DISSERTATION

IMPROVING CONSTRUCTION MACHINE ENGINE SYSTEM DURABILITY IN LATIN AMERICAN CONDITIONS

Submitted by

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ABSTRACT

IMPROVING CONSTRUCTION MACHINE ENGINE SYSTEM DURABILITY
IN LATIN AMERICAN CONDITIONS

Between 2016 and 2030, the Latin America region needs to spend $7 trillion dollars (Bridging global infrastructure gaps, 2016). Thus, for the foreseeable future, the Latin American market will experience high demand for construction equipment such as backhoes, excavators, crawler-dozers, and loaders to construct roads, housing, airports, and sea ports. Construction equipment employed in Latin America operates in conditions which are often more severe compared to developed countries such as the United States. Consequently, the durability of construction equipment diesel engines is reduced within the context of the system engineering life cycle. This results in a greater number of warranty claims, increased customer product dissatisfaction, and delays in completing contracted projects.

Peer-reviewed literature lacks information regarding the wear and failure of construction equipment diesel engines operating in Latin America. Thus, the purpose of this research is to contribute to the system and maintainability engineering fields of knowledge by analyzing oil samples taken from diesel engines operating in Latin America. Oil samples are leading indicators and predictors for wear in specific components of diesel engines, as they directly connect to the use conditions of actual work environments.

The methodology approach considers data points from different sources and countries. The engine oil sample analysis results are evaluated in the context of local diesel fuel quality, machine diagnostic trouble codes, and the work environments for the following countries: Bolivia, Colombia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Honduras, Mexico, Paraguay, Peru, and Uruguay. The following data sources are used to answer the research questions: (1) database of oil sample laboratories of eleven countries, (2) construction equipment diagnostic trouble codes, (3) construction equipment surveys, (3) John Deere service manager's surveys, (4) two John Deere 200D excavators, (5) engine operating data, and (6) Engine Control Unit sensor data.

It is determined that cross-system contamination was key contributors of oil contamination. Contamination related to environmental conditions in which the equipment was operated is also a key factor, as there is a high statistical correlation of sodium, silicone, and aluminum oil contamination present in the oil of equipment operating at higher altitudes. It is determined that sulfur, diesel fuel quality, humidity, bio-diesel, temperature, and altitude are factors that must be considered in relation to diesel engine reliability and maintenance. The research found that by correlating the engine oil sample contamination with the environment risk drivers (a) altitude and diesel fuel quality have the greatest impact on iron readings, (b) bio-diesel impacts copper, and (c) precipitation and poor diesel quality are associated with silicon levels. Wear metals present in the oil samples indicate that scheduled maintenance frequency must not exceed 250 hours for diesel engines operating in many areas of Latin America. The leading and earliest indicator of engine wear is a high level of iron particles in the engine oil, reaching abnormal levels at 218 hours. The research found that engine idling for extended periods contributes to soot accumulation.

ACKNOWLEDGEMENTS

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- Kurt

DEDICATION

To Ashley Campagnoli Azevedo

“Knowledge is the best wealth that a human can attain”

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CHAPTER 1: INTRODUCTION

1.1. Purpose

According to Blanchard and Fabrycky (2011), system engineers look at systems and their problems using a top-down approach rather than from the bottom up. Thus, their approach is to determine how the system performs and interacts with its operating environment. A system engineer examines the system input, process, and output, compared to the system-specific limits and design scope. Frequently, system engineers do not determine how an individual part or component can be improved as this is considered a task for function engineering (e.g., the mechanical engineer). However, a holistic understanding of the system components and possible areas of improvement can lead to improved system durability.

The main objective of this research is to employ system engineering theory and tools to identify correlations between reduced engine durability in construction equipment operating in Latin America and the environmental factors common to that region. The research identifies the key factors in diesel engine wear such as diesel fuel quality, machine application, and deployment at high elevations.

1.2. Benefits

The research helps fill the gaps of the current maintenance literature regarding the diverse operating conditions diesel engines are exposed to globally and the impact these conditions have on engine durability. By determining the key factors of engine wear through engine oil analysis, system engineers will be able to form an inter-disciplinary solution to improve the durability and longevity of diesel engine systems. For instance, the benefits of this research could extend to specific engineering disciplines within the system life cycle, mainly design (development) and system support (supportability and maintainability). Thus, this research advocates a strong link between system support and system design, a relationship not fully explored in system engineering publications. Finally, the nature of this research supports the international approach to system engineering as proposed by the National Academy of Engineering (NAE) publication, Educating the Engineer of 2020 (National Academy of Engineering, 2005).

The application of system engineering processes to this research leads to practical design changes to improve diesel engine durability for equipment operating in conditions such as those found in Latin America. For instance, by understanding an environmental factor such as the quality of diesel fuel available to operators in Latin America, mechanical engineers could implement component design changes to address that factor. By understanding oil analysis results for this region, test design engineers could improve product verification and validation cycle-time during the product development process. The understanding of multiple variable system applications will lead to a detailed risks analysis. Finally, maintenance engineers can implement maintenance strategies to avoid early engine failures.

1.3. Research Target Audience

Four chapters of this dissertation were submitted to, or published in, the International Council of System Engineering (INCOSE) 2017 International Symposium, the System Engineering Journal, and the Journal of Quality in Maintenance Engineering. Thus, the target audience of the research includes system engineers, mechanical engineers, and maintenance engineers.

