil Filter Feasibility in WSF Vessels study. The four objectives of the overall study are:

1. Can self-cleaning oil filters be retrofitted on WSF vessels providing the same level or better of contaminant removal as paper filters?
2. Is the use of self-cleaning oil filters a cost effective solution that reduces environmental risks? (LCA)
3. Will self-cleaning filters save money by extending maintenance change out lube oil periods and reducing environmental disposal costs and risks? (LCCA)
4. Can improved monitoring and analysis of lube oil lengthen the time period between lube oil changes while maintaining the life of the engine?

Washington State University has focused on answering Questions 2 and 3. Preliminary answers were provided in a Part 1 Report entitled “Assessment of Lube Oil Management and Self-Cleaning Oil Filter Feasibility in WSF Vessels: Phases II and III: Part 1 Report,” dated October 22, 2014, with report number 2013-S-WSU-0044, as published by Pacific Northwest Transportation Consortium University Transportation Center for Region 10. Copies were previously provided to the Washington State Department of Transportation.

The preliminary report (Part 1 Report) covered lube oil analysis programs in detail, provided an LCA on lube oil acquisition and disposal, and provided a preliminary LCCA based on the initial collected data. This report herein adds to that information by including:

- Oil analysis data collected over the study period (Chapter 2)
- LCA data on the filters and housing, and also the parasitic consumption of additional diesel fuel needed to operate the self-cleaning filters (Chapter 3)
- An updated life cycle cost assessment with the new fuel consumption information (Chapter 4)
- An overall summary of the project (Chapter 5)

2. OIL ANALYSIS

2.1 Background

One component of both the cost assessment and environmental assessment is the quantity of lubricating oil used (or similarly, the frequency of oil changes). This is because the amount of oil needed for a ferry vessel is significant, and is therefore expected to have a significant effect on cost and environmental impacts. Accordingly, it is important to quantify how much oil will be used, which in turn depends on the oil change interval (because the volume of oil needed for each oil change is roughly constant).

Oil change intervals in vessels are generally set by an engine manufacturer at a specified number of engine operating hours. However, that does not necessarily represent the real frequency needed for oil changes because such a need is actually dictated by oil condition, which is only estimated by time periods. Oil analysis can be used to determine the real need for oil changes.

Oil analyses were performed monthly on both main propulsion engines of the M/V Chetzemoka since December 2010. The purpose of the oil analysis program was to monitor engine condition and oil condition in case of anomalies, not to be used for extending oil drain intervals. Prior to this research oil changes had been timed following the engine manufacturer hours-based recommendation (2500 hours). The data were retained and each property tested was trended against engine hours, oil hours, and date (though only trending against oil hours was included in this report, as it was the most relevant indicator of oil health for statistical analysis). That trending allowed each property's rate of degradation to be analyzed.

The self-cleaning oil filter was installed on Engine 2 in February 2014. Oil analysis was continued on the monthly interval for both engines. That provided two controls to assess if the self-cleaning filtration system was impacting oil property degradation rates: (1) comparisons between the same engine with the different filtration systems at different time periods, and (2) between different engines with different filtration systems during the same time period. These two controls help minimize the possible error associated with differences between engines and differences between operating characteristics, oil quality, etc., which may depend on the time period of study or engine. For the purpose of oil analysis comparisons, the time period from December 2010 to December 2013 is defined as "Pre" (pre self-cleaning installation) and the time period from March 2014 to February 2016 is defined as "Post" (post self-cleaning installation). Figure 2.1 summarizes these two comparisons.

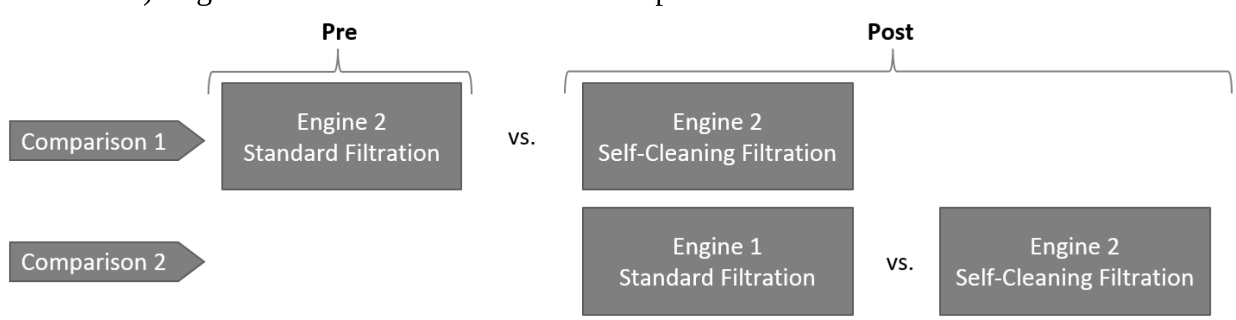

Figure 2.1 Depiction of two comparisons made across temporal and engine variables.

Through analysis of the data and background literature, it has been determined that the most important trended properties are mostly likely base number, acid number, and viscosity (Langfitt and Haselbach 2014). While concentrations of many wear metals trend fairly well, they do not approach limits nearly as quickly as some physical and chemical properties. Accordingly, assessment of the filtration performance is mainly focused on base number, acid number, and viscosity. Descriptions of the data for iron, copper, and lead are provided, however, none of those properties have approached limits in the datasets analyzed.

2.2 Temporal Comparison: Engine 2 in Pre and Post Time Periods

The graphs presented in this section (Figure 2.2 through Figure 2.5) compare oil properties over oil age for Engine 2 before and after the filtration system upgrade (Pre and Post time periods). The gray triangular markers represent the data collected with the standard filtration system and the black circle markers with the self-cleaning filtration system. The gray and black dotted lines interspersed with the data are least-squares linear regression lines for the Pre and Post time periods, respectively. The equations for those lines and the correlation coefficient (r^2) are provided in the top left and top right of the graphs. The lines labeled “Limit” are the severe alarm levels for each property, at which point oil may no longer provide proper lubrication and should be immediately changed. For viscosity at 40°C the limit was estimated from literature sources (see Table 2.3 in the Part 1 Report by Langfitt and Haselbach 2014). For the other three properties, the limits were provided by the engine manufacturer (EMD 2008). Pooled variance t-tests on slopes for two independent samples were carried out to examine if slopes were different by a statistically significant margin (based on Zaiontz 2016). The results of those t-tests are provided in the form of p-values near the top center of each graph. In this case, the p-value represents the likelihood that differences seen in the slopes of the linear regression lines are based on chance, and not on actual differences between the filtration systems. Therefore, lower p-values represent a higher probability that differences in oil property trends are related to differences between the performance of the oil filtration systems. In this study, the threshold (alpha level) is set at 0.05, which means that all p-values lower than 0.05 are considered statistically significant. P-values near one imply little difference between the compared slopes.

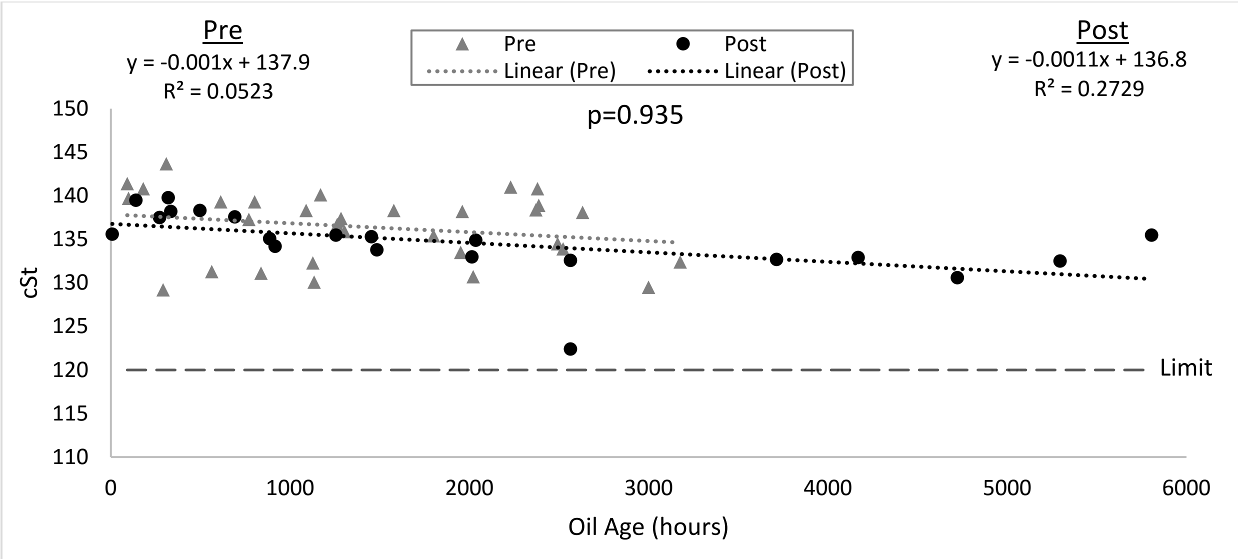

Figure 2.2 Oil analysis trending of viscosity at 40° C (temporal comparison).

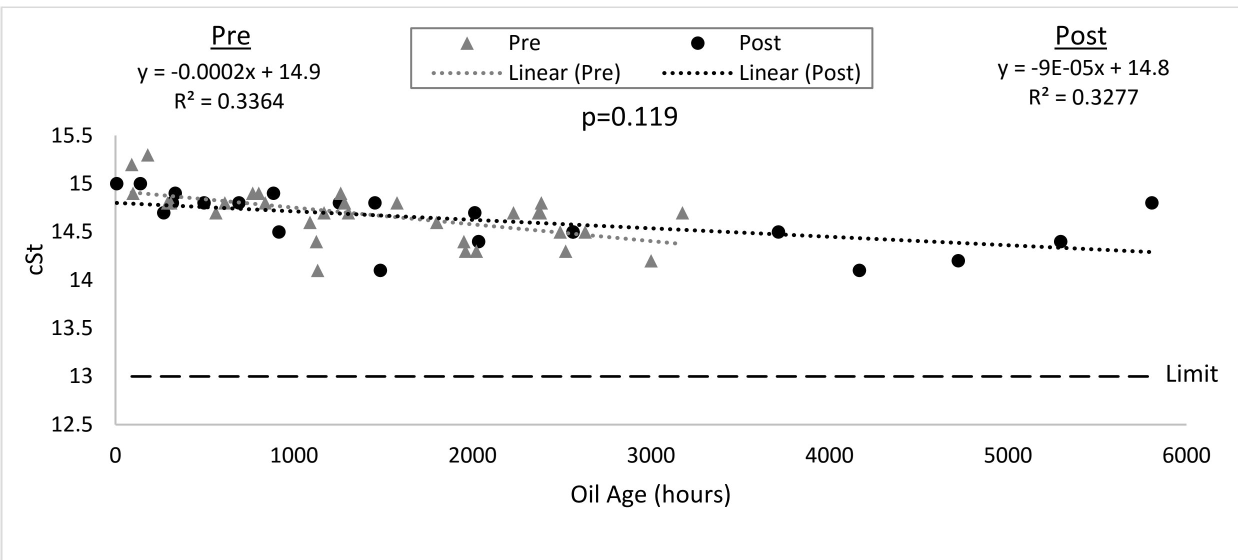

Figure 2.3 Oil analysis trending of viscosity at 100° C (temporal comparison).

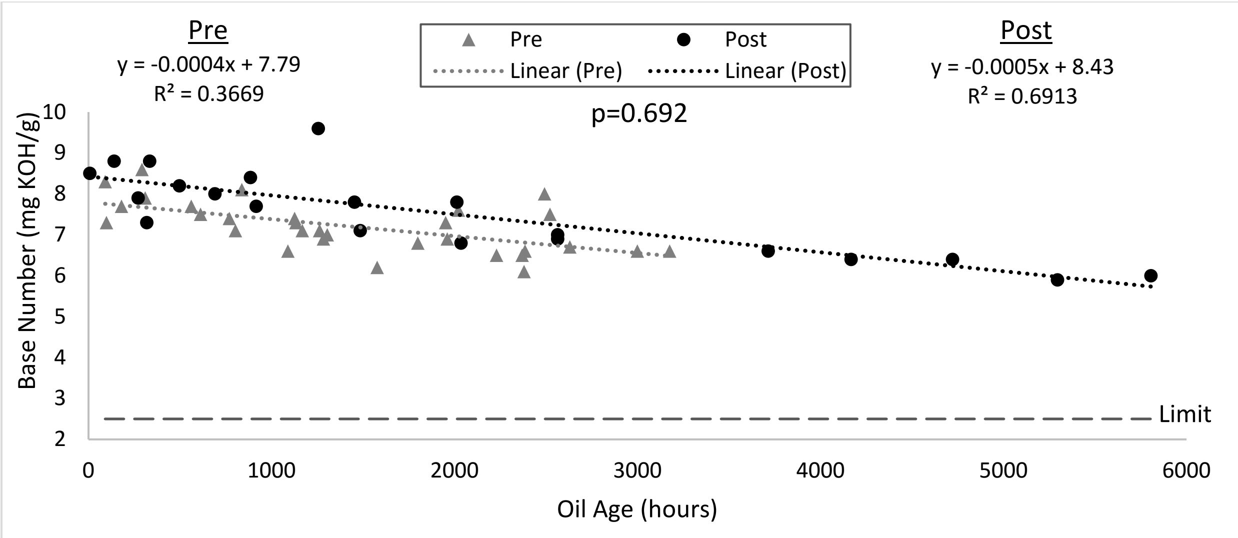

Figure 2.4 Oil analysis trending of total base number (temporal comparison).

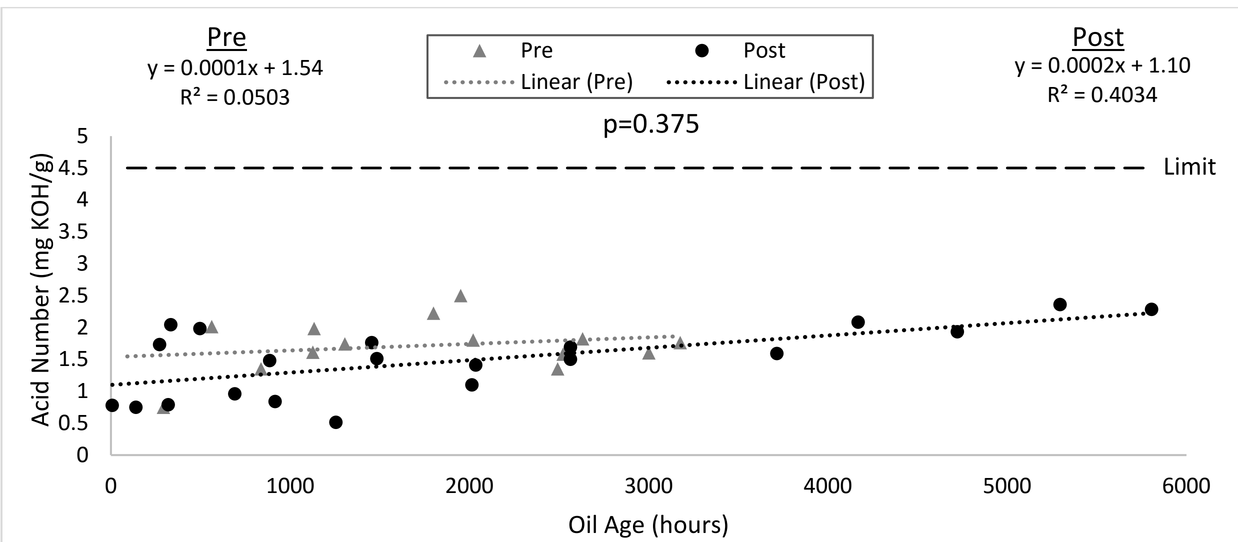

Figure 2.5 Oil analysis trending of total acid number (temporal comparison).

Based on the properties analyzed in Figure 2.2 through Figure 2.5, no statistically significant differences in trends could be detected. In fact, all trend lines appeared to have fairly similar slopes. No trend lines were approaching the limits for any of the properties by 6000 hours, suggesting that such an extension might be feasible.

Copper, iron, and lead did not approach limits. The highest concentration of iron reported was 6 ppm (limit 125 ppm), copper was 21 ppm (limit 150 ppm), and lead was 7 ppm (limit 75 ppm). For iron and copper, the self-cleaning system appeared to outperform the standard, and the two systems seemed to perform similarly for lead. However, again, it is unlikely that these parameters would drive an oil change decision due to the proximity to limits compared to the proximity to limits of viscosity, base number, and acid number.

2.3 Engine Comparison: Engine 1 versus Engine 2 in Post Time Period

Figure 2.6 through Figure 2.9 show the comparisons of key oil property degradation based on a comparison of Engine 1 and Engine 2 in the Post time period. Therefore, Engine 1 (grey triangles and line) represents the standard filtration system, while Engine 2 (black circles and line) represents the self-cleaning filtration system.

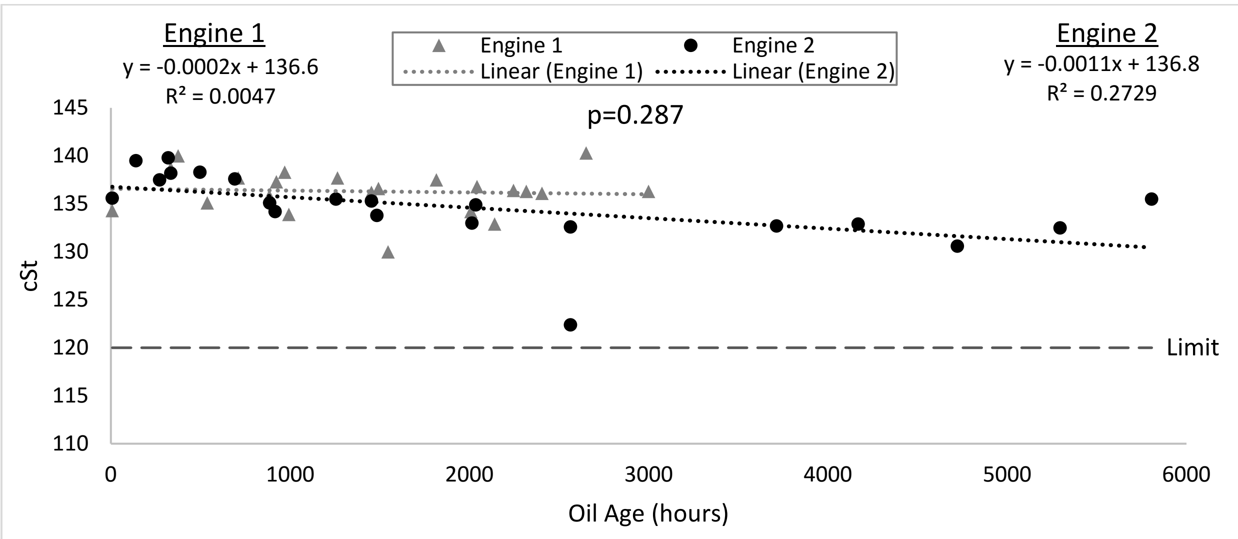

Figure 2.6 Oil analysis trending of viscosity at 40° C (engine comparison).

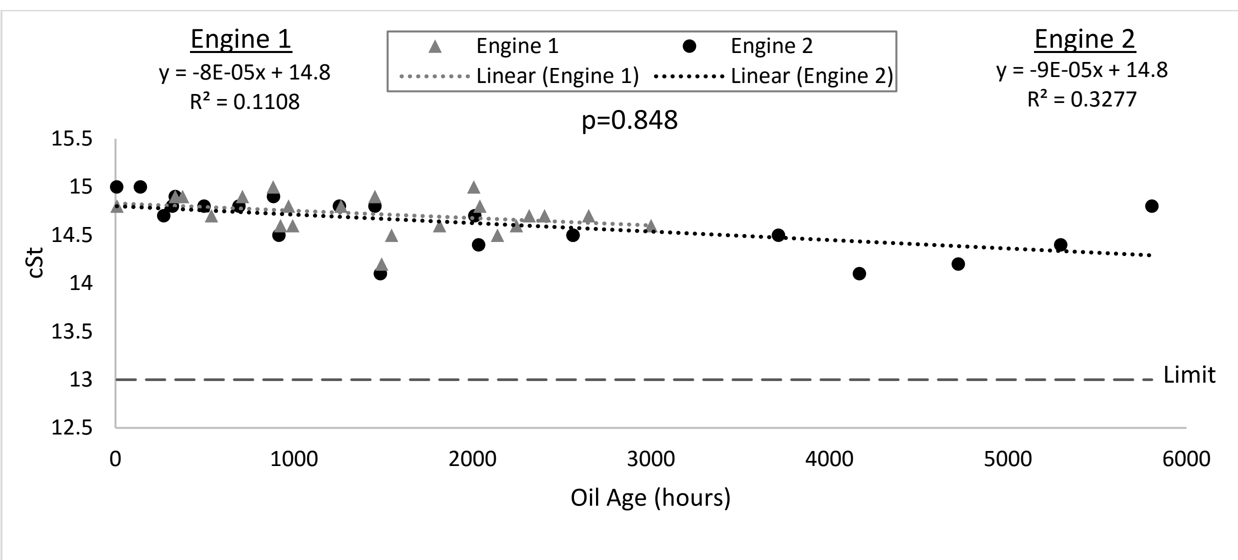

Figure 2.7 Oil analysis trending of viscosity at 100° C (engine comparison).

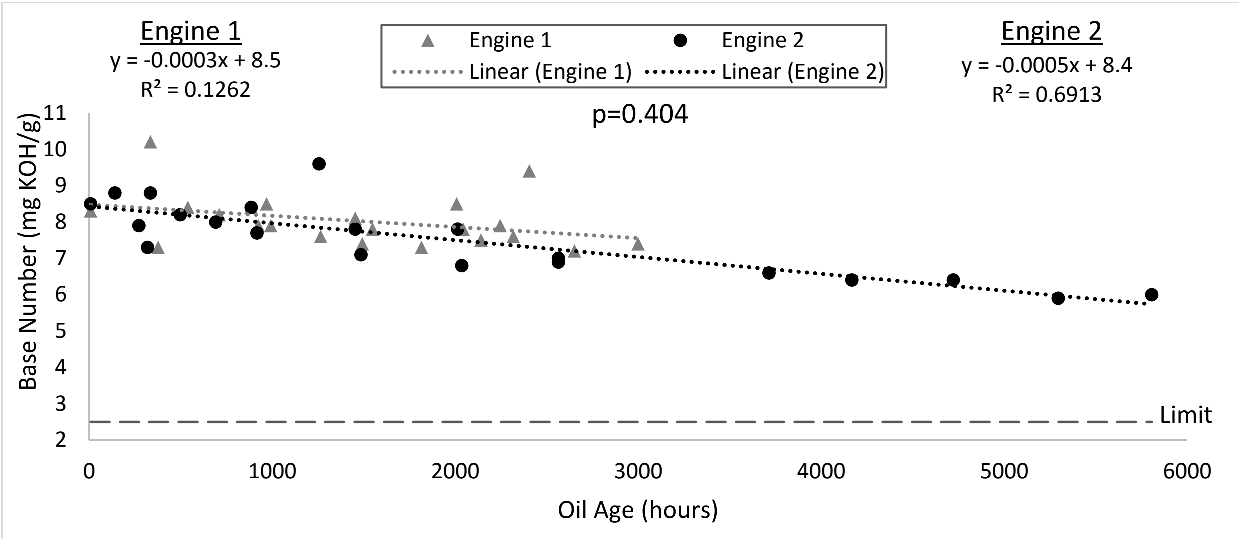

Figure 2.8 Oil analysis trending of total base number (engine comparison).

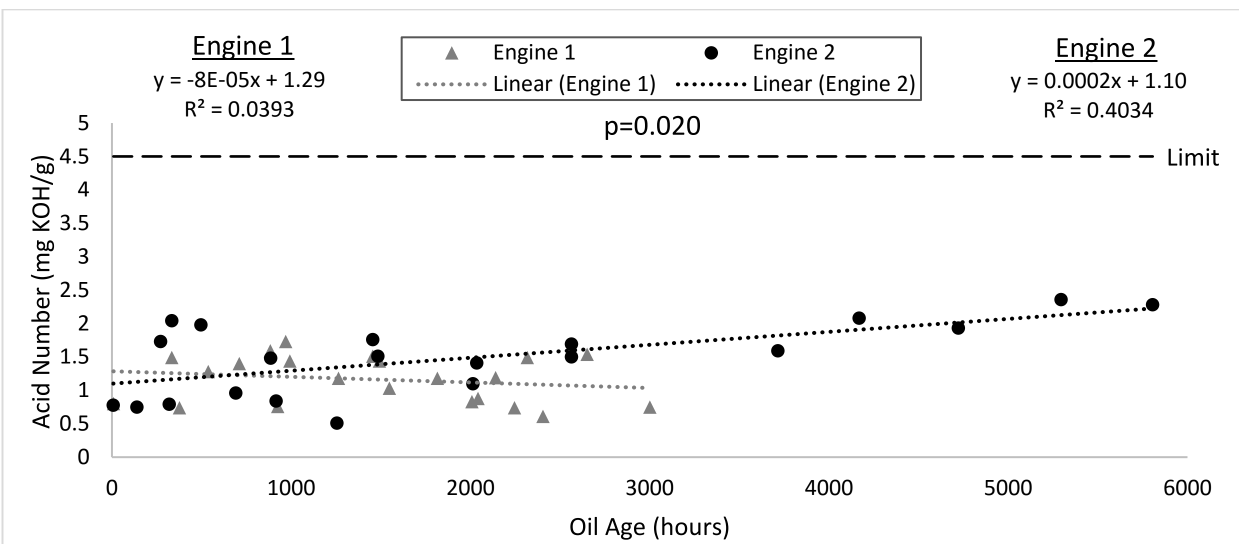

Figure 2.9 Oil analysis trending of total acid number (engine comparison).

Based on the engine-wise comparisons over the Post time period, only total acid number showed a statistically significant difference in trending ($p=0.02$). In that case Engine 1 (standard filter) showed a decreasing trend over time, whereas Engine 2 (self-cleaning filter) showed an increasing trend. Typically, acid number increases over oil life, so it is difficult to explain the trend in Engine 1. Still, Engine 2 is not approaching the limit by 6000 hours. Wear metal levels were similar to those in the temporal comparison, with none approaching property limits.

2.4 Conclusion

The oil analysis data presented in this section were mostly unable to show significant differences between the rates of oil degradation between oil filtration systems. Difficulty in using oil analysis results to determine differences in filtration systems has been documented in the literature (Fleetguard 2003). Oil analysis is designed to determine oil condition so it follows that it should be able to assess the oil filter's ability to retain the oil's condition. However, there is quite a great deal of variability in most oil analysis data and gaps in coverage of properties could limit the effectiveness of results. Indeed, studies have both shown definitive differences between oil filtration systems demonstrated by oil analysis results (Lin et al. 1993) and failed to identify differences based on oil analysis despite the knowledge that the filtration systems had vastly different efficiencies (Fleetguard 2003).

In both comparisons (temporal and engine) there are potential confounding factors. In order to conclude that either system provides an advantage it would be preferable to see that advantage under both comparisons (Engine 2 pre vs. Engine 2 post; Engine 1 post vs. Engine 2 post). The statistical significance analysis relied upon linear correlations. While the data appear to be roughly linear and literature supports that type of trend for oil properties (Toms 1998, Fitch 2007), that assumption may not hold for longer oil life. The self-cleaning system had data for longer oil lifetimes. While it cannot be said if either system is better than the other, it does appear likely that the self-cleaning system could provide at least double the oil change interval that is being currently used (it may be that the standard system could use longer oil changes as well, however, data has not been collected for sufficiently high oil hours to assess such a hypothesis). Only one set of data was extended to that length, however, so it would be recommended to collect more data before setting a longer interval. The remainder of the study considers extended drain intervals as an assumption of the self-cleaning system, but also presents the data for non-extended drain intervals.

An extended oil change interval scheme could be implemented for either system with the data available and continuous collection during interval extension. Langfitt and Haselbach (2016a) provide a methodology for modestly increasing oil drain intervals using oil analysis and life cycle cost analysis as a way to balance benefits and risks. That methodology relies on overlaying the degradation rates of various oil parameters relative to their specified limits on a graph of life cycle costs, both dependent on oil change interval to select an initial trial interval. Then, oil is extended to that interval, with collection of regular oil analysis data still occurring. The approach allows engine operators to extend drain intervals at a level that captures most of the available cost benefits, while reducing the risk of extending oil to its limits, and allowing maintenance to be scheduled in advance.

3. LIFE CYCLE ASSESSMENT (LCA)

Life cycle assessment (LCA) is a methodology for estimating the environmental impacts of a product or process over its entire life cycle. In this report, life cycle assessment is used to assess various components of both the standard and self-cleaning oil filtration systems.

There are strict rules for *comparative* life cycle assessment (ISO 2006b), which go beyond the scope of this report. Therefore, the results presented herein are not meant to constitute a comparative life cycle assessment. Rather, they are meant to provide individual life cycle assessments of various components of the two oil systems. Following the life cycle assessments, compilation of the data for each systems is made based on expected annual use of each component, but that portion of the analysis should not be considered a comparative life cycle assessment because it does not meet some of the ISO standards for comparative LCA.

3.1 Goal

The goal of this study was to assess the environmental impacts of key oil filtration system components which are used in various types of oil filtration systems appropriate for marine ferry vessels. The results are intended to be used in decision-making processes regarding installation of alternative filtration systems in ferries in the Washington State Ferries (WSF) fleet, particularly with respect to paper cartridge, self-cleaning, and centrifugal oil filtration systems. Life cycle assessment data were requested by WSF to allow a range of environmental concerns to be taken into account as one portion of a larger decision-making process, which also included cost and effectiveness assessments. Washington State Ferries decision-makers are the main intended audience, with other vessel operators as a secondary audience. Accordingly, the results are intended to be publicly released. While the data developed from the life cycle assessments on individual components were eventually compiled to give general guidance on various oil filtration systems, no comparative assertions were made with respect to the portions of this study that are considered part of the life cycle assessment.

3.2 Scope

3.2.1 Functional Unit

The function of both oil filtration systems under consideration in this report is to maintain lubricating oil properties at a level sufficient for proper lubrication of a large marine diesel engine. A functional unit is an equivalent basis on which to compare multiple systems that is based on accomplishing an equal quantity of the same function. Therefore, in a comparative life cycle assessment the functional unit would dictate the length of time or amount of service that each oil filtration system should provide filtration to a specified quality. However, this study is not designed to directly compare the two alternatives, but rather to provide decision-making support based on rough estimates with respect to various components of the engine oil system. Therefore, an alternative type of unit which does not directly consider function, *declared units*, are used throughout this study.

A declared unit is not based on the function of the product; rather, it is based on a quantity (Simonen 2014). Table 3.1 lists the declared units that were used for each component analyzed in this report.

Table 3.1 Declared Units for Components Analyzed with LCA

Component	*Declared Unit*
Oil	1 gallon of oil
Filter cartridges	1 filter cartridge
Self-cleaning filter housing	1 self-cleaning filter
Diesel fuel	1 gallon of diesel fuel

3.2.2 System Boundary

Figure 3.1 is the system diagram containing the major processes and flows within each ferry lube oil system component that were analyzed (lube oil, diesel fuel, and self-cleaning filter housing, and filter cartridges). A system boundary is included to demonstrate which process were included in this study, and which were excluded. No quantitative cutoff criteria were used to decide which processes to include within the system boundary. Instead, processes were excluded if either data could not be reasonably obtained for that process or if, by the judgement of the authors, the process would have a negligible contribution to the total impacts.