1.4. Motivation

The primary motivation for this research is the reduced engine durability experienced by users in Latin America. Construction equipment is exposed to severe operating conditions that range from poor diesel fuel quality to high operating elevations. These risks are not quantified in the peer-reviewed literature. Testing products (i.e., construction equipment) for all Latin America countries is a cost prohibited task for any manufacturer. However, engine life can be affected by operating conditions that fall outside the scope of conventional system engineering test plans. Figures 1.1 through 1.3 are examples of failures of construction equipment diesel engines with as few as 500 hours operating in Latin America. In comparison, similar engines operating in the United States are expected to last up to 10,000 hours. From the user's perspective, reduced engine durability leads to machine down-time, project delays, and possible contract penalties. Because construction equipment is often used to complete complex production system and infrastructure projects, each hour that a machine is not operating causes a ripple effect leading to costly delays in production systems (e.g., gravel or asphalt production plants), project delay fees, and loss of future infrastructure project contracts. For instance, the cost overruns due to project delays for the expansion of the Panama Canal were $5.7B USD (Webber, 2017).

Figure 1.1: Oil pan of a 200D excavator in Colombia

Figure 1.2: Engine head of a 200D excavator in Bolivia

Figure 1.3: Engine oil viscosity of a 200D in Peru

1.5. Research Questions

This research addresses the following questions:

- What are the engine oil contamination characteristics associated with construction equipment diesel engines running in Latin America?
- How does engine oil contamination relate to the environmental factors in Latin America?
- How do the engine durability issues manifest as engine fault codes and engine failures?

1.6. Methodology

The approach of this research was developed by employing system engineering applications. The research considers local operational conditions and how oil samples can be employed as a predictor of, or a history of premature engine failure. System engineering concepts applied to this research include the following: System Environment, Performance Systems Attributes versus Cost, System Degradation, and System Maintainability. The research utilizes several data sources, engine oil laboratory results, machine telematics data, user surveys, a survey of John Deere dealership service personnel, and engine computer data. The data was collected from 11 Latin American countries, Costa Rica, Colombia, Ecuador, Peru, Guatemala, Bolivia, Mexico, Honduras, Paraguay, Uruguay, and Dominic Republic. Existing literature was reviewed to determine what is already understood in the field of oil contamination for machines deployed in Latin America. The research includes citations to indexes, journals, and the utilization software tools such as MATLAB and Eureqa (to determine data trends and correlations), analysis of local industry data, trade and industry historical data, construction machine population statistics, the International Council on the System Engineering (INCOSE) website, and two key System Engineering books: "Systems Engineering Principles and Practice" (Kossiakoff et al, 2011) and "Systems Engineering and Analysis" (Blanchard and Fabrycky, 2011). This research applies Evolutionary Synthesis of Knowledge, as named by Blanchard and Fabrycky (2011). In complex systems, such as a diesel engine, this research will provide a combination of science (tribology), social aspect, and technology (engine system mechanical and technical components) (Blanchard and Fabrycky, 2011).

1.6.1. Oil Laboratory Equipment

The primary source for the research is an engine oil database containing over 7,561 engine oil sample evaluations. These oil samples were obtained between October 2010 and April 2015 from equipment operating in Costa Rica, Colombia, Ecuador, Peru, Guatemala, Bolivia, Mexico, Honduras, Paraguay, Uruguay, and Dominic Republic. Figure 1.4 is a map of the oil laboratory locations.

The laboratory in each country employed the same oil analysis equipment, the OSA3 micro-laboratory. This laboratory equipment is produced by Spectro Scientific, the world largest supplier of fluid analysis instruments (About us, 2015). The OSA3 micro-laboratory can perform fluid chemistry, viscosity measurements, particle counts, and elemental analysis. The laboratory is composed of the following subsystems: infrared spectrometer, kinematic viscometer, light (laser) blockage particle counter, and an optical emission spectrometer (OES) (Spectro Scientific, 2013). For fluid chemistry analysis, the infrared spectrometer tests for total base number (TBN), soot, water, oxidation, and glycol. For oil viscosity, the kinematic viscometer tests for viscosity at 40 and 100°C. For particle count analysis, the light blockage particle counter tests for particle count and particle size are used. For element analysis, the OES tests are implemented for 20 types of wear metals. Figure 1.5 is an image of the OSA3 micro-laboratory used for this research (Spectro Scientific, 2013).

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Figure 1.4: Oil laboratory network

Figure 1.5: OSA3 micro-laboratory

1.6.2. Machine Telematics Data

Construction equipment telematics data was obtained through the use of John Deere's JDLink website. JDLink website allows remote access to engine Diagnostic Trouble Codes (DTCs). These system fault codes provide valuable information about engine alerts and failures. Also, telematics data can provide geo-fencing and operational data. Data from construction equipment is transmitted via a cellular network or transmitted via satellite from remote locations. Then, the data is gathered and analyzed in a central location in each country as seen in Figure 1.6. This type of information is critical as it provides insight regarding engine operation, equipment operation, environment conditions, fuel quality, and maintenance. A total of 4,969 country-specific DTCs were gathered and analyzed. Data cataloged included water in fuel alerts, coolant temperature, oil pressure, exhaust manifold temperature, engine coolant temperature, engine air filter restriction, and fuel filter restriction alerts. Figure 1.6 shows the Peruvian machine telematics monitory center.