Oil processes were assumed to start at the point of extraction of crude oil include transport, refining, blending, use, and disposal. Offset products from oil recycling were considered to be within the system boundary and were accounted for. Additive blending processes to create the final lube oil product from the base oil product were accounted for as well, however, there was high data uncertainty for that portion of the analysis.

Disposable filter cartridge processes were considered to be extraction and transport of raw materials, manufacture, transport of filters, and use. Disposal of the filters (and offset metal production from filter recycling) was considered to be outside the scope of this study due to data for those processes being unavailable. The canister which holds the filter cartridges, the rack which allows them to drain after use, and other components, such as piping, of the standard filtration system were not included in the system boundary as they would not be relevant to the decision-making support stated in the goal of this LCA (those components would already be present whether or not a self-cleaning system were retrofitted).

Production of the self-cleaning filter housing was included in the system boundary, but with significant limitations. Only extraction, processing, and transport of the major housing materials were considered. All other processes, such as the production of bolts, filter elements, etc. were outside the system boundary. This was to limit complexity as these impacts were assumed to be negligible compared to the overall scale of impacts. Additionally, disposal of the self-cleaning system was not considered because the method of disposal was highly uncertain and was unlikely to significantly alter the results. Also, associated materials, such as piping, used to install the self-cleaning filter were not considered.

Geographic boundaries were limited to the United States, when possible, through the use of US literature sources and the GaBi6 (2015) extension database "XVII: Full US." In cases of electrical grid mix, United States averages were applied. A notable exception is that lubricating oil additive blending was based on European data.

Environmental effects of manufacturing, maintaining, and disposing of equipment and buildings related to any of the included processes was excluded from the system boundary. For example, producing the filter housing requires various machines for bending, gluing, and packaging filters, and a building in which those processes occur. However, the construction of the building and production of those machines, as well as anticipated demolition and disposal, were not included in the system boundary. Such omissions were made because the machines and buildings have high lifetime throughput, so the impact allocated to any individual filter is likely very small.

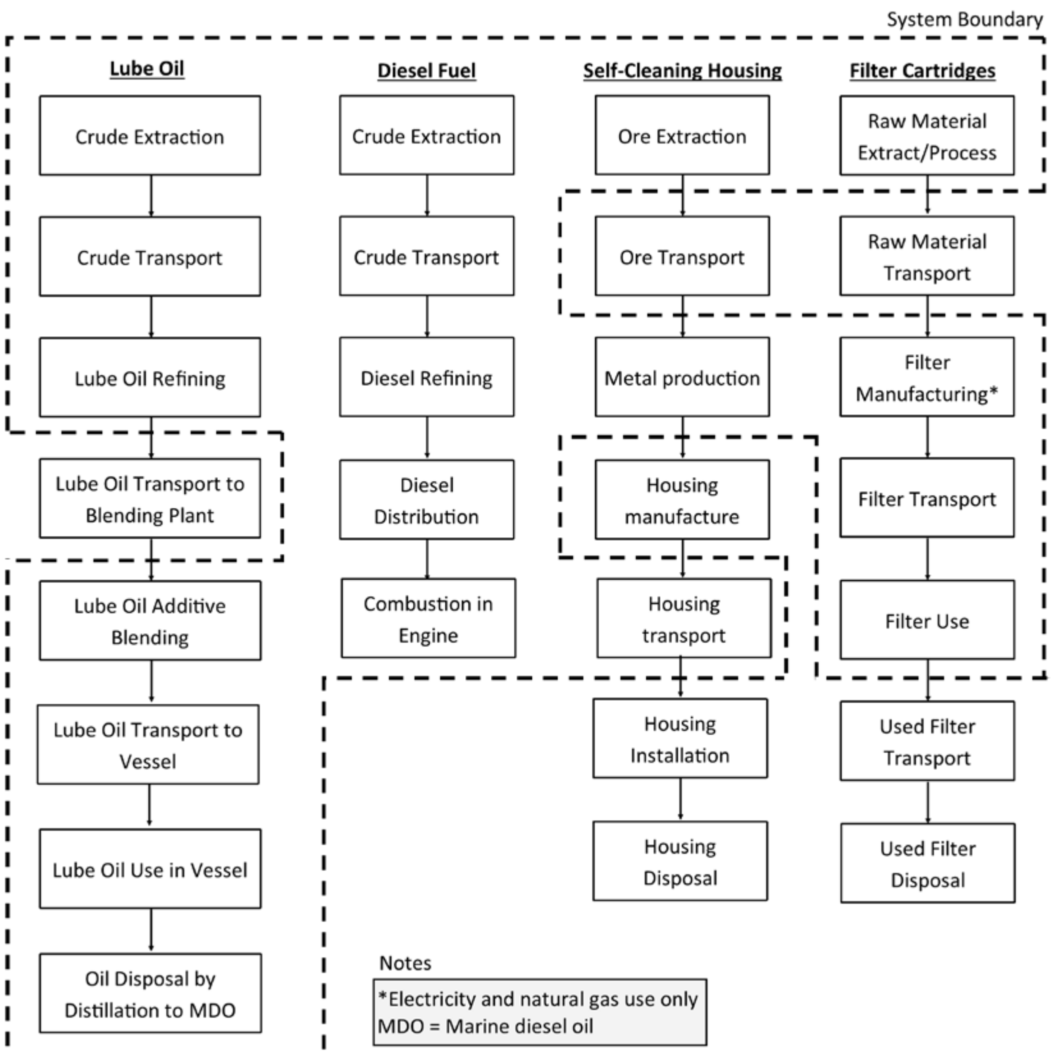

Figure 3.1 LCA system diagram (Updated from Langfitt and Haselbach 2016b).

3.2.3 Impact Assessment

Life cycle inventory (LCI) data contains the types and quantities of flows in to and out of the analyzed system, such as emissions of pollutants and uses of energy. However, these inventories can be difficult to interpret. Life cycle impact assessment (LCIA) converts the quantities of these flows into the magnitudes of potential impacts they could have on the environment, in the impact categories included in the study. That is accomplished through linear characterization factors to convert flows into equivalent units in each impact category to which a flow contributes (e.g., kg CO_2-eq for global warming). *Impact assessment methodologies* contain these characterization factors. Various impact assessment methodologies exist from a number of sources and vary in their geographic coverage, impact category coverage, methods of developing characterization factors, and position in the chain of events leading to environmental impacts (midpoint vs. endpoint). (Midpoint impacts are the direct effects, whereas endpoints are the final effects on the environment. Endpoint indicators are easier to understand, but midpoint indicators require less assumptions and are therefore more objective, according to Heijungs and Guinée 2012).

The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) 2.0 (Bare 2011) was used as the impact assessment methodology in this study. This impact assessment methodology was chosen primarily because it is the only one specifically developed for assessments in the United States. Furthermore, it is supported by the GaBi 6 LCA software, is the same impact assessment methodology used in studies that served as data sources for this study, and is a midpoint assessment methodology.

3.2.4 Environmental Impact Categories

ISO 14044 calls for LCAs to include a "comprehensive set" of environmental impact categories (ISO 2006b). To that end, and to provide effective decision-making support, every impact category in the TRACI 2.0 methodology was included in this study. The full list of categories, along with each category abbreviation in parentheses and equivalent unit in brackets is:

- Acidification Potential (AP) [H^+ moles-Equiv.]
- Ecotoxicity Potential (ETP) [CTUeco]
- Eutrophication Potential (EP) [kg N-Equiv.]
- Global Warming Potential (100 yr.) (GWP) [kg CO_2-Equiv.]
- Human Health Cancer Potential (HHCP) [cases]
- Human Health Non-Cancer Potential (HHNCP) [cases]
- Human Health Criteria Air Potential (HHCAP) [kg PM_{10}-Equiv.]
- Smog Creation Potential (SCP) [kg O_3-Equiv.]
- Stratospheric Ozone Depletion Potential (ODP) [kg CFC-11-Equiv.]

3.2.5 Assumptions

A few major assumptions were made throughout the LCA. Current technology with US average grid mixes were used for energy generation processes. Current technology for oil and filter production and disposal were assumed. It was assumed that all oil was disposed of properly (i.e., no leaks or spills during transfer or transport). Other assumptions used when collecting and analyzing data are addressed individually throughout this report, especially in the LCI section.

3.2.6 Limitations

Secondary data from literature sources and databases were used extensively in this study, as primary data availability was low. Some of these sources only presented results in impact category indicators, so in those cases data were integrated in impact category indicator form, rather than inventory data form. Many of the processes involved in oil filtration systems have not been examined environmentally, so significant assumptions had to be made about "equivalent" processes. This type of estimation is preferable to the alternative of omitting processes that have not been specifically studied (Klöpffer and Grahl 2014). The LCIA portion of the life cycle assessment is inherently built upon assumptions surrounding the characterization of environmental impacts resulting from the life cycle inputs and outputs.

3.3 Life Cycle Inventory

Most of the data were collected from literature or the US database in GaBi 6. Attempts were made to obtain primary data directly from oil production, oil disposal, disposable filter production, and self-cleaning filter production companies, but few of these companies were able to provide data.

3.3.1 Lubricating Oil

Sources of data and characterization of environmental impacts for the ferry lubricating oil life cycle have been previously covered in detail by Langfitt and Haselbach (2014, 2015). Some background information and the main data sources selected for those reports are covered in this section as a summary of that prior work.

Throughout the life cycle of oil, from crude oil exploration through final disposal, there are potential impacts on the environment (O'Rourke and Connolly 2003, Epstein et al. 2002, Saha and Gamkhar 2005). All processes from exploration for oil through base oil production, have been modeled by the developers of GaBi 6 (2015) with a base year of 2010 and location of the United States and this data is used as the life cycle inventory for production of base lubricating oil. All effects related to the feedstock (crude oil) are allocated on an energy basis while all refinery processes are allocated on a mass basis. Each process in the refinery is individually modeled and inputs and outputs of the process are allocated by the mass fraction of oil to be used as lubricant (GaBi 2015).

Base oil is a stock product that must be blended with additives for the particular application for which the oil will be used. Blending of additives is generally not included in LCAs on oil, but one study has examined the potential effects of blending (Raimondi et al. 2012). Data from that study, which were based on European sources, were used as a proxy for the blending process based on the percentage of additional impact in each impact category over base oil production alone. Limitations of this approach are detailed in the Part 1 Report (Langfitt and Haselbach 2014).

The oil manufacturer was contacted to ask about the blending process and what additives are used in the oil, but they were unable to provide the information. Therefore, environmental impacts of the blending processes were assumed to constitute the same percentage increase over base oil impacts that were determined in Riamondi et al. (2012). (Note that WSF used zinc-free oil in the vessel under study, so impacts from zinc-based additives were removed).

Some lubricating oil is "used" in the form of combustion in the engine, and some is conserved and must be disposed of otherwise. Use of lubricating oil is considered to be the oil that is combusted in the engine.

Lube oil combusted in a marine diesel engine was assumed to follow a combustion profile consistent with used lube oil burned for energy recovery. This combustion profile is dependent upon the concentrations of compounds within the oil, including sulfur, chlorine, and metals which are present as additives or from wear within the engine. Audibert (2006) provides the method used as a basis for calculating emissions from used lube oil on a basis of 1 kg oil burned where results are presented as mass concentration per standard volume of flue gas. Organic compounds were not considered due to a lack of reliable data.

Oil analysis reports from the M/V Chetzemoka, for the time period December 2010 to December 2013 were used to determine concentrations of various constituents in the oil, with the mean value of all samples being used as the concentrations for analysis. Since ppm_m=mg/kg, the ppm reported for each constituent on the oil analysis reports is equivalent to that mass in mg of the constituent in 1 kg of oil. The results of these average concentrations and mass emissions profile of combusting one kg of oil, derived using the aforementioned procedure, are shown in Table 3.2. For those constituents above the middle separating line, the average oil properties as reported by Audibert (2006) were used as proxies since those constituents were not measured in oil analyses.

Inventory data for lube oil disposal methods is scarce due to proprietary data confidentiality agreements. A particularly complete study was done by the California Department of Resources Recycling and Recovery (Geyer et al. 2013) that provided current, in-depth information about different used oil disposal pathways. Additionally, one other source (Boughton and Horvath 2004) quantified environmental impacts of used oil distillation into MDO, however, this study employed greatly simplified processes and was outdated, as the industry has changed over time. However, Geyer et al. (2013) did not include ODP, so that data came from Boughton and Horvath (2004).

Table 3.2 Air Emission Inventory for Lube Oil Combustion with Average Chetzemoka Properties

Constituent	*Concentration in dry oil (ppm)*	*Mass emission in kg per kg dry oil*
CO_2	-	2.88
H_2O	-	2.59
N_2	-	18.25
O_2	-	0.663
SO_2	-	0.010
HCl	-	7.00E-04
NO_x	-	4.14E-03
Dust	-	9.71E-03
Ba	<1	-
Ca	3211	3.21E-03
Mg	2.4	2.40E-06
B	<5	-
Zn	1.8	1.80E-06
P	42.4	4.24E-05
Fe	6.5	6.50E-06
Cr	<1	-
Al	2	2.00E-06
Cu	12.4	1.24E-05
Sn	1.4	1.40E-06
Pb	2.7	2.70E-06
Mo	61.4	6.14E-05
Si	2.3	2.30E-06
Na	0.7	7.00E-07
Ni	<1	-

Note: All constituents below center separating line are from Chetzemoka data, whereas emissions above the line are for generic lubricating oil.

3.3.2 Disposable Filter Cartridges

The standard oil filtration system requires periodic replacement of disposable filter cartridges (Figure 3.2). These cartridges are housed within a filter canister.

Filter cartridge production was modeled using the mass of materials in each filter and the energy use to produce filters from two data sets on car and heavy duty oil filters (IAC 2006, IAC 2007). The filter cartridges used by WSF are from Electromotive Diesel (EMD; part number 8345482). They are 6.5 inches in diameter and 30 inches long. Clark Filter (2010) lists the media as being cotton with a 12 micrometer filtration size.

Figure 3.2 Standard filtration system components.

The materials make-up of the filter cartridges used in this vessel was determined by physically deconstructing and weighing various components, and then making informed assumptions about the material of each component. Deconstruction of the filter (Figure 3.3) revealed a structure consisting of a center support (a), filter media wrapped around that support (a), endcaps on both sides attached by means of a rubber-like glue to the filter media (b and c), a fitting on the top endcap for connection to the filter system (d), a small rubber o-ring within that fitting (d), and a cardboard surround holding together the filter media (e). Table 3.3 contains the detailed data for each piece including the name of the component, the mass and percentage of overall mass, and the material assumed for environmental assessment in the GaBi 6 database (or in the case of cotton paper, from PE Americas and Tryskele 2011).

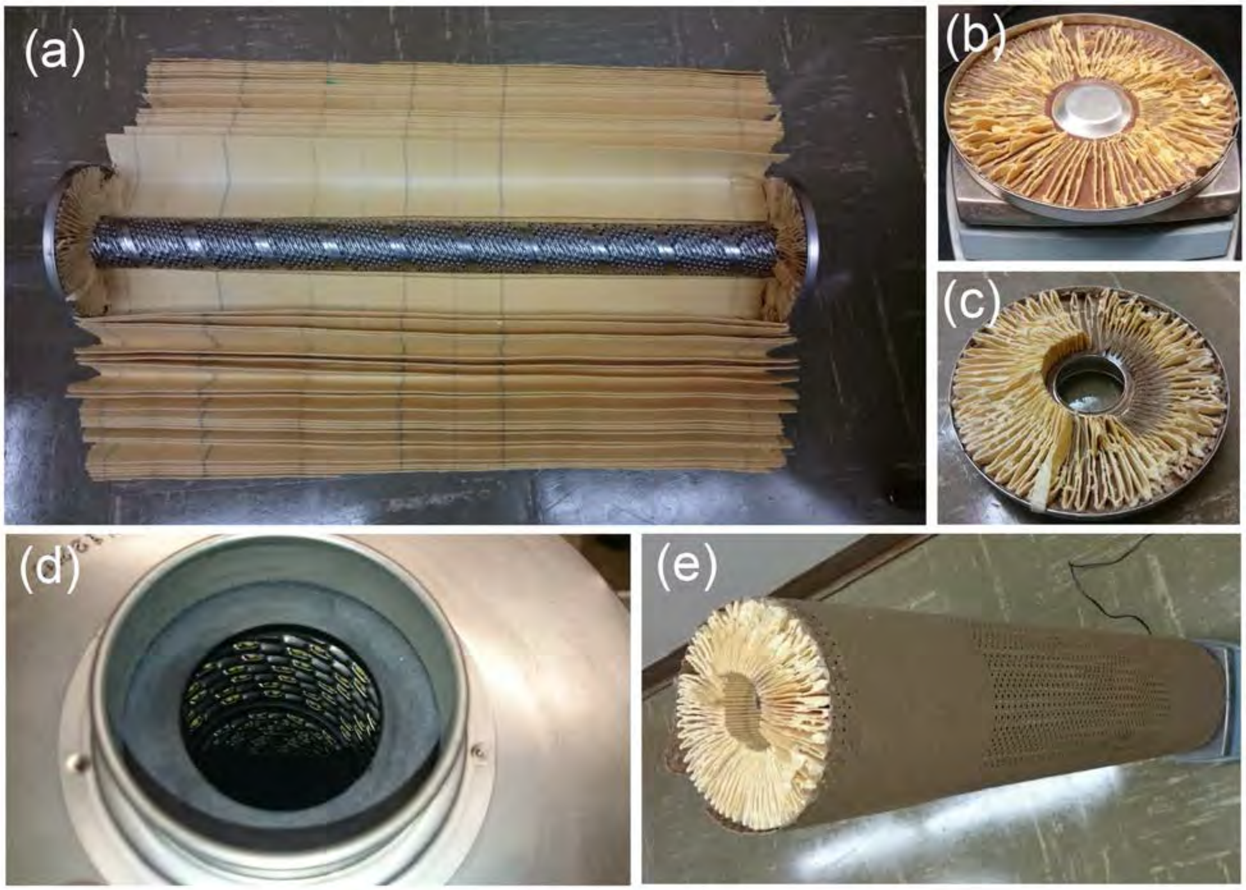

Figure 3.3 Disposable filter cartridge components. (a) Paper filter media and center support rod, (b) bottom cap, (c) top cap, (d) fitting and o-ring, and (e) cardboard surround around filter media.

Table 3.3 Material Composition of Paper Filter Cartridge and Material Assumptions for LCA

Component	*Mass (g)*	*Percent of total mass*	*Material used in analysis*
Center support	403.5	22.3%	Hot rolled sheet steel
Gasket	9.6	0.5%	Styrene-butadiene rubber
Filter media	1004.8	55.6%	Cotton paper (bank notes)
Surround	84.4	4.7%	Containerboard
Top fitting	18.0	1.0%	Hot rolled steel
Top cap	71.9	4.0%	Hot rolled steel
Bottom cap	79.9	4.4%	Hot rolled steel
Adhesive (top+bottom)	84.3	4.7%	Styrene-butadiene rubber
Paper stuck to glue	51.7	2.9%	Cotton paper (bank notes)

Note: material used in analysis may not be actual component material, but best estimate with available data

A mass balance was carried out to compare the component weights to the total filter weight (weighed before filter deconstruction). This revealed an error of 0.07%, suggesting that all components were accounted for and accurately recorded.

Variability between filters was also examined by comparing the total masses of four filters (Table 3.4). The percent difference between the smallest and largest filter was 0.67%. This difference was small, so it was assumed for the analysis that the component masses would be nearly the same between any filters. For the impacts of shipping filters, the mass of the packaging was included and the weight of a four filter box was measured as 8189 g.

Table 3.4 Mass of Filters and Packaging

Part	*Mass (g)*
Filter 1	1809.3
Filter 2	1814.8
Filter 3	1814.3
Filter 4	1821.5
Packaging	929.3
Total	8189.2 (18.1 lb)

All materials assumed for the filter components were included in the GaBi 6 database, with the exception of cotton paper. Therefore, other data sources were consulted to estimate the environmental impacts of the paper. Only one study could be found which specifically examined the production of cotton paper (PE Americas and Tryskele 2011).

However, other data sources for standard paper and cotton fabrics were examined as a check. Printing paper was analyzed by Dias et al. (2007), general paper (Paper Mill) through the EIO-LCA (Carnegie Mellon 2015), and cotton fabric in the GaBi 6 database (2015). Results of these studies are shown in Table 3.5 in terms of 40 kg of product.

Table 3.5 Impact Category Indicators for 40 kg of Paper-Like Product from Various Sources

Category	*Unit*	*Cotton paper (PE & T)*	*Paper* (EIO-LCA)*	*Printing paper (Dias)*	*Cotton fabric (GaBi)*
GWP	kg CO_2	9.98E+01	7.68E+01	5.01E+01	2.10E+02
AP	mol H^+	5.08E+01	3.19E+01	2.66E+01	7.16E+01
EP	kg N	4.81E-01	1.57E-02	5.97E-02	2.55E+00
ETP	CTU	1.40E-01	2.75E-01	Not reported	6.22E+01
HHCP	cases	1.73E-09**	1.54E-08	Not reported	3.85E-07
HHNCP	cases		2.59E-06	Not reported	-1.83E-04
HHCAP	kg PM_{10}	Not reported	1.90E-01	5.48E-01	2.25E-01
SCP	kg O_3	1.30E-02	8.04E+00	9.82E-02	2.64E+01
ODP	kg CFC-11	7.82E-05	6.60E-05	Not reported	4.20E-08

*Assuming a 2002 purchaser price of $1.50 per kg. **Only sum of HHCP and HHNCP reported. In subsequent analysis, this is partitioned equally between the two categories.

As can be seen in Table 3.5, there is significant variation between data sources for many of these impact categories. The cotton paper data was used because it appeared to be most similar to the product used in the oil filters. Results may have differed if another source of paper data were used.

Transportation impacts of filters were calculated based on the weight of four filters in their shipping box as weighed in the laboratory. This weight was 8189 g (18.05 lb). Transport was modeled as a Class 8b truck driving from McCook, IL to Seattle, WA. The distance of this trip was determined using Google Maps and a path that primarily consisted of I-90 W, which resulted in a trip distance of 2,080 miles. McCook, IL was chosen as the origin of the filters because the shipping package had a sticker bearing LaGrange, IL and upon further inspection, EMD has a large manufacturing facility in McCook which is directly adjacent to LaGrange, so it is likely that the filters are manufactured there.

Hot rolled steel was used for the center support and endcaps, with data coming from the NREL US LCI (2015). As with all of the data points in this database, this was a fully aggregated data point. Some of the inventory flows were negative, suggesting net benefits for those flows. Source documentation (Athena 2002) revealed that negative flows were mostly a result of process water cleaning, where the source water had higher concentrations of some compounds than the discharged process water due to highly effective treatment of that water before discharge.

The average energy use from the two data sources for oil filter production energy (IAC 2006, IAC 2007) was used for this study. While the types of filters produced for these data sets were not well defined, they are assumed to be sufficiently close to the filters used by WSF, because industrial filter manufacturers were unable to provide primary data.

The electricity use for producing one filter:

$$\frac{1}{2} * \left[\left(\frac{11{,}725{,}746\ kWh}{12{,}000{,}000\ filters}\right)^{*} + \left(\frac{20{,}060{,}581\ kWh}{30{,}000{,}000\ filters}\right)^{\dagger}\right] = 0.823\ kWh/filter \qquad [3\text{-}1]$$

Natural gas use for producing one filter:

$$\frac{1}{2} * \left[\left(\frac{33{,}989\ MMBtu}{12{,}000{,}000\ filters}\right)^{*} + \left(\frac{30{,}759\ MMBtu}{30{,}000{,}000\ filters}\right)^{\dagger}\right] = 0.002\ MMBtu/filter \qquad [3\text{-}2]$$

*IAC 2007, †IAC 2006

3.3.3 Self-Cleaning Filtration System

The self-cleaning filter was modeled for production and transport to the vessel. End-of-life was not included since it is assumed that the filter will remain with the vessel when it is retired. The overall weight of the Eliminator filter unit is roughly 300 kg (Alfa Laval 1997). The filter is made mainly from four metals including cast iron, aluminum, steel, and stainless steel. The housing is cast iron. The distributor, filter element supports, and other various pieces are aluminum. Most of the nuts, washers, screws, piping, and plates are steel. The full flow filter elements are stainless steel. There is no indication of individual masses of components, so a materials composition was crudely estimated based on the parts list. It was assumed that cast iron comprises 75% of the overall mass, steel comprises 10%, stainless steel comprises 10%, and aluminum comprises 5%, resulting in the materials composition listed in Table 3.6.

Table 3.6 Material Composition of Self-Cleaning Filter Housing

Listed material	*Assumed mass (kg)*	*Percent of total mass*	*Material used in analysis*
Cast iron	225	75%	Iron and steel, production mix
Steel	30	10%	Hot rolled sheet, steel, at plant
Stainless steel	30	10%	Hot rolled sheet, steel, at plant
Aluminum	15	5%	Aluminum, secondary, rolled

Data for extraction and processing of these materials was based on the GaBi 6 database. Processing was assumed to be only casting for all parts, though some of these parts would undergo additional or other processing. US data was used for the materials, however, differences in electricity grid mixes and other factors between the US and France (location of filter manufacture) would affect impacts of materials production. In order to scale the impacts of production to an annual indicator, the actual functional output of that filter must be considered, including the lifetime. Therefore, the lifetime was considered equal to that of the expected remaining life of the vessel, 50 years.

In addition to the self-cleaning filter housing, there was also an external centrifuge. This centrifuge weighed only 9.4 kg (Alfa Laval 2000). Due to its small size, production of the centrifuge was assumed to cause a negligible impact and was not included in the analysis. Additionally, small paper liners were used to collect the contaminants removed in the centrifuge. Those were only changed about twice yearly and were landfilled, so the liners were also omitted from the analysis.

3.3.4 Marine Diesel Fuel

Oil must be continuously circulated to provide cooling and ongoing filtration. Therefore, there is pumping power used to move the oil, which is dependent on the flow rate and the pressure of the oil in the filtration circuit. The self-cleaning filtration system requires a higher pressure than the standard system and therefore is expected to consume additional diesel fuel.

Environmental impacts of additional fuel consumption were sourced from the US Extension Database in GaBi (2015) under the aggregated process for combustion of diesel fuel in an inland vessel. This process is based on data for the same process from the US LCI (NREL 2015), with augmentation made by thinkstep (formerly PE International) to include additional flows not quantified in the US LCI. These data were compared to a more limited data set of inventory emissions from Washington State Ferries vessels from a report by Starcrest Consulting Group (2013) to corroborate some of the inventory flows. The Starcrest (2013) report provides only NO_x, PM_{10}, DPM, SO_2, and CO_2 flows on the basis of total emissions from particular vessels over a particular time period. Gallons of fuel consumed by the same vessels over the same time period was available in a separate report by Starcrest (2015), allowing for the calculation of those inventory flows on the basis of per gallon of fuel consumed. Therefore, as a check, the inventory flows of NO_x, SO_2, PM_{10}, and CO_2 from GaBi (2015) were compared with those from Starcrest (2013) on a per gallon of fuel basis as shown in Table 3.7.

Table 3.7 Comparison of Environmental Inventory Flows for Marine Diesel Fuel Combustion

	NO_x (kg/gal)	SO_2 (kg/gal)	PM_{10} (kg/gal)	CO_2 (kg/gal)
Starcrest	1.56E-01	1.10E-04	9.05E-03	11.12
GaBi	1.51E-01	1.77E-04	4.85E-03	12.45
% Difference*	-3%	+61%	-46%	+12%

Note: Inventory flows in GaBi dataset were provided based on 1000 kg-km of transport and converted to per gallon of fuel using the input flow quantity of diesel from the original dataset in the US LCI ($9.59*10^{-3}$ L). GaBi data is aggregated dataset including production of the fuel, Starcrest is only tailpipe emissions. *% difference based on increase from Starcrest to GaBi.

The GaBi dataset was chosen over that provided by Starcrest (2013) because it provided additional inventory flows that greatly affected some impact categories, such as human health and ecotoxicity. It should be cautioned that the sulfur dioxide and particulate matter emissions may be particularly uncertain due to the differences between the datasets.

3.3.5 Transportation

Trucks were assumed to be the mode of transportation for oil and filters. The class of trucks were assumed to be the same as those assumed in the California used oil disposal study (Geyer et al. 2013), because the type of trucks used to transport oil are likely similar between California and Washington. Truck types for smaller deliveries were estimated separately. Transport distances were estimated with Google Maps and Google Earth, and distances used in the study are shown in Table 3.8.

Table 3.8 Transportation Processes – Details and Assumptions

Process	*Origin*	*Destination*	*Dist. (mi)*	*Vehicle Type*
Lubricating Oil				
Crude oil to refinery	Not quantified (included as representative average in base oil production process)			
Lube oil from refinery to seller	Chevron Way, Richmond, CA	13th Ave SW Seattle, WA	965	Ocean Freighter
Lube oil from seller to vessel	13th Ave SW 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 oil to re-refinery	Airport Way, Seattle, WA	Alexander Ave, Tacoma, WA	31	Class 8b Truck
Self-Cleaning Filter				
Filter from producer to origin port	Élancourt, France[a]	Le Havre Port, France	119	Class 8b Truck
Filter from origin port to destination port	Le Havre Port, France	Port of Seattle, Seattle, WA	10,000	Cargo Vessel
Filter from port to WSF	Port of Seattle, Seattle, WA	Point Defiance, Tacoma, WA	40	Class 6 Truck
Disposable Filter Cartridges				
Filter raw materials to producer	Not quantified (data unavailable)			
New filter from producer to WSF	W 55th St. McCook, IL	Point Defiance, Tacoma, WA	2,080	Class 8b Truck
Old filter from WSF to disposal	Point Defiance, Tacoma, WA	Airport Way, Seattle, WA	38	Class 6 Truck

[a]Manufacturing location of Eliminator filter based on communication with Murphy (2015).

Some of these trucking and shipping routes were more uncertain than others. Particularly uncertain was the route used to import the self-cleaning filter. As listed in Table 3.8, it was assumed that the filter ships on a vessel from France directly to Seattle through the Panama Canal, as shown in Figure 3.4. That route was based on major shipping routes identified by Rodrigue (2015). It is possible that the filter would be shipped to another port, such as one on the East Coast of the United States and trucked to Seattle instead.

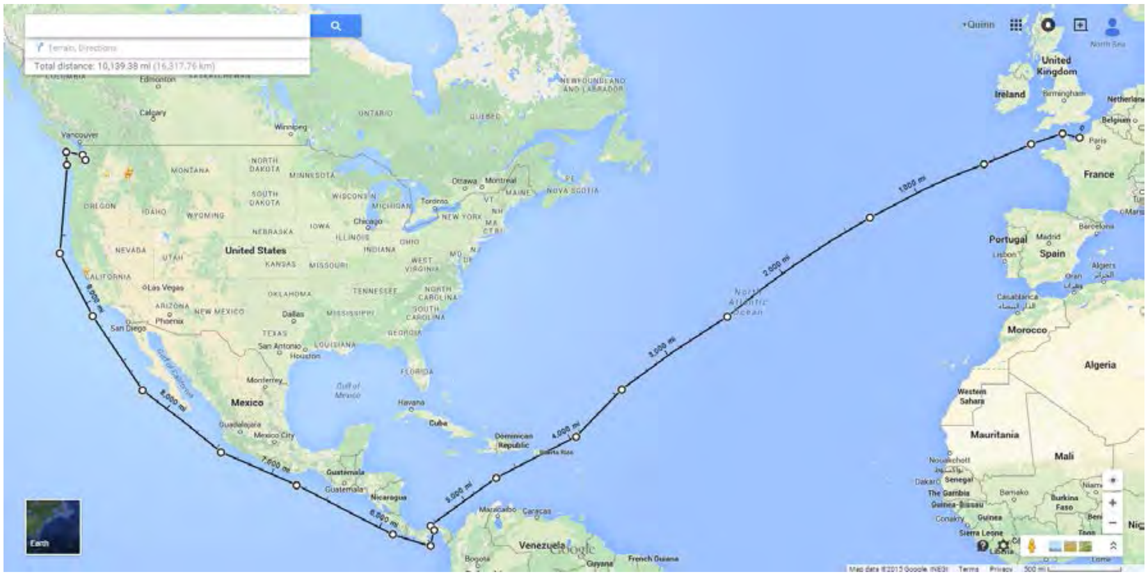

Figure 3.4 Assumed self-cleaning filter shipping route from France to United States.