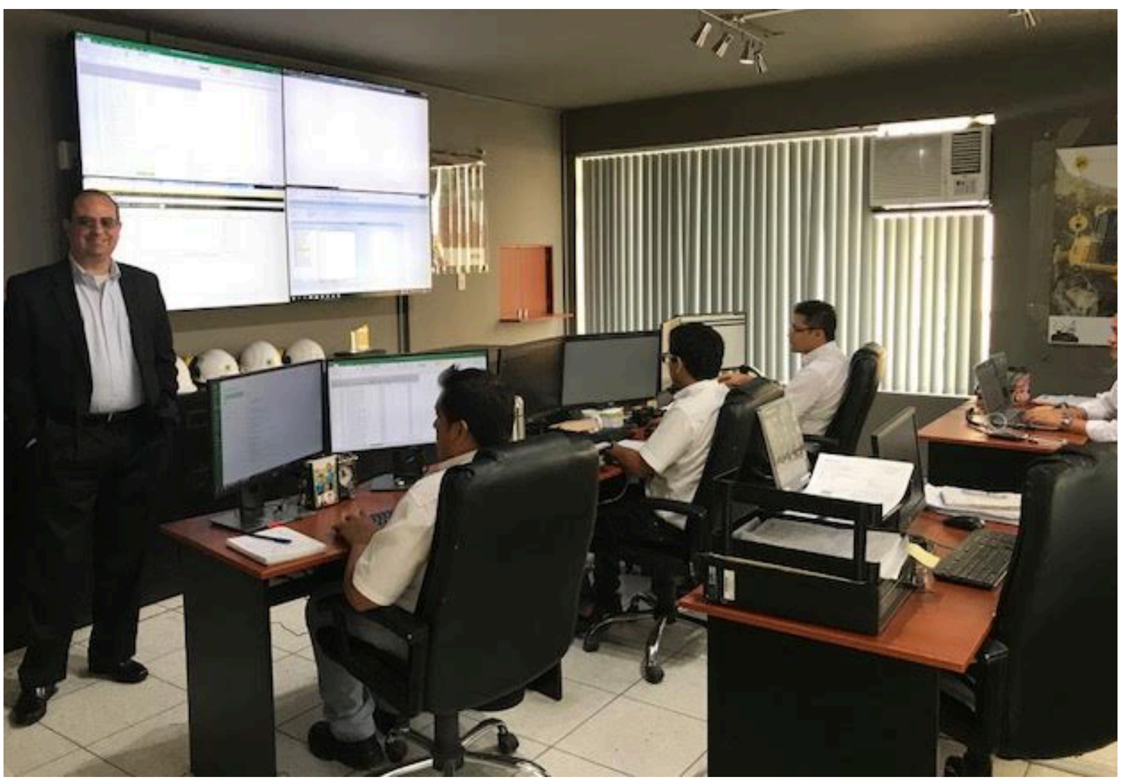

Figure 1.6: Peruvian machine telematics monitoring center

1.6.3. Testing Construction Equipment

Two excavators operating in very different conditions in Latin America were evaluated for the period of three months. The excavators evaluated are located in La Paz and Santa Cruz, Bolivia. Both excavators are equipped with the 6.8 liters John Deere PowerTech Plus diesel engines. Equipment telematics data was obtained to determine their operating and diagnostic trouble code data. Operational data was gathered for both machines for a period of up to 260 hours. The oil analysis results spanned an operational period of up to 252 hours. Figure 1.7 shows a comparison of the operating elevations for both excavators. The La Paz excavator operated at 3657 meters above sea level. This equates to the standard barometric pressure of 66 kPa (496 mmHg) with temperatures ranging from -3°C to 12°C. The Santa Cruz excavator operated at an altitude of 416 meters above sea level. This equates to a standard barometric pressure of 97 kPa (725 mmHg) with temperatures ranging from 15.9°C to 26°C. Figure 1.8 shows the excavator prior to being shipped to the La Paz job site.

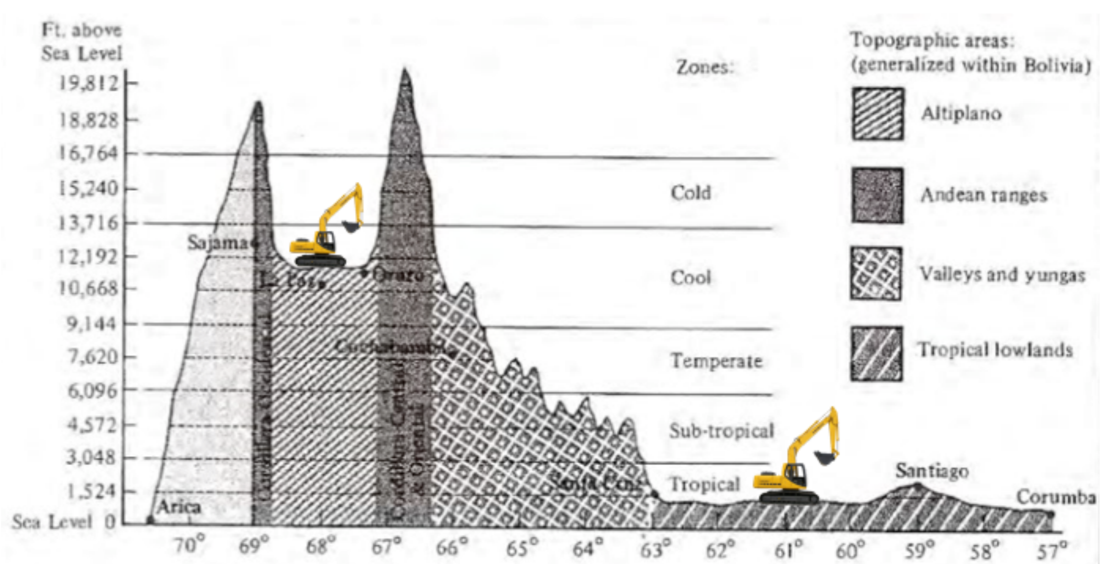

Figure 1.7: Bolivian altitude operation

Figure 1.8: Bolivian excavator

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CHAPTER 2: SYSTEM ENGINEERING ANALYSIS OF CONSTRUCTION EQUIPMENT OPERATING IN LATIN AMERICA[1]

2.1. Introduction

The necessity to improve the infrastructure in Latin America has led to annual sales of construction equipment exceeding 14,000 units (Construction Machine Import Data, 2017). The demand continues for construction equipment such as backhoes, excavators, crawler dozers, and loaders to support the construction of roads, houses, airports, and ports. The need to expeditiously deploy construction equipment in Latin America markets has resulted in equipment sold into markets without applicable field tests. Consequently, the durability of construction equipment diesel engines within the context of the utilization and support elements of the system engineering life cycle often do not achieve the same durability levels as equipment deployed in the United States. The result is a greater number of warranty claims, customer dissatisfaction with products, and delays in completing contracted projects.