3.4 Life Cycle Impact Assessment

The following sections present the impact category indicators for each system investigated on the basis of the declared units stated in Table 3.1. In some cases, the results are separated into sub-processes to reveal the contributions from each of those sub-processes, and to provide the data necessary for analyzing future systems with different sub-process use characteristics. All results in this section are in terms of TRACI 2.0 indicators.

3.4.1 Lubricating Oil Impact Category Indicators

Estimated impact category indicators for acquisition, use, and disposal of lubricating oil are presented in Table 3.9. These are presented separately to facilitate their potential use in future studies and to show the contributions from each life cycle stage. As can be seen, acquisition and use contribute impacts to all of the analyzed categories, while in most of the impact categories, disposal (by distillation to MDO) benefits the impact indicators. The latter effect is the result of offset fuel production (i.e., according to the analysis, there are generally lower environmental impacts to produce marine fuel from lube oil than from crude oil directly).

Table 3.9 Estimated Impact Indicators for 1 Gallon of Lube Oil Acquisition, Use, and Disposal

Category	*Unit*	*Acquisition*[a]	*Use*[b]	*Disposal*[c]
GWP	kg CO_2	5.31E+00	2.88E+00	-8.66E-01
AP	mol H^+	1.21E+00	6.74E-01	-2.66E-01
EP	kg N	6.32E-04	2.31E-04	-1.37E-04
ETP	CTU	1.56E+00	3.28E-01	0.00E+00
HHCP	cases	9.63E-09	7.27E-11	-2.50E-10
HHNCP	cases	4.41E-07	1.56E-07	-4.39E-08
HHCAP	kg PM_{10}	3.88E-03	1.78E-03	-1.05E-03
SCP	kg O_3	2.00E-01	1.03E-01	-8.14E-02
ODP	kg CFC-11	2.16E-10	0.00E+00	1.33E-09

[a]GaBi 2015, Raimondi et al. 2012; [b]Modeled from Audibert 2006; [c]Geyer et al. 2013, Boughton and Horvath 2004

3.4.2 Disposable Filter Cartridge Impact Category Indicators

Estimated impact category indicators for producing a single disposable filter cartridge for the standard system are shown in Table 3.10. No single component of the filter cartridges was responsible for the majority of impacts across most categories. Production energy was a relatively low contributor to all categories.

Table 3.10 Estimated Impact Category Indicators for Production of 1 Disposable Filter Cartridge

Category	*Unit*	*Rubber*[a]	*Steel*[a]	*Filter Media*[b]	*Cardboard*[a]	*Production Energy*[c]	***Total***
GWP	kg CO_2	3.53E-01	1.32E+00	2.64E+00	5.47E-02	5.86E-01	**4.95E+00**
AP	mol H^+	3.20E-02	2.42E-01	1.34E+00	2.66E-01	9.20E-02	**1.97E+00**
EP	kg N	4.03E-05	-4.86E-03	1.27E-02	3.14E-04	7.80E-05	**8.27E-03**
ETP	CTU	3.78E-02	-1.39E+00	3.71E-03	1.51E-01	2.02E-02	**-1.18E+00**
HHCP	cases	7.73E-10	1.89E-10	2.28E-11	4.30E-10	1.04E-10	**1.52E-09**
HHNCP	cases	9.36E-08	-3.40E-08	2.28E-11	1.85E-08	1.10E-08	**8.91E-08**
HHCAP	kg PM_{10}	8.88E-05	9.00E-04	5.03E-03*	2.07E-03	3.77E-04	**3.44E-03**
SCP	kg O_3	1.20E-02	4.13E-02	3.43E-04	7.17E-02	1.60E-02	**1.41E-01**
ODP	kg CFC-11	1.47E-11	2.80E-09	2.07E-06	6.32E-11	2.48E-10	**2.07E-06**

[a]GaBi 2015; [b]PE Americas and Tryskele 2011 [c]East cost grid mix GaBi 2015 *From EIO-LCA

3.4.3 Self-Cleaning Filtration System Impact Category Indicators

Estimated impact category indicators for the production of one self-cleaning filter housing (as described in section 3.3.3) are presented in Table 3.11. Results are first separated by metal type, and then combined into a total. Negative impact category indicators in this table are mostly the result of process water effluent being cleaned to lower nutrient and pollutant levels than the incoming water.

Table 3.11 Estimated Impact Category Indicators for Production of Self-Cleaning Filter Housing

Category	*Unit*	*Rolled aluminum*	*Hot-rolled steel*	*Iron and Steel, mix*	***Total***
GWP	kg CO_2	4.38E+01	1.38E+02	2.02E+02	**3.84E+02**
AP	mol H^+	3.06E+01	2.53E+01	2.85E+01	**8.44E+01**
EP	kg N	1.74E-02	-5.10E-01	-8.46E-01	**-1.34E+00**
ETP	CTU	-1.40E+01	-1.45E+02	-2.40E+02	**-3.99E+02**
HHCP	cases	-4.90E-09	1.98E-08	3.13E-08	**4.62E-08**
HHNCP	cases	7.48E-07	-3.53E-06	-5.97E-06	**-8.75E-06**
HHCAP	kg PM_{10}	8.37E-02	9.42E-02	1.09E-01	**2.87E-01**
SCP	kg O_3	9.30E+00	4.33E+00	5.68E+00	**1.93E+01**
ODP	kg CFC-11	5.44E-10	2.94E-07	3.84E-07	**6.79E-07**

Note: This analysis assumes that rolling is the only processing. Some parts may be cast and include other processing. Negative values are the result of effluent process water being cleaned to higher standards than the influent water for metal production processes (Athena 2002). Data from GaBi (2015).

3.4.4 Diesel Fuel Consumption Impact Category Indicators

Estimated impact category indicators for the combustion of one gallon of diesel fuel in a marine vessel are presented in Table 3.12. These values are directly from the GaBi (2015) process for inland vessel operation, scaled to represent impacts per gallon of fuel combusted.

Table 3.12 Estimated Diesel Fuel Impacts for 1 Gallon of Fuel Combusted in a Marine Vessel

Impact Category	*Unit*	*Diesel Fuel*
Global Warming	kg CO_2 eq	1.28E+01
Acidification	mol H^+ eq	7.00E+00
Eutrophication	kg N eq	7.28E-03
Ecotoxicity	CTUeco	6.96E+00
Human Health Cancer	cases	3.06E-09
Human Health Non-Cancer	cases	1.55E-07
Human Health Criteria Air	kg PM_{10} eq	1.43E-02
Smog Creation	kg O_3 eq	4.11E+00
Ozone Depletion	kg CFC-11 eq	4.95E-10

Note: Data from GaBi (2015)

3.4.5 Transportation Impact Category Indicators

This section contains the impact category indicators for the transportation of oil, disposable filters, and the self-cleaning filter housing. These indicators are specific to Washington State Ferries as they are dependent upon shipping distances and suppliers. Transportation of one gallon of oil is shown in Table 3.13, for one disposable filter cartridge in Table 3.14, and for one self-cleaning filtration system housing in Table 3.15.

Table 3.13 Estimated Lube Oil Transport Impacts for 1 Gallon of Oil

Impact Category	*Unit*	*Refinery to Seller*	*Seller to Vessel*	*Vessel to Pre-processing*	*Pre-processing to MDO Distillation*	***Total***
Global Warming	kg CO_2 eq	5.89E-02	3.14E-02	2.99E-02	1.58E-02	**1.36E-01**
Acidification	mol H^+ eq	6.83E-02	8.92E-03	8.49E-03	4.96E-03	**9.06E-02**
Eutrophication	kg N eq	6.59E-05	9.02E-06	8.59E-06	5.06E-06	**8.86E-05**
Ecotoxicity	CTUeco	3.14E-02	1.84E-02	1.75E-02	9.22E-03	**7.65E-02**
Human Health Cancer	cases	1.38E-11	1.30E-11	7.69E-12	4.06E-12	**3.85E-11**
Human Health Non-Cancer	cases	6.99E-10	4.13E-10	3.90E-10	2.06E-10	**1.71E-09**
Human Health Criteria Air	kg PM_{10} eq	1.38E-04	2.63E-05	2.50E-05	1.29E-05	**2.02E-04**
Smog Creation	kg O_3 eq	3.56E-02	4.20E-03	4.00E-03	2.42E-03	**4.62E-02**
Ozone Depletion	kg CFC-11 eq	2.22E-12	1.30E-12	1.24E-12	6.53E-13	**5.41E-12**

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

Table 3.14 Estimated Disposable Filter Cartridge Transport Impacts for 1 Filter

Impact Category	*Unit*	*New Filter: Producer to WSF*	*Used Filter: WSF to Disposal*	***Total***
Global Warming	kg CO_2 eq	5.48E-01	2.73E-02	**5.75E-01**
Acidification	mol H^+ eq	1.71E-01	8.48E-03	**1.80E-01**
Eutrophication	kg N eq	1.75E-04	8.65E-06	**1.84E-04**
Ecotoxicity	CTUeco	3.20E-01	1.59E-02	**3.35E-01**
Human Health Cancer	cases	1.41E-10	6.98E-12	**1.48E-10**
Human Health Non-Cancer	cases	1.72E-08	3.55E-10	**1.75E-08**
Human Health Criteria Air	kg PM_{10} eq	4.45E-04	2.22E-05	**4.68E-04**
Smog Creation	kg O_3 eq	8.30E-02	4.13E-03	**8.73E-02**
Ozone Depletion	kg CFC-11 eq	2.27E-11	1.12E-12	**2.38E-11**

Table 3.15 Estimated Self-Cleaning Filter Housing Transport Impacts

Impact Category	*Unit*	*Ocean Freighter*	*Truck*	***Total***
Global Warming	kg CO_2 eq	8.85E+01	1.17E+01	**1.00E+02**
Acidification	mol H^+ eq	1.03E+02	3.46E+00	**1.06E+02**
Eutrophication	kg N eq	9.90E-02	2.51E-03	**1.02E-01**
Ecotoxicity	CTUeco	4.71E+01	6.86E+00	**5.40E+01**
Human Health Cancer	cases	2.07E-08	3.01E-09	**2.37E-08**
Human Health Non-Cancer	cases	1.05E-06	1.53E-07	**1.21E-06**
Human Health Criteria Air	kg PM_{10} eq	2.07E-01	9.70E-03	**2.17E-01**
Smog Creation	kg O_3 eq	5.37E+01	1.65E+00	**5.53E+01**
Ozone Depletion	kg CFC-11 eq	3.34E-09	4.85E-10	**3.83E-09**

3.5 Aggregating the LCA Data into Approximate Impacts by Oil System

As stated previously, the LCA data developed in this report are not comparative in nature. However, to aid decision-makers in using the individual LCA results, each oil system's approximate environmental impacts are estimated here, based on the quantity of disposable filter cartridges, gallons of oil, gallons of parasitic diesel consumption, and housing production (self-cleaning system only) used by each system in a typical year on the Chetzemoka. Those quantities are determined in the following sections and are again used in the life cycle cost analysis.

3.5.1 Quantities of Component Uses

3.5.1.1 Quantity of Oil Use

There are multiple portions of the lubricating oil life cycle, including those falling under the larger labels of production, use, disposal, and transportation. The quantity of oil involved in each of these steps may not be the same. That is, the amount of oil acquired might be different than the amount that must be disposed of, as some of the oil may be lost through combustion or other processes. However, in the Chetzemoka, records reflect that little of the oil is combusted (about 14 gallons/month, on average) so it is assumed that the same quantity of oil must be acquired and disposed of, with none of the oil combusted. (Note that on some other vessels, a much larger quantity of oil might be combusted and therefore be an important consideration.) The rate of oil use for one engine on the Chetzemoka is determined by Equation 3-3.

$$\underbrace{\left(300\,\frac{gal}{change}\right)}_{\substack{Oil\ change\\ fluid\ volume}} * \underbrace{\left(OCI\ \ \left[\frac{hr}{change}\right]\right)^{-1}}_{\substack{Oil\ change\\ interval}} * \underbrace{\left(6{,}000\,\frac{hr}{yr}\right)}_{\substack{Annual\\ operating\\ hours}} = Oil\ Volume\ Rate\ [gal/yr] \qquad [3\text{-}3]$$

The oil change interval (OCI) is the only variable that might change with different oil filtration systems. The standard system oil change interval of 2,500 hours results in oil usage of approximately 720 gal/year for one engine. Under the assumption that the oil change interval is doubled, which is the suggested assumption for the self-cleaning filtration system, the use of oil is reduced to approximately 360 gal/year for one engine.

3.5.1.2 Quantity of Disposable Filter Cartridge Use

Only the standard filtration system uses disposable filter cartridges. One engine uses ten filter cartridges which are replaced every 1250 operating hours. The approximate annual filter cartridge need for one engine is 48, as calculated in Equation 3-4.

$$\underbrace{\left(10\,\frac{cartidges}{change}\right)}_{\substack{Canister\ filter\\ capacity}} \underbrace{\left(\frac{1\ change}{1250\ hr}\right)}_{\substack{Filter\ Change\\ Interval}} \underbrace{(6{,}000\ hr)}_{\substack{Func.\ unit\\ operating\\ hours}} = 48\ Filters \qquad [3\text{-}4]$$

3.5.1.3 Quantity of Parasitic Diesel Fuel Use

Both filtration systems require power to drive the oil scavenging pump, which circulates oil through the filters. That power is derived from the main engines of the vessel, and as such, affects the diesel fuel consumption of those engines.

Oil must be continuously circulated to provide cooling and ongoing filtration. Therefore, there is pumping power used to move the oil which is dependent on the flow rate and the pressure of the oil in the filtration circuit. The paper cartridge filter system results in a back pressure of roughly 15-22 psi in this circuit and the self-cleaning filter uses a pressure regulating valve to achieve a pressure of roughly 55 psi in the circuit. Both systems draw from, and deposit to, a sump at atmospheric pressure. Therefore, the pressure in the circuit is the differential pressure that must be supplied by the oil scavenging pump. A flow rate of 390 gallons per minute must be maintained in either system to provide proper cooling. Table 3.16 contains the general characteristics of each filtration system and those which are shared between the systems, which are relevant for calculating fuel requirements.

Table 3.16 Conditions of Both Oil Filtration Systems Relevant to Oil Pumping and Fuel Consumption for One Engine on the M/V Chetzemoka

Filtration system	Parameter	Value
Both standard and self-cleaning	Oil circulation rate	390 gpm[a]
	Brake specific fuel consumption	0.355 lb/hp-hr[b]
	2014 fuel price per gallon	$2.75[b]
	Engine hours (Jul 2014-Jun 2015)	5629 hours[c]
	Fuel use (Jul 2014-Jun 2015)	135,189 gallons[c]
	Pump efficiency	80% (0.8)[b]
Standard cartridge filter	Oil pressure	~15-22 psi[b]
Self-cleaning filter	Oil pressure	~55 psi[b,d]

[a]EMD 2009, [b]Email with WSF naval architect, [c]WSF 2015, [d]Alfa Laval 1997

Equation 3-5 describes the relationship between flow rate, oil pressure, and power output required for pumping oil for one engine. For this calculation, it was assumed that the paper cartridge filter system has 20 psi of back pressure. The power output required for the standard system is 3395 W and for the self-cleaning system is 9337 W, based on inserting system oil pressures for x in Equation 3-5 (x=20 for standard, x=55 for self-cleaning).

$$Power\ output = \left(\underbrace{390\frac{gal}{min}}_{flow\ rate}\right)\underbrace{\left(\frac{m^3}{264\ gal}\right)\left(\frac{1\ min}{60\ s}\right)}_{unit\ conversions}\underbrace{(x\ psi)}_{\substack{pressure\\ increase}}\underbrace{\left(6895\frac{\overbrace{kg * m^{-1}s^{-2}}^{Pascals}}{psi}\right)}_{unit\ conversion} \quad [3\text{-}5]$$

The oil scavenging pump is a gear pump and efficiency is estimated to be 80%. Using the pumping power output requirement from Equation 3-6 and the assumed efficiency of the pump, the power input needed for the oil scavenging pump was calculated by Equation 3-6. The result is 5.7 hp for the standard system and 15.7 hp for the self-cleaning system, based on inserting power outputs from Equation 3-5 into Equation 3-6 (3395 W for standard, 9337 W for self-cleaning).

$$Power\ supplied\ to\ pump = \frac{[Power\ output\ ]W}{\underbrace{0.8}_{\eta}}\ \underbrace{\left(\frac{1\ hp}{745.7\ W}\right)}_{unit\ conversion} \quad [3\text{-}6]$$

The brake specific fuel consumption of the engine was used to calculate the fuel needed to provide power to the oil scavenging pump, as shown in Equation 3-7. Based on inserting power supply requirements from Equation 3-6 into Equation 3-7, the standard system requires 1519 gallons of diesel/year, and the self-cleaning system 4183 gallons of diesel/year.

$$Fuel\ use = ([power\ supplied]\ hp)\underbrace{(5629\ hr/yr)}_{engine\ hr}\underbrace{\left(0.355\frac{lb}{hp-hr}\right)}_{\substack{brake\ specific\\ fuel\ consumption}}\underbrace{\left(\frac{1\ gal}{7.5\ lb}\right)}_{\substack{diesel\ fuel\\ density}} \qquad [3\text{-}7]$$

The estimates of fuel used by each system from Equation 3-7 are based on theoretical calculations because the additional fuel consumption expected by either system is small in comparison to the total fuel use of a vessel, so it would be difficult to directly measure with high certainty. Nevertheless, an analysis was carried out in an attempt to validate the theoretically calculated fuel consumption difference between the two systems. A two tailed t-test with pooled standard deviation was performed between monthly fuel use per engine hour for the time periods March 2013-December 2013 (standard) and March 2014-June 2015 (self-cleaning). As expected, the result was non-significant (p=0.65) so results are not discussed further. The diesel fuel consumption figures calculated in Equation 3-7 are included in inventories for the self-cleaning oil filtration system for the environmental and cost comparisons.

3.5.1.4 Quantity of Self-Cleaning Housing Use

It was assumed that the self-cleaning filtration system would last approximately for the remaining life of the vessel. Therefore, the annual "use" of the housing was assumed to be one fiftieth (1/50) of the total impacts to produce the housing.

3.5.2 Compilation of LCA Data for Environmental Analysis of Standard and Self-Cleaning Systems

This section should not be considered a comparative life cycle assessment. It is an environmental data comparison, based on underlying LCA data and the approximate annual quantities of use determined in the previous section.

3.5.2.1 Impact Category Indicators

Impact category indicators are presented for the standard system in Table 3.17 and for the self-cleaning system in Table 3.18 and Table 3.19 (doubled oil life and no oil life extension, respectively).

Table 3.17 Environmental Data Compilation for Standard Filtration System (Annual)

Category	*Unit*	*Lube oil*	*Diesel fuel*	*Transport*	*Filters**	*Housing*	***Total***
GWP	kg CO_2	3.20E+03	1.95E+04	1.26E+02	2.38E+02	0.00E+00	**2.31E+04**
AP	mol H^+	6.82E+02	1.06E+04	7.39E+01	9.46E+01	0.00E+00	**1.15E+04**
EP	kg N	3.57E-01	1.11E+01	7.26E-02	3.97E-01	0.00E+00	**1.19E+01**
ETP	CTU	1.12E+03	1.06E+04	7.12E+01	-5.66E+01	0.00E+00	**1.17E+04**
HHCP	cases	6.76E-06	4.65E-06	3.48E-08	7.30E-08	0.00E+00	**1.15E-05**
HHNCP	cases	2.98E-04	2.36E-04	2.07E-06	4.28E-06	0.00E+00	**5.40E-04**
HHCAP	kg PM_{10}	2.04E+00	2.17E+01	1.68E-01	1.65E-01	0.00E+00	**2.41E+01**
SCP	kg O_3	8.55E+01	6.24E+03	3.75E+01	6.77E+00	0.00E+00	**6.37E+03**
ODP	kg CFC-11	1.11E-06	7.53E-07	5.03E-09	9.94E-05	0.00E+00	**1.01E-04**

*Disposable filter cartridges. Does not include disposal of the filters.

Table 3.18 Environmental Data Compilation for Self-Cleaning Filtration System Based on Doubled Oil Life (Annual)

Category	*Unit*	*Lube oil*	*Diesel fuel*	*Transport*	*Filters*	*Housing**	***Total***
GWP	kg CO_2	1.60E+03	5.37E+04	1.49E+02	0.00E+00	2.00E+00	**5.55E+04**
AP	mol H^+	3.41E+02	2.93E+04	1.39E+02	0.00E+00	2.12E+00	**2.98E+04**
EP	kg N	1.78E-01	3.05E+01	1.34E-01	0.00E+00	2.04E-03	**3.08E+01**
ETP	CTU	5.62E+02	2.91E+04	8.15E+01	0.00E+00	1.08E+00	**2.97E+04**
HHCP	cases	3.38E-06	1.28E-05	3.76E-08	0.00E+00	4.74E-10	**1.62E-05**
HHNCP	cases	1.49E-04	6.50E-04	1.82E-06	0.00E+00	2.42E-08	**8.01E-04**
HHCAP	kg PM_{10}	1.02E+00	5.98E+01	2.90E-01	0.00E+00	4.34E-03	**6.11E+01**
SCP	kg O_3	4.28E+01	1.72E+04	7.19E+01	0.00E+00	1.11E+00	**1.73E+04**
ODP	kg CFC-11	5.56E-07	2.07E-06	5.78E-09	0.00E+00	7.66E-11	**2.63E-06**

*Total impact to produce the housing dividing by 50-year expected lifetime

Table 3.19 Environmental Data Compilation for Self-Cleaning Filtration System Based on No Oil Life Extension (Annual)

Category	*Unit*	*Lube oil*	*Diesel fuel*	*Transport*	*Filters*	*Housing**	***Total***
GWP	kg CO_2	3.20E+03	5.37E+04	1.98E+02	0.00E+00	2.00E+00	**5.71E+04**
AP	mol H^+	6.82E+02	2.93E+04	1.71E+02	0.00E+00	2.12E+00	**3.02E+04**
EP	kg N	3.57E-01	3.05E+01	1.66E-01	0.00E+00	2.04E-03	**3.10E+01**
ETP	CTU	1.12E+03	2.91E+04	1.09E+02	0.00E+00	1.08E+00	**3.03E+04**
HHCP	cases	6.76E-06	1.28E-05	5.14E-08	0.00E+00	4.74E-10	**1.96E-05**
HHNCP	cases	2.98E-04	6.50E-04	2.44E-06	0.00E+00	2.42E-08	**9.50E-04**
HHCAP	kg PM_{10}	2.04E+00	5.98E+01	3.62E-01	0.00E+00	4.34E-03	**6.22E+01**
SCP	kg O_3	8.55E+01	1.72E+04	8.86E+01	0.00E+00	1.11E+00	**1.74E+04**
ODP	kg CFC-11	1.11E-06	2.07E-06	7.72E-09	0.00E+00	7.66E-11	**3.19E-06**

*Total impact to produce the housing dividing by 50-year expected lifetime

Figure 3.5 and Figure 3.6 show the portion contributions of each system (i.e., lube oil, diesel fuel, filter cartridges, housing, and transportation) to each impact category indicator for the standard and self-cleaning filtration (EF=2) systems, respectively. For the standard system, diesel fuel contributes the majority of impacts in six of the nine categories. Lubricating oil contributes the majority of impacts to human health cancer and non-cancer potentials. While the disposable filters contribute almost all of the identified ozone depletion potential, as will be demonstrated later in this report, the total ozone depletion potential of the analyzed oil systems are extremely small in comparison to many of the other impact categories. For the self-cleaning system diesel fuel contributed the majority of impacts in every impact category.

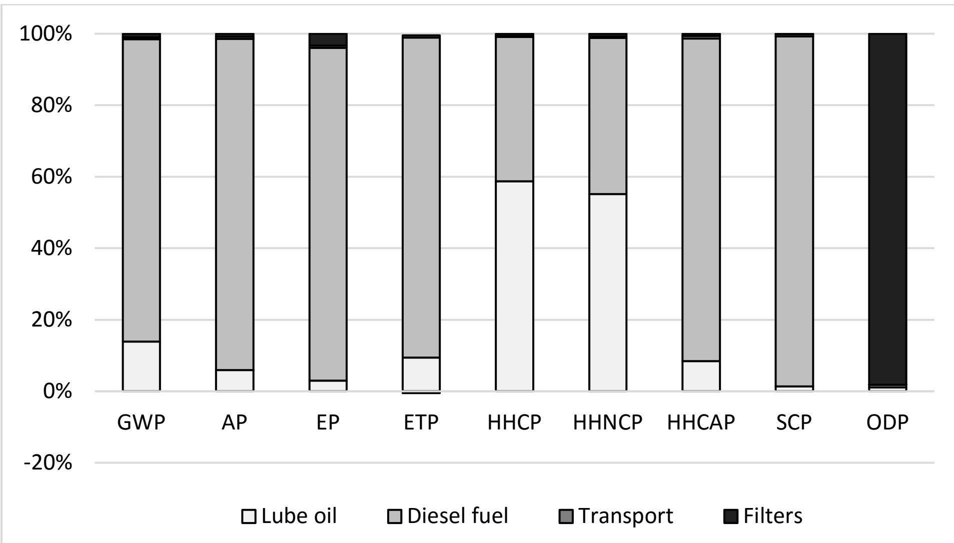

Figure 3.5 Environmental impact category contributions by source for standard filtration system.

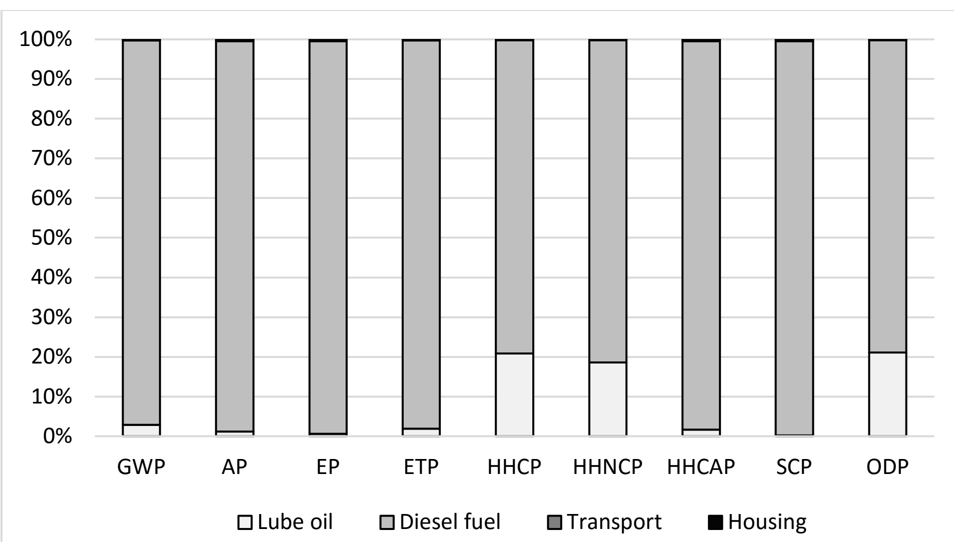

Figure 3.6 Environmental impact category contributions by source for self-cleaning filtration system (EF=2).

3.5.2.2 Normalized Results

Normalization is the process of converting the environmental impact results into a relative magnitude compared to a reference value. This results in a unitless characterization of impacts in each impact category. Normalization can be internal or external. Internal normalization uses values from within the current study to normalize results, such as comparing the impacts between two alternative product systems for a comparative LCA. External normalization uses a reference value derived from outside of the study, commonly the total or per capita contribution for each impact category on a global, regional, or local level, to demonstrate the share of impacts contributed by the studied systems (Norris 2001).

Normalization is optional according to ISO (ISO 2006b), but is useful to communicate the relative significance of contributions to each impact category, to compare systems more directly, and to aid in identifying errors (ISO 2006b, Heijungs and Guinée 2012, Matthews et al. 2015). However, it should also be noted that normalization usually makes results appear insignificant, can be affected by study parameters such as boundary definitions and characterization models, and databases used to generate external characterization normalization references often contain significant data gaps (Heijungs et al. 2007, Matthews et al. 2015, Kim et al. 2013).

Accomplishing external normalization is easiest and most useful when the normalization references come from a published set of reference data. Generally, practitioners use either global or national normalization references. Bare et al. (2006) and Ryberg et al. (2014) have developed national US characterization factors using the TRACI methodology (versions 1 and 2.1, respectively). With the absence of a normalization reference database developed for TRACI 2.0, Ryberg et al. (2014) was used as the primary source of normalization references (NRs) because it represents the most current underlying data. These reference values (slightly adjusted to account for some changes between TRACI 2.0 and 2.1) are listed in Table 3.20 and are the normalization references for annual United States impacts.

Table 3.20 US Normalization References for TRACI Impact Categories (Ryberg et al. 2014)

Impact Category	*TRACI 2.0 Unit*	*TRACI 2.0 NR*
AP	mol H^+-eq	1.5×10^{12}
ETP	CTUeco	3.5×10^{12}
EP	kg N-eq	6.6×10^{9}
GWP	kg CO_2-eq	7.4×10^{12}
HHCP	Cases	1.5×10^{4}
HHNCP	Cases	2.4×10^{5}
HHCAP	kg PM_{10}	2.2×10^{10}
ODP	kg CFC-11-eq	4.6×10^{7}
SCP	kg O_3-eq	4.2×10^{11}

Note: Values are annual (i.e. per 1 year).

Normalization using a normalization reference database is accomplished through Equation 3-8.

$$N_i = S_i/R_i \qquad [3\text{-}8]$$

where

N_i = normalized characterization of impact category i
S_i = calculated impact of the product system under study of impact category i
R_i = normalization reference value of the impact category i (values in Table 3.20)

Externally normalized results compared to US daily per capita impacts are presented for the standard system in Figure 3.7 and for the self-cleaning system (doubled oil life) in Figure 19.

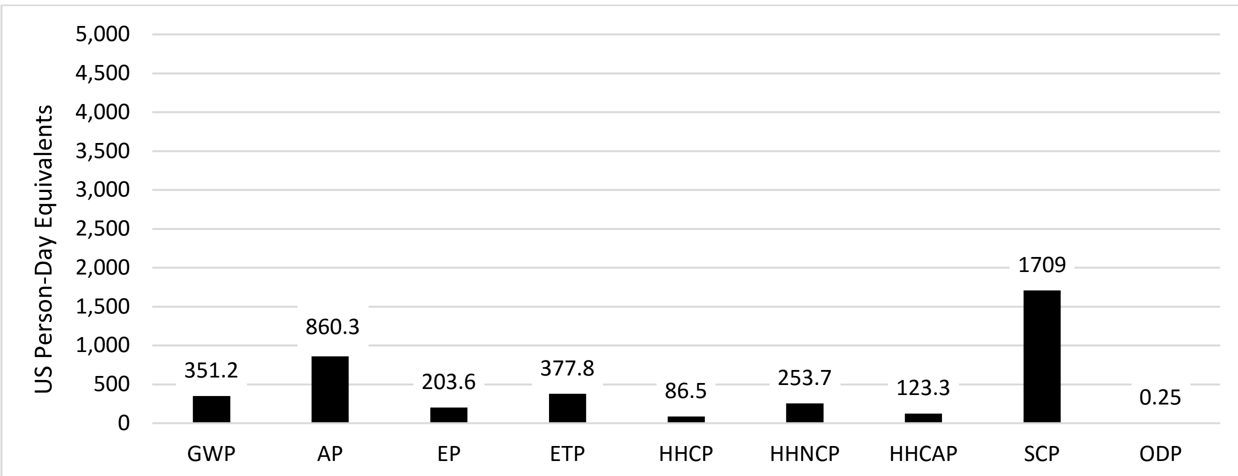

Figure 3.7 Environmental analysis of standard system normalized to US daily per capita.