Engine durability is defined as a design attribute that "affects the quality or reliability of the engine" (Xin, 2011, p.42). Durability is associated with engine endurance and not to be confused with engine reliability (Xin, 2011). A definition is laid out in the Advanced Product Quality Planning manual: "durability is the probability that an item will continue to function at customer expectation levels, at the useful life without requiring overhaul or rebuild due to wear-out" (Xin, 2011, p.42). In construction equipment, a 20-ton excavator engine should last in optimum conditions about 8,000 hours prior overhaul (Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling, 2002). However, engines in construction equipment were failing as low as 200 hours in Latin America.

In the context of the construction equipment life-cycle, this paper addresses the durability issues impacting diesel engines used in construction equipment in the Latin America environment. Specifically to the machine Use and Support phase of the life cycle (Figure 2.1), literature lacks information regarding

[1] Conference paper presented and published in 27th Annual INCOSE International Symposium 2017.

diesel engine component wear and failure when deployed in Latin America. Thus, the purpose of this study is to fill the literature knowledge gap by analyzing the diesel engine oil as a leading indicator for wear specific to the use conditions experienced within actual work environments in Latin American. The two research questions explored are: (1) What are the engine oil contamination characteristics of diesel engines deployed in Latin America? (2) How does engine oil contamination relate to the environmental factors in Latin America?

2.2. System Engineering Approach

The system engineering process as suggested by Blanchard and Fabrycky (2011), INCOSE Systems Engineering Handbook (2015), and Kossiakoff (2011) is utilized to determine the application engine durability in product life cycle. The following are some benefits of this approach:

- System engineering provides a holistic understanding of the phases of construction equipment life cycle (See Figure 2.1). Blanchard and Fabrycky (2011) suggest that the system engineering discipline could provide "greatest benefit being derived from its emphasis on the early stages" of the product life cycle (p.50). It is accomplished by influencing the early activities machine design such as "needs analysis, requirements definition, functional analysis and allocation" (p.50).
- By providing an understating of diesel engines operation in the construction market in Latin America, the system engineering approach will provide a systematic correlation of machine operation, failure modes, and the environment.
- The system engineering discipline will also provide the design improvement inferences where specific engineering specializations (e.g. mechanical engineers) could improve specific engine component.

Figure 2.1 is adapted from Blanchard and Fabrycky (2011) to the construction equipment industry. This figure is useful to frame the system engineering process and its impact during the early design phase. The construction machine lifecycle in Latin America has seven phases: (1) conceptual design, (2) detail design, (3) manufacturing, (4) machine use and support, (5) machine re-life, (6) machine extended use and support, and (7) machine disposal. The time-frame of a machine lifecycle is: conceptual design (six months), detail development (2 years), manufacturing which includes testing and product validation (2 to 3 years), machine usage and support (10 years, but it is conditional on usage hours and type of application), re-life (2 to 5 months), extended life as the result of re-life (6 to 7 years, but is conditional based on usage hours and the type of application), and disposal.

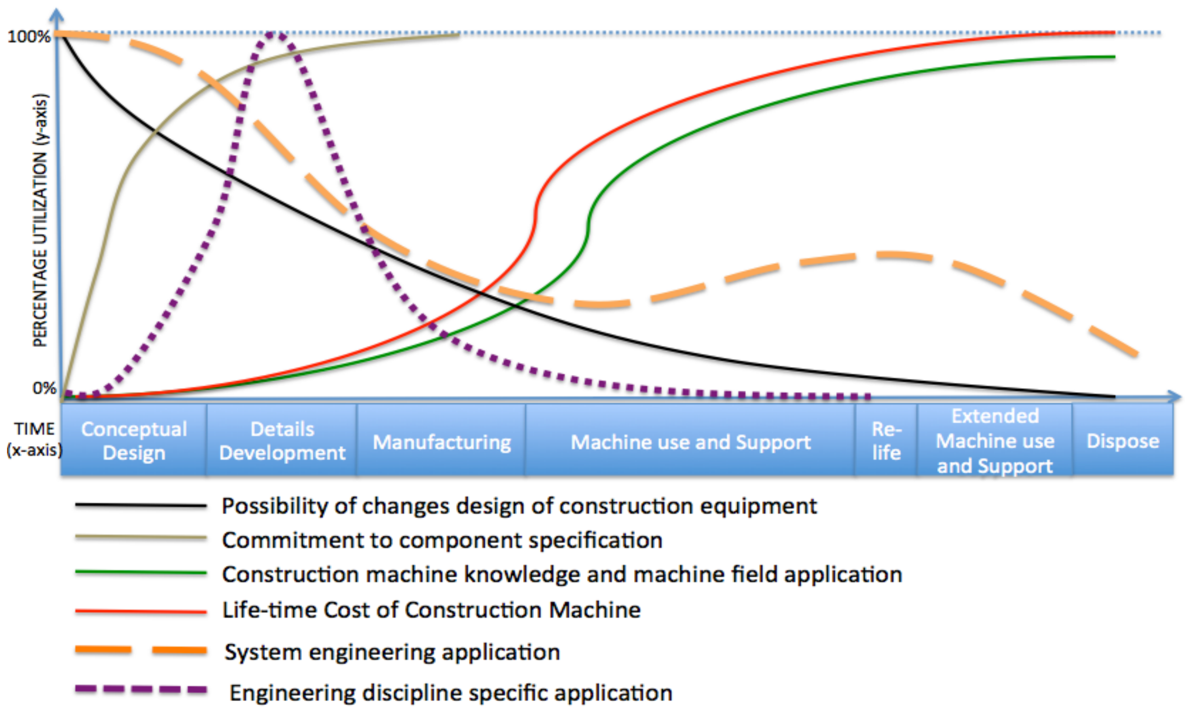

Figure 2.1: Life cycle of construction machines deployed in Latin America (adapted from Blanchard and Fabrycky 2011)

Figure 2.1 exemplifies the level of interaction with each phase of construction equipment lifecycle. Below is a brief explanation of the interactions:

- As portrayed by the black line, the probability of design changes in the conceptual design is high because the needs and requirements for the equipment are not yet fully identified. It decreases at a fast rate as components are adopted. Usually with the choice of off-the-shelf subsystems (e.g., fuel injection pump), the probability of change of design becomes more rigid with time.
- The gray line shows that often the commitment to a specific technology increases quickly during the conceptual design and level out in the detail development. By the end of the manufacturing phase,

components are locked in design. Quite often decisions are made regarding engine components that are not fully tested in the diverse conditions of Latin America.

- The green line represents the level of understanding of Latin America operations. Often, it is not until the construction equipment is sold that reliability and durability issues become evident. Engines are seldom tested for local environmental factors such as diesel quality, sulfur levels, and bio-diesel mixtures. Consequently, little or no data is available to complete a comprehensive evaluation. Caterpillar recommends meeting ASTM D975 or EN590 requirements (Abi-Akar, 2008) and is cautious with blends over 20% (B20 on ASTM 7467) as it is considered a severe application (Cat Commercial Diesel Engine Fluids Recommendations, 2014, p.57). John Deere state that engines without after-treatment exhaust filter systems are designed operate up to 100% biodiesel blends (Using Biodiesel in John Deere Engines, 2016). These companies assume that fuel producers in Latin America countries are meeting American Society of Testing Material D6751 and 7467 ASTM standards.
- As a result of insufficient local testing and evaluation, machine life cycle cost increases rapidly after manufacturing. These costs are verified through the warranty claims and product recalls as represented by the red line.
- The orange dotted line represents the interaction of system engineers in the life cycle of the construction machines. It tends to decrease rapidly after the detail development phase only to increase again when machines experience failures in Latin American markets. Systematic knowledge is necessary to address complex equipment operators' experience of failures in diverse usage conditions.
- Conversely, the purple dotted line represents discipline-specific engineering that focuses the majority of their effort during detail development. However, limited interactions are observed in the re-life of an engine as components might not be available for engine overhauls and component specifications must be altered to increase system life.

By reviewing the lifecycle of construction machines deployed in Latin America, system engineering offers value to understand application patterns and their effects in the subsystem interrelationships. The system engineering lifecycle as presented here could determine areas of improvement prior to deploying construction equipment in Latin American markets.

Blanchard and Fabrycky (2011) suggest key benefits are realized by understanding the product lifecycle, including:

1) Visibility and communication improvements of market-specific failure modes.
2) Cost reduction throughout the machine lifecycle (e.g., warranties, returns, credits, and allowances).
3) Clear identification of support capabilities.
4) Understanding of subsystem integration, testing, and validation.
5) Cost reduction by employing off-the-self components that can be sourced locally.
6) Understanding local operations leading to component design improvements to be implemented earlier in the design phases prior to the system integration and testing; thus, reducing costs such as product recalls.
7) Reduction of the time needed to conduct local testing.
8) Forward thinking to create risk analysis and planning by determining risk and impact drives and their respective probabilities.
9) Clearer identification of local customer design-dependent parameters (DDP), design independent parameters (DIP), and technical performance measures (TPMs).
10) The system engineering lifecycle will provide recommendations for future conceptual designs as they relate to engine architecture for Latin America applications and the durability metrics and outcomes expected by customers.

This research is framed in the system engineering life cycle processes. The research will lead to new inferences to improve diesel engine system durability for the Latin American markets in the machine use and support phase of the life cycle (Figure 2.1). Also, by determining the key drivers for engine wear and associating them with engine oil analysis, system engineers will be able to form interdisciplinary solutions pertaining how to improve diesel engine systems in the conceptual design and detail development phases of the machine life-cycle (Figure 2.1). Thus, engine oil analyses are evaluated in the context of local diesel fuel quality, machine diagnostic trouble codes, and the work environments for the following countries: Bolivia, Colombia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Honduras, Mexico, Paraguay, Peru, and Uruguay. Together, these countries represent 70% (9,800 units) of the Latin America market in 2014 (Construction Machine Import Data, 2017).

2.3. Motivation

2.3.1 Manufacturers' Needs

Due to infrastructure expansion, economic growth potential, and the availability of raw materials, Latin America is a significant market for earth moving equipment. For instance, the "Colombian construction sector is growing at one of the fastest rates in the world, driven by infrastructure investment" (Peters and Barston, 2015, p.22) such as road construction and a hydropower plant on the Cauca River (Peters and Barston, 2015). Other projects include the US$ 3.2 billion expansion of the Panama Canal, the US$4.4 billion rail link project for between Mexico City and Queretero, the US$9.2 billion Mexico City airport upgrade, and the US$5.4 billion Lima Peru metro extension. Furthermore, in the next ten years China plans to invest US$250 billion in Latin America (Peters and Barston, 2015). Figure 2.2 illustrates the total construction spending in key Latin American markets from 2015 and the estimated average growth to 2025.