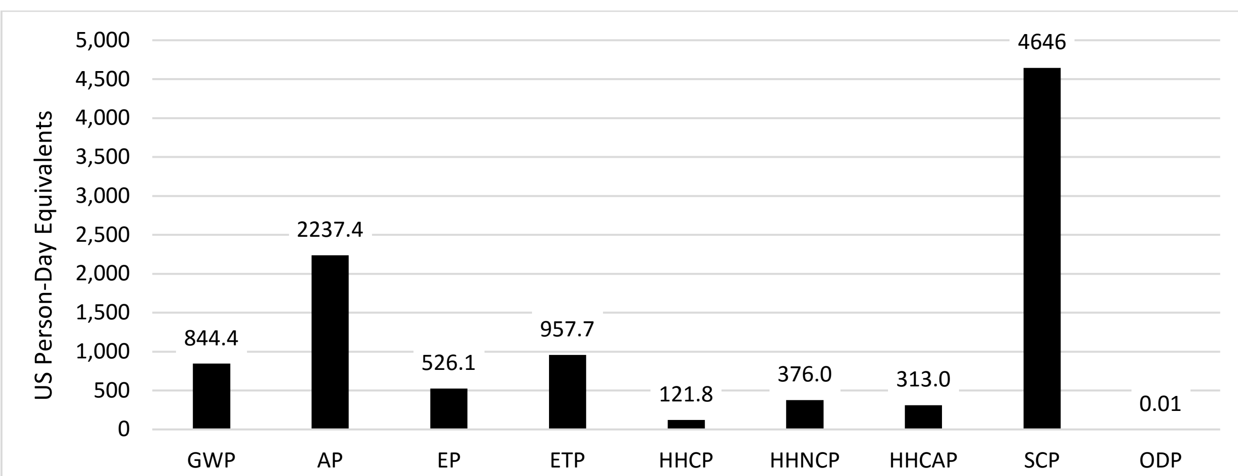

Figure 3.8 Environmental analysis of self-cleaning system normalized to US daily per capita.

3.6 Discussion and Conclusions

Based on the aggregated environmental results, it appears that the diesel fuel consumption to operate the oil scavenging pump is the largest overall environmental forcer in either system. That is more apparent in the self-cleaning system, which uses more diesel fuel, and depending on the scenario parameters may be considered to use less oil and filter cartridges. The oil does contribute significantly in human health impacts, and disposable filters dominate ozone depletion.

Under the United States daily per capita normalization, it is apparent that the highest contributions are to smog creation potential and acidification potential. That is due to those impacts being particularly common in fuel consumption and the overwhelming impact of the diesel fuel consumption process. Ozone depletion is nearly imperceptible under the normalized results, since petroleum product production and use generally has low effects on ozone depletion. However, these results are not to say that smog creation and acidification are necessarily the most relevant decision points, since different regions and decision-makers have different environmental issue priorities.

It is important to keep in mind that the impacts identified herein are potentials. The LCA methodology, which was used as the guiding basis of the analysis, has poor resolution in space and time (Reap et al. 2008), uncertain effects in the impact chain (Bare et al. 2002), and is only as accurate as the underlying data. As is standard in LCA, the analysis did not consider unexpected events, such as direct oil spills when handling filters or oil over the water. Additionally, not every possible type of environmental impact was analyzed.

4. LIFE CYCLE COST ANALYSIS

4.1 Objectives

The economic goal of this study was to determine if installation of a self-cleaning oil filtration system on the second engine in the pilot vessel would result in cost savings, taking into consideration applicable costs from the entire life cycle. This was accomplished by comparing the life cycle cost, through a life cycle cost analysis, of the standard filtration system to that of the self-cleaning filtration system. Results from this analysis are presented for decision support with respect to a possible second installation. A detailed literature review of LCCAs on oil and other filtration systems was included in the Part 1 Report (Langfitt and Haselbach 2014).

4.2 System Definition and Scoping

Before starting a life cycle cost analysis, a clear definition of the system and its boundaries needs to be formulated. This makes later decisions about which costs to be included during the analysis more straightforward. In this study, the oil filtration system included all components that directly interact with the lubricating oil with the exception of the engine (combustion chamber/pistons). All maintenance and repairs regarding these physical components would ideally be included such as labor for cleaning, repairs, and for changing oil and filters (including transportation, handling, ordering, and warehousing) as well as any material needs for maintenance. While this is the definition of the system under consideration, some of these costs are sunk, the same between options, or insignificant/too difficult to collect, and were left out of the analysis. The exact processes and components for which costs were determined are shown in Figure 4.1.

The analysis only considered direct economic costs incurred by WSF. Therefore, no indirect costs, such as opportunity cost of rider queuing time, were included. Sunk costs (i.e., those already incurred) were not included. Similarly, costs which would be incurred no matter which system is chosen, such as the cost of the oil analysis program, were not included because the LCCA is comparative. Figure 4.1 makes explicit which processes were included and which were not. Those within the system boundary (dashed line) were included, and those outside of it were not.

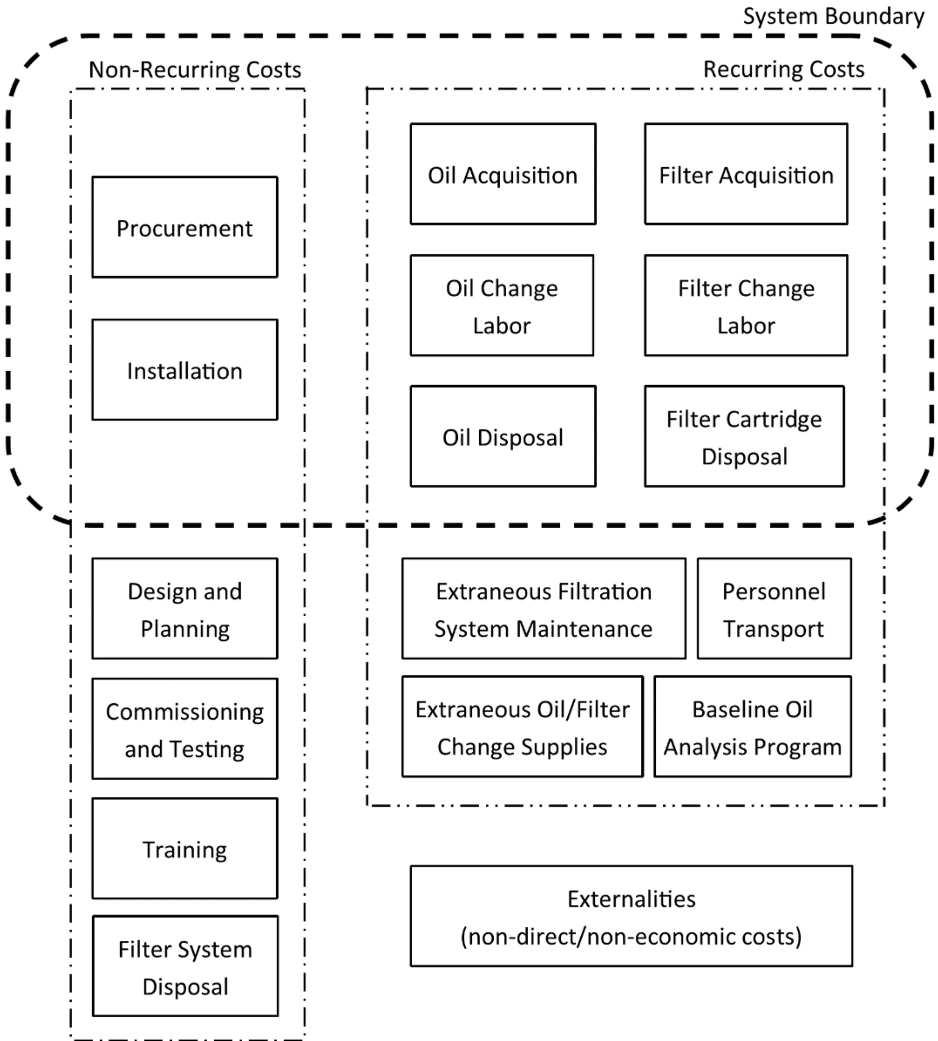

Figure 4.1 Ferry filter life cycle cost analysis system diagram.

4.3 Time

The time period of analysis of an LCCA affects the overall costs of each analyzed system. It may also affect the comparative costs of systems because initial and final costs are only accounted for once, but operational costs change with the length of the study period. In this case, both filtration systems are expected to last the life of the vessel. Therefore, an analysis period set to be approximately equal to that of the remaining life of the ferry was chosen. Most ferries in the WSF fleet are designed to last 60 years (WSDOT 2012), and the Chetzemoka has been in service for about five years. For simplicity, the analysis considers a 50-year time frame. That time frame begins in 2014 as that was the year of installation of the self-cleaning filter, and therefore, initial costs are in 2014 dollars. Results of the entire LCCA were calculated to be in terms of 2014 US dollars.

4.4 LCCA Methodology

4.4.1 Model

Cost models are equations which allow the classification of costs into pre-determined categories. This allows the modeler to better organize data collection and analysis procedures, and to have a way of differentiating relative costs of different associations. The following model, as discussed by Dhillon (2010), was used in this the study,

$$LCC = RC + NRC \quad [4\text{-}1]$$

Where:
LCC=Life cycle cost
RC=Recurring costs
NRC=Non-recurring costs

The model in Equation 4-1 is general in nature. Specific to the filtration system comparison is a further breakdown of the recurring and non-recurring costs by specific cost parameters. Non-recurring costs to be included in the model are outlined in Equation 4-2. Only the self-cleaning filtration system incurs any non-recurring costs because the standard filtration system is already in place on the engine.

$$NRC=C_p+C_i \quad [4\text{-}2]$$

where:

- C_p=Procurement costs
- C_i=Installation costs

The recurring costs specific to the oil filtration system analysis are calculated as in Equation 4-3. These recurring costs are compounded annually and the uniform present value factor (UPVF) accounts for the time value of money.

$$RC= (C_o+C_f+C_{oc}+C_{fc}+ C_{od}+C_{fd}+C_{df})*(UPVF) \quad [4\text{-}3]$$

- 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_{od}=Cost of oil disposal
- C_{fd}=Cost of filter or liner disposal
- C_{df}=Cost of diesel fuel use
- UPVF=Uniform present value factor

The exact inclusive costs and/or formulas to calculate these costs are detailed in the Appendix. The uniform present value factor is used to adjust annually recurring costs for the time value of money, so that results are in terms of the value of the dollar in the first year the of analysis. The time value of money refers to the concept that a sum of money paid in the future does not have the same value as that sum of money paid in present time. The inflation rate (i) and discount rate (d) dictate that relationship and can be algebraically combined into one term (Addison 1999, Eisenberger et al. 1977) called the real discount rate (D), as in Equation 4-4. Finally, the real discount rate may be used along with the number of years of annually recurring cost to determine the uniform present value factor, as in Equation 4-5.

$$D = \frac{1+d}{1+i} - 1 \qquad [4\text{-}4]$$

$$UPVF = \frac{(1+D)^n - 1}{D(1+D)^n} \qquad [4\text{-}5]$$

where
UPVF=Uniform present value factor,
D=Real discount rate, and
n=years between present value year and cost incurred year.

4.4.2 Price Escalation

Some costs may change over time due to reasons other than inflation. For instance, real crude oil prices may increase or decrease in the future, causing lube oil prices to increase or decrease as well. However, the rates of change (increase or decrease) are very difficult to predict as the market is highly volatile. To avoid the additional error that might be built into assuming price escalations of products or services, it has been assumed that nominal prices of all considered costs will only increase due to inflation and that fuel and lubricating oil prices are those of the base year average (2014).

4.4.3 Uncertainty and Risk

Uncertainty refers to information which is not known and for which probably distributions cannot be applied. This may be the due to information regarding future events or for which the analyst simply does not have access to the information. Risk refers to outcomes which could occur and for which there is a probability associated with those events occurring (Fuguitt and Wilcox 1999). In this study, uncertainty related to the length of possible oil life extension is considered through sensitivity analysis. Risks, such as those associated with spilling oil or damaging an engine are not included because the probabilities of such events are unknown. However, note that no instances of oil spills related to these processes have been reported to the authors and as such, based on this and WSF procedures, such risks are considered to be low.

4.4.4 Sensitivity Analysis

Sensitivity analysis is a method for investigating how much uncertainty could be affecting analysis results. Sensitivity analysis gauges how much a change in a particular input variable affects the outputs in cost assessments. It is done by varying each input variable of interest independently (i.e. one at a time) and analyzing how that change affects output values (Fuguitt and Wilcox 1999). Merrifeld (1997) points out that sensitivity analysis “can make a Benefit-Cost Analysis (BCA) much more informative, can discourage abuse, and can make inadvertent bias more transparent.” The same applies to an LCCA.

The most uncertain parameter is this study that is likely to have a large effect is the oil change interval that could be implemented with the self-cleaning filtration system. More data would need to collected to effectively estimate that. Therefore, the results of this LCCA are presented in terms of various oil change interval extension factors to support decisions when likely oil change intervals are known. The oil change interval extension factor (EF) is defined as the multiplicative extension of the oil change interval over the standard system’s interval of twice per year.

4.5 Data

4.5.1 Data Collection and Quality

Cost data was obtained from a number of sources including the WSDOT project Technical Advisory Committee, official billing for WSF, informal discussions with workers at WSF, and the contract between WSF and Emerald Services for oil and filter disposal. Discount and inflation rates were estimated by adopting those used in similar WSF research (Glosten Associates 2008). Labor rates were estimated from the project proposal, written by those familiar with these pay rates at WSF. Oil and filter change frequency for the standard filtration system was estimated to follow the engine manufacturer recommendations, an assumption which was confirmed by WSF workers. The resulting volumes of oil and numbers of filters used were previously presented during the life cycle data collection summary. Estimations of labor time needed to complete oil and filter changes, as well as to order, warehouse, and any other tasks associated with oil and filters, were obtained from informal discussions with workers at WSF. The Emerald Services contract details the exact costs that are billed to WSF for each task associated with oil and filter changes.

The source and estimated quality of each data point collected is addressed by Table 4.1. Estimated quality can be low, medium, or high, and is classified according to the judgment of the cost assessment analyst (researchers carrying out this study), so there is a level of subjectivity to the quality assignment. Much of the data is considered medium to high quality because it was obtained directly from sources at WSF familiar with pricing and from explicit contracts.

Table 4.1 Data Sources and Estimated Quality for LCCA

Data Piece	*Source*	*Quality*
Inflation rate	Estimated from Glosten Associates (2008)	Low
Discount rate	Estimated from Glosten Associates (2008)	Low
Oil price	Discussion with WSF employees	Medium*
Laborer rate	Preliminary project proposal documentation	Low
Oil change time	Discussion with WSF employees	Medium
Oil transferred in oil change	Discussion with WSF employees	High
Oil pumping charge rate	Emerald Services contract (#01110)	High
Oil pickup callout charge	Emerald Services contract (#01110)	High
Oil per gallon disposal cost	Emerald Services contract (#01110)	High
Oil change interval (standard)	Engine manufacturer specification	High
Oil change interval (self-cleaning)	No set interval (left as variable in analyses)	N/A
Filter cartridge price	Preliminary project proposal documentation	Medium
Filter cartridge change interval	Engine manufacturer specification	High
Filter cartridge change time	Discussion with WSF employees	Medium
Oil lost during filter change	Discussion with WSF employees	Low
Self-cleaning filter acquisition	WSF accounting records	High
Self-cleaning filter installation	WSF accounting records	High
Diesel fuel price	Discussion with WSF employees	Medium*
Parasitic diesel consumption (self-cleaning additional use)	Calculations based on operating manual specs and discussion with WSF employees	Medium

*Quality assessed with respect to accuracy of oil/fuel price in 2014. Price escalations were not included in the assessment and the future price of oil/fuel is very difficult to estimate.