To support the infrastructure growth, construction equipment manufacturers must design equipment to perform in a variety of operational conditions and test them in the appropriate geographical locations to meet reliability and durability metrics. However, during the system engineering life cycle, manufacturers tend to design and test engines exclusively in their home market. While engine durability and reliability have been tested in laboratory environments and in the U.S. operational conditions, there remains a significant lack of system understanding regarding construction equipment diesel engine component wear and failure in equipment deployed in Latin America. Thus, system engineering performance attributes are not balanced as there are multiple unknown factors affecting engine life. For instance, predominant unexpected engine wear mechanisms specific for this region are related to turbochargers and exhaust gas recirculation valve failures. Premature failure of engine bearings, pistons, and rings also occur leading to low engine durability and high warranty cost.

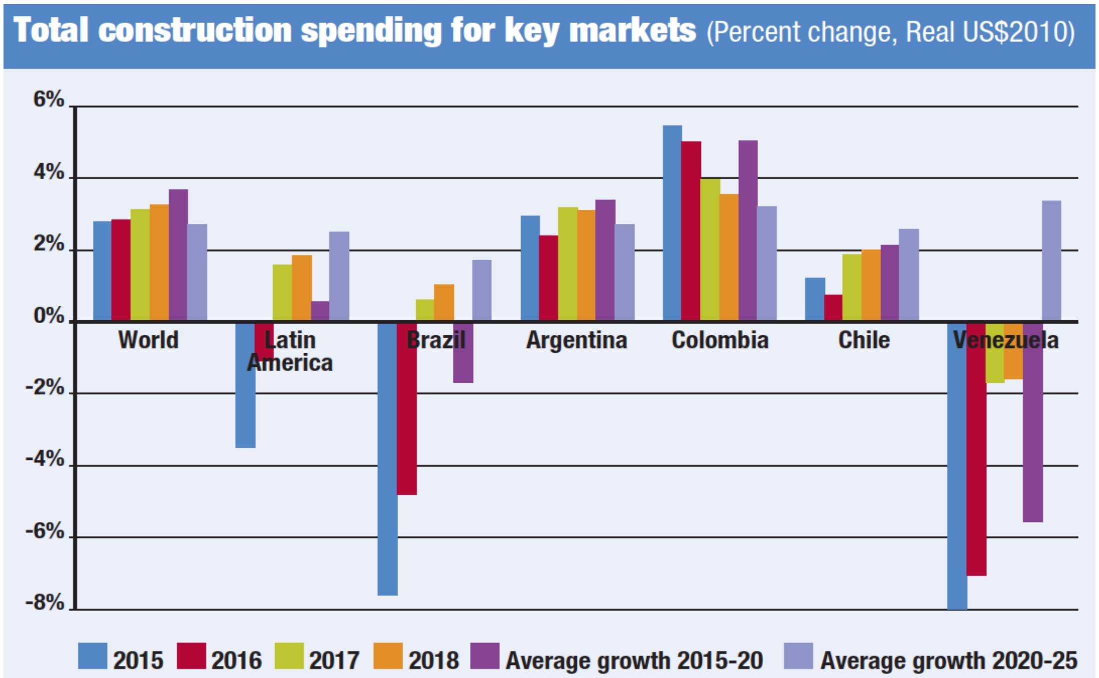

Figure 2.2: Total construction spending for key markets (Hazelton, 2016)

2.3.2. Users' Needs

When evaluating a system, a cornerstone of the application of system engineering principles is to understand the customers' requirements. Blanchard and Fabrycky (2011) state that the "definition of needs at the system level is the starting point for determining customer requirements and developing design criteria" (p.38). The common mistake taken by design engineers is to assume that customer requirements, application, design dependent parameters of the machine, and the design independent parameters identified in the manufacturer home market are transferable globally.

After searching peer-reviewed database such Academic Search Premier, Web of Science, and Google Scholar on the topics of construction equipment in Latin America, it was determined that there is a lack of publications leading to the understanding construction customer requirements and construction machine applications in Latin America. Thus, when visiting customers in Latin America, it was determined that construction machines are deployed in applications that were not considered by manufacturers. For instance, the majority of the excavators sold in Paraguay are employed to agricultural application such as digging ditches for rice plantations. This application can lead to equipment failure due to water contamination in the hydraulic system, an issue not considered during manufacturer testing. Thus, it is difficult to apply the Blanchard and Fabrycky (2011) suggestion that "Functional requirements must be met by incorporating design characteristics within the system at the appropriate level" (Blanchard and Fabrycky 2011, 40) for global applications. However, given the importance of the Latin American market, customer requirements must be considered. These requirements must be compared with the machine reliability and durability leading to system balance. Surveyed Latin American customers rate the following as desired machine attributes in order of importance: (1) reliability, (2) parts availability, (3) durability, (4) maintenance and repair costs, (5) performance, (6) fuel economy, (7) dealer support, and (8) operator comfort. Thus, the research focus to improve the understanding of how engine durability is affected by the environmental factors in Latin America such as altitude. The final impact will be the reduction warranty claims, improvement of customer satisfaction, and delays in construction project completion.

2.4. Latin America Construction Market and Geography

2.4.1. Latin America Construction Market

The system engineering approach to failure analysis requires a holistic view of the problem. Thus, it is essential to understand the Latin America construction market at its macro-level as a system of systems prior decomposing it to its granular component. The first step is to understand the machine population. The Latin America market (excluding Brazil) is composed primarily of (1) backhoes, (2) excavator, (3) loaders, (4) motor graders, and (5) bulldozer crawlers. These machines are classified as construction machinery and their engines are the focus of the analysis.