4.5.2 Major Assumptions

The following is a listing of many of the major assumptions made to carry out this LCCA.

- 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 $8 per gallon (2014)
- Diesel fuel costs $2.75 per gallon (2014)
- Diesel fuel is used at the rate calculated in previous sections
- 2.4 oil changes and 4.8 filter changes occur per year for the standard system (as outlined in LCA section)
- Periodic maintenance costs are the same for both filtration systems
- No unexpected costs during installation of the self-cleaning filter
- Costs of drum pickup, including storage drums, removal, and transport are negligible
- Liner (for self-cleaning system's centrifuge) disposal costs are negligible
- 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
- Costs identified in the project proposal, current Emerald Services oil and filter disposal contract, and verbal communication with WSF are sufficiently accurate (see data quality section)

4.6 Results

Cost assessment results rely upon the oil change interval selected. Therefore, the results are in the form of a sensitivity analysis. A breakdown of every cost in the detailed cost model for the 50-year life of each filtration system and oil extension factors (EFs) of 1, 2 and 3 are presented in Table 4.2.

Table 4.2 Results of LCCA by Individual Cost Parameters

	Non-Recurring		*Recurring (in total cost over the life cycle)*							*Total (50-yr)*
	C_p	C_i	C_o	C_f	C_{oc}	C_{fc}	C_{od}	C_{fd}	C_{df}	
Standard Filtration	Sunk	Sunk	227,303	33,376	6630	96,604	51,096	20,520	164,843	**600,000**
Self-Clean (EF=1)	19,560	28,000	227,303	789	6630	2762	51,096	Neg.	453,945	**790,000**
Self-Clean (EF=2)	19,560	28,000	113,651	789	3315	2762	25548	Neg.	453,945	**648,000**
Self-Clean (EF=3)	19,560	28,000	75,768	789	2210	2762	17,032	Neg.	453,945	**600,000**

Note: All costs in 2014 dollars.

The 50-year total cost trend with a larger range of extension factors is shown by the dashed line in Figure 4.2. Compared to the standard system (solid line), the cost of the self-cleaning system is much higher for short EFs, equilibrates at EF=3, and becomes lower for EF>3. The cost savings of the standard system at low EFs are much higher than the cost savings of the self-cleaning system at long EFs, suggesting there is less potential for significant cost savings from the self-cleaning system than from the standard system.

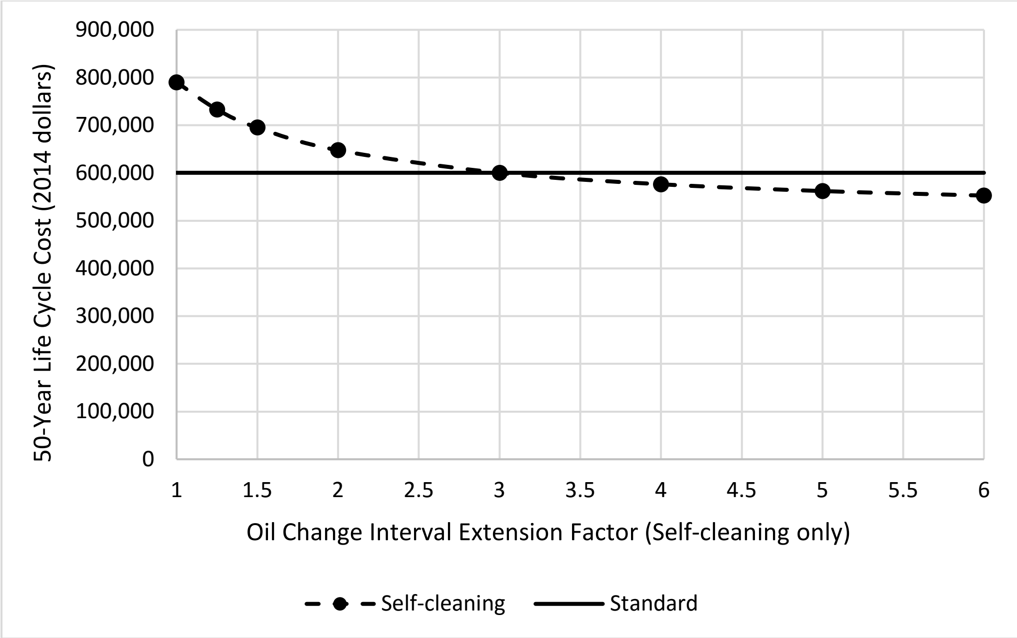

Figure 4.2 50-year life cycle cost of self-cleaning oil filtration system at various oil change intervals and reference to standard system with interval extension factor of 1.

Figure 4.3 shows the component-wise breakdown of 50-year costs for the standard filtration system and for the self-cleaning filtration system at various EFs. As can be seen, oil and oil change costs (including materials and labor) are the largest contributor to the total cost of the standard system, with substantial contributions also coming from filter changes and fuel use. With the self-cleaning filtration system fuel use is the most dominant factor in cost with oil and oil change costs being more important (but still secondary) at lower EFs. The initial cost of purchasing and installing the self-cleaning filtration system is relatively small in comparison to the operational costs.

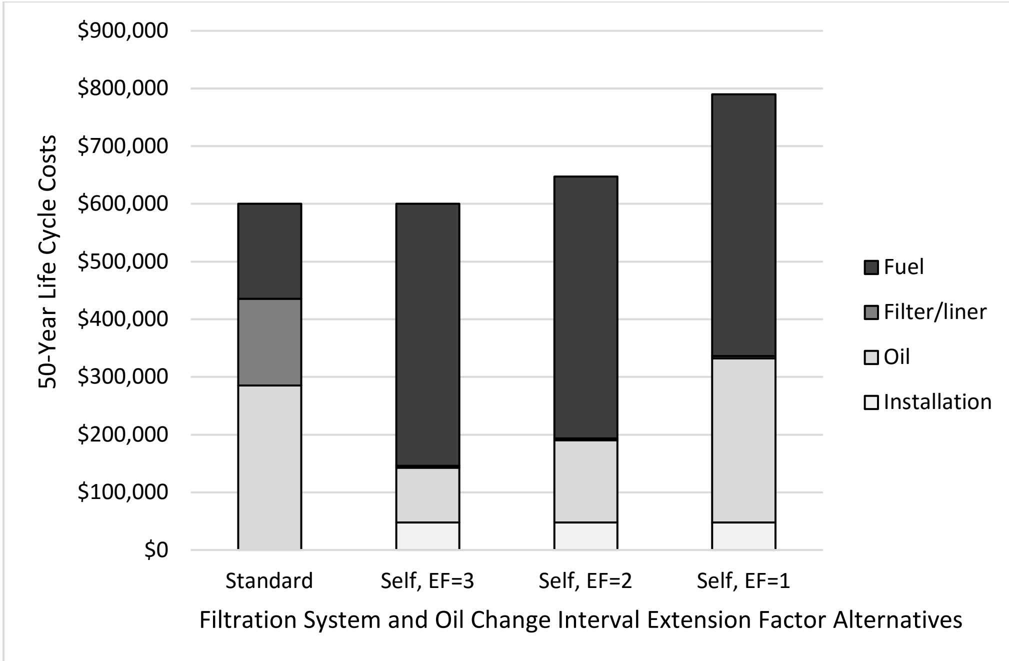

Figure 4.3 Cost contributions from each filtration system component for standard and self-cleaning oil filtration systems (where 3, 2, and 1 are oil change interval extension factors).

4.7 Discussion and Conclusions

It is unlikely that the use of the self-cleaning filtration system would save money over a 50-year time period. The oil change interval extension factor would need to be at least 3 under the assumptions used in this analysis to attain payback in 50 years. Even at an extremely high oil change interval extension (EF=6) the savings would be less than $50,000 over the 50-year period. In order to attain significant cost savings with an alternative filter of this style, the flowrate of oil or oil pressure would need to be significantly reduced. Figure 4.4 indicates the payback period that would occur if pressure and/or flowrate were reduced (assuming all other parameters and costs are the same) under an oil change interval extension factor of 2. Such alternatives that use a reduced flow of oil through the filter are available and WSF might consider these alternatives. In addition, possible cost savings from a possible reduced risk of oil spills has not been included in this analysis. Note that no instances of oil spills related to these processes have been reported to the authors and as such, based on this and WSF procedures, such risks are considered to be low.

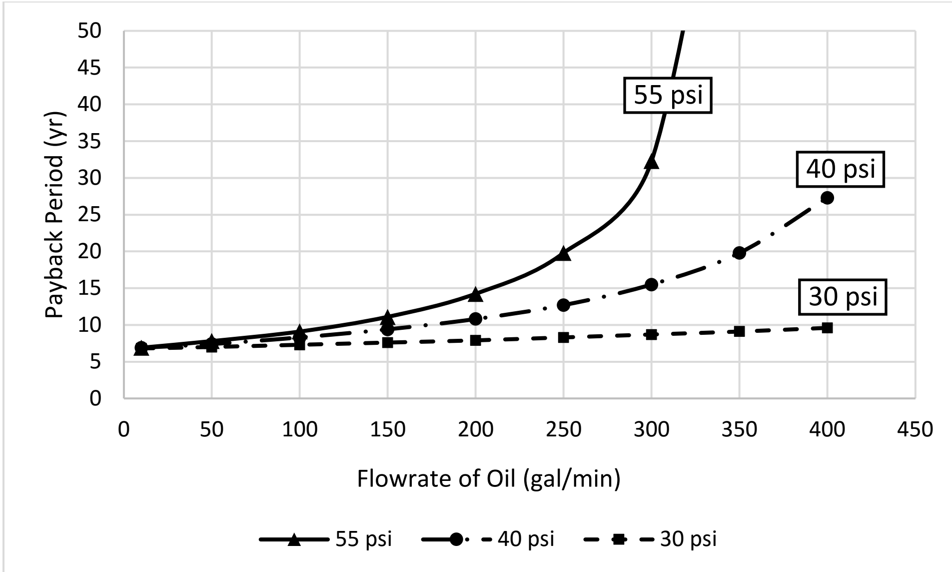

Figure 4.4 Effect of oil flowrate and pressure on economic payback period.

5. SUMMARY, CONCLUSIONS, AND ANCILLIARY OUTCOMES

This research examined the feasibility of using self-cleaning oil filtration systems in the Washington State Ferries fleet from a three-pronged perspective: (1) filtration effectiveness, (2) environmental impact, and (3) cost impact. Such systems were initially hypothesized to increase filtration effectiveness, and decrease cost and environmental impacts. However, the analyses reported herein suggest those expected benefits would not be realized in actual installations of a self-cleaning oil filtration systems if the particular system requires significant amounts of parasitic diesel fuel consumption (as in the system in this analysis).

Oil analysis results for various oil properties showed little change in property degradation rates between the standard and self-cleaning oil filtration systems over the period studied. Longer study periods may have provided additional information. Still, the same analysis showed that based on linear trends and property limits established by the engine manufacturer it may be feasible to extend oil change intervals on either oil filtration system. The self-cleaning filtration system was allowed to extend the oil drain interval to more than twice the standard oil change interval without losing a fairly linear trend (the standard system was not tested beyond the standard change interval, so a continuing linear trend is a major assumption for that system).

For the self-cleaning system, there was decreased impacts from oil and filter use, but additional diesel fuel consumed by that system outweighed the benefits in many impact categories. For most of the environmental impact types analyzed in both types of filtration systems, diesel fuel consumption for pumping oil dominated total system impacts.

Life cycle cost analysis showed that over a 50-year analysis period the standard system would likely have a lower overall monetary cost than the self-cleaning system. According to the analysis, if an oil drain interval extension greater than three-fold were achieved with the self-cleaning system (without any increase with the standard system), it may become less expensive. However, the filtration effectiveness analysis did not seem to support the necessary condition of an extension of such length being feasible in the self-cleaning system, while any extension being infeasible in the standard system.

The analyses in this report considered environmental and cost implications under the assumption that both systems operate as expected. That is, they did not consider costs or environmental impacts associated with the risk of unlikely events. For example, there was no consideration for the potential of reduced risk of oil releases into Puget Sound as a result of less handling and dock storage of oily filters with the self-cleaning system. Risk factors such as these should be assessed separately from the conclusions of this report to determine if such changes in risk factors are significant enough to affect filtration system decisions.

Based on the results of the filtration effectiveness, environmental, and cost analyses, decision-makers at WSF elected to remove the pilot installation of the self-cleaning filtration system (executed in March 2016) and have no immediate plans to implement such systems on other vessels in the fleet. Nevertheless, other similar systems with different operational parameters or characteristics might perform differently, and the conclusions of this report are not to suggest that another self-cleaning or centrifugal filtration system would result in a similar outcome. For example, if a similar system that only filtered oil through a bypass (rather than full flow) were selected, the diesel fuel consumption might be reduced, altering the results of the cost and environmental analyses.

The communication of this research to a wide variety of stakeholders, data access granted, and close work with transportation agency personnel provided a platform for additional value-added research to come from this endeavor. Specifically, two major research trajectories as a part of the first author's PhD dissertation and an additional paper were outcomes not otherwise central to the content of this report. Through collection and synthesis of data from a wide range of WSF operations, a simplified agency-wide evaluation of environmental impacts was created, and the resulting database used to develop and demonstrate a new concept in results presentation – hybrid normalization. That work resulted in two publications: a conference paper under review on developing the database (Langfitt and Haselbach 2016c) and a journal paper on hybrid normalization (Langfitt and Haselbach 2016b). Partially informed by the experience gained working with decision-makers at transportation agencies and difficulties noticed during the scoping of the LCA included in this report, a rubric for assessing the quality of functional units for transportation sector studies was developed and a paper is currently under development (Langfitt and Haselbach 2016d). Finally, as previously mentioned in this report, a graphical tool for helping engine operators weigh the cost benefits and risks of extended oil drain intervals was developed, based on data and experience from this project (Langfitt and Haselbach 2016a).

6. ACKNOWLEDGEMENTS

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APPENDIX: LIFE CYCLE COST ANALYSIS DETAILED MODEL EQUATIONS

LCC=RC+NRC

NRC=C_p+C_i

C_p = Purchase price of the Eliminator, including any taxes and shipping charges as well as cost of spare parts that need to be on hand

C_i = Labor costs during installation, including miscellaneous parts costs

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

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

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

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

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

$$\mathrm{C_{od}} = \left\{\left(\text{Cost per pickup }\left[\frac{\$}{\text{change}}\right]\right) + \left(\text{Cost per gallon }\left[\frac{\$}{\text{gal}}\right]\right)\left(\text{Gallons per change }\left[\frac{\text{gal}}{\text{change}}\right]\right)\right\}\left(Change\ frequency\ \left[\frac{change}{yr}\right]\right)$$

$$\mathrm{C_{fd}} = \left\{\left(\text{Cost per pickup }\left[\frac{\$}{\text{change}}\right]\right) + \left(\text{Cost per filter }\left[\frac{\$}{\text{gal}}\right]\right)\left(\text{Filters per change }\left[\frac{\text{gal}}{\text{change}}\right]\right)\right\}\left(Cange\ frequency\ \left[\frac{change}{yr}\right]\right)$$

$$\mathrm{C_{df}} = \left(\text{Unit cost diesel }\left[\frac{\$}{\text{gal}}\right]\right)\left(\text{Diesel fuel used per year }\left[\frac{\text{gal}}{\text{year}}\right]\right)$$