According to customs import machine data for each country, in 2014, the Latin America market included close to 14,000 machines (Construction Machine Import Data, 2017). Brazil is not in the scope of this analysis because it does not have high attitude applications and oil sample data could not be collected from the same testing equipment. The target countries (Bolivia, Colombia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Honduras, Mexico, Paraguay, Peru, and Uruguay) have 67% of total number of backhoes, 74% of the total excavators, 62% of the total loaders, 74% of the total motor graders, and 79% of the total bulldozers sold in Latin America in 2014 (Construction Machine Import Data, 2017). A comprehensive understanding of machine population is important because (1) it adds weight to research statistical significance and scope, (2) supports correlation between the oil sample database and where machines are deployed, (3) supports the assumptions that the research results could be extrapolated to non-targeted Latin American countries, and (4) offers the evidence of diverse environment conditions leading to the completeness of this research. Figure 2.3 compares the target country machine populations to the total machine population distribution.

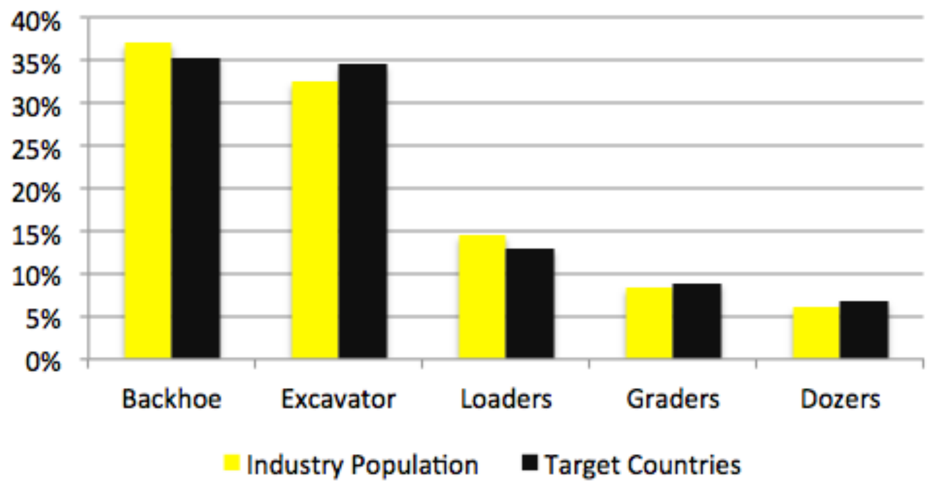

Figure 2.3: Latin America construction machine population in 2014

As depicted in Figure 2.3, the machine population distribution is similar in each machine family between the industry population and the target countries. Also, this graphic shows that backhoes and excavators have the greatest number of units. When, reviewing the machine specifications, it was determined that the most common backhoes include the CAT 416E/F2, John Deere 310K/L, CASE 580N, and the JCB 3CX. They are rated in the 79 to 100 horsepower gross engine capacity range. For the excavators, the most common include the CAT 323F, John Deere 210G, Case CX210D, and Komatsu PC200. They are classified in the 159 to 161 net horsepower range with an operating weight of 22.91 to 23.5 metric tons. Regarding wheel loaders, the most common machines include: the CAT 950M, the John Deere 524K, and the Case 521F. They are classified in the 4 to < 5 cubic yards bucket capacity category.

For graders, the most common include the CAT 120M2, John Deere 670G, and Case 865B VHB. They are rated in the 173 to 182 net engine horsepower range. Regarding bulldozers, the most common engines include the CAT D6T, John Deere 750K and 850K, Case 850M, and Komatsu D39PXI-23 and D65PX-17. They are rated in the 125 to 207 net engine horsepower range.

2.4.2. Latin America Geography

Latin American countries offer a unique operating environment for construction equipment and their diesel engines. As seen in Figure 2.4, the Pacific coast of Latin America includes extreme elevation (in excess of 4,000 meters above sea level). Within a few kilometers of the high elevations are the lowlands characterized by high humidity. Given that 70% of the machine population operates in these conditions, it is critical to take into consideration geography as a key variable leading to abnormal engine oil readings and diesel engine durability.

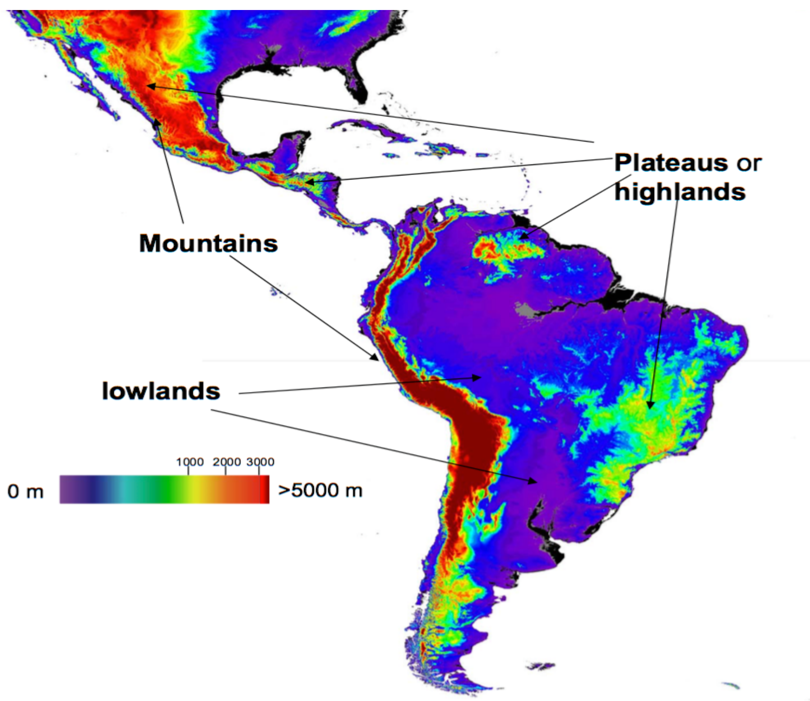

Figure 2.4: Latin America altitude map (Pujana, 2005)

High altitude operation leads to the increase of particulate matter resulting from inefficient diesel combustion. Particulate mater (PM) can change engine oil viscosity, causing low oil flow resulting in low lubricity and cooling. Thus, operating altitude should be considered when analyzing oil results for this research. There is evidence in the literature of the impact of high altitude on the durability of diesel engines. Research conducted by Ghazikhani, Ebrahim-Feyz, Mahian, and Sabazadeh (2013) indicates that soot increases by 40% when operating diesel engines at altitudes of 250 to 975 meters. The authors attribute this to the "the relatively lower the air density introduced into the cylinders in higher altitudes that leads to the increase of auto ignition delay time which could shorten the late combustion phase; hence, the soot burnout process deteriorates" (Ghazikhani, Ebrahim-Feyz, Mahian, and Sabazadeh, 2013). Research conducted by He et al (2011) suggests that engine smoke increased by rates of 30% to 34% when operating diesel engines above 1,000 meters. Liu, Shen, Bi, and Lei (2014) reported a direct correlation between atmospheric pressure and the level of soot generated in diesel engines.

2.5. Literature Review

This section addresses content published in recent (newer than the year 2000) peer reviewed literature regarding the two questions of this research: (1) What are the engine oil contamination characteristics of diesel engines deployed in Latin America? (2) How does engine oil contamination relate to the environmental factors in Latin America?

While no specific research addresses diesel engines oil analysis in Latin America, the following are some publications that could relate to the operating conditions experienced in Latin America.

- Problems related to high concentration of biodiesel:
  - Diesel fuel with high concentration of biodiesel can reduce engine life. Delalibera, Campolina, Weirich, and Ralisch (2012) when analyzing the performance of diesel engine fuel with a preheated blend of high concentration of biodiesel had identified that engine fuel injectors had reduced life, common rail system was unstable in delivering fuel, and there an increase of particulate mater (PM).
  - The type of engine oil sold in Latin America could impact engine durability. A presentation published by Frank Lauterwasser from Chevron Oronite LLC (2009) states that oil manufacturers in the past developed their products based on reliability, performance, and operating cost. However, today, products must address compliances, globalization, fuel economy, new engine technology,

and fuel quality. For instance, CJ-4 oils were created to support Exhaust Gas Recirculation (EGR) and Diesel Particulate Filter (DPF) technologies. Also, engine oil additives were adapted to perform with lower quality of bio-diesel fuel as it increases engine deposits and corrosion. However, engine oil improvements have not provided a complete solution in all countries in Latin America. According to Lauterwasser (2009), the introduction of high concentration of bio-diesel fuels in Ecuador has: (1) increased injector deposits, (2) increased fuel filter plugging, (3) reduced injector pump durability, and led to (4) material incompatibility, (5) fuel instability, (6) inability to manage low temperatures, (7) a reduction of detergency and anti-foaming attributes of fuel, (8) an impact on after-treatment systems and sensors, (9) an increase of NOx emissions, (10) corrosion, (11) oil viscosity changes, (12) oil oxidation, (13) deposit on pistons, and (14) crankcase deposits.

- Biodiesel Development in Latin America: The International Energy Agency (Biofuels for Transport Roadmap, 2011) estimates that Bio-Fuel Consumptions in Latin America will grow from 0.5 Exajoule (EJ) in 2020 to 3.5 EJ in 2050. However, bio-diesel production and demand in Latin America will not be synchronized and production will not be standardized. This region is composed of several countries with different levels of biodiesel production development and fuel consumption. The reason determined by McRae (1999) is that diesel consumption in Latin America is sensitive to the development of each country and their respective Gross Domestic Product (GDP). For those economies in Latin America that rely on the agricultural sector, bio-diesel is the natural option for supporting local diesel demand and economic growth. This hypothesis is validated by the research conducted by Hamelinck and Fajaij (2006) where it was determined that bio-diesel is the primary strategy to meet local demand of fuel, as its production costs are comparable to gasoline in Latin America. However, the International Energy Agency (Biofuels for Transport Roadmap, 2011) suggests that since 2010, most countries in Latin America do not have consistent bio-diesel production as they are still determining biodiesel quality, land utilization, commercialization, and technology. As a result, there is great variability of bio-diesel quality in Latin America negatively affecting engine oil life and durability.

2.6. Methods

2.6.1. Lube Oil Analysis

Setting the limits for oil analysis is the most basic approach to evaluate oil samples. However, there is no consensus regarding specific limits for metal contamination. Van Rensselar (2016) determined that there are four commonly used methods for determining oil analysis limits and ranges: (1) Industry standards, (2) statistical distribution such as cumulative distribution or Gaussian distribution, (3) trend-base or rate of change limits, and (4) user defined limits. Van Rensselar (2016) also informs that these methods are affective when the oil sample results can be traced to a specific source and engine oil properties are known and can be traced to operating conditions.

Van Rensselar (2016) determined that there are several perspectives when analyzing oil samples. There are the engine manufacturer, oil blender, laboratory, and end-user perspectives. Each entity places emphasis on different aspect of oil analysis. A system engineering, tribosystem approach will be used by focusing on the correlation of all four (Blau, 2006). This approach has not been conducted yet in Latin America. For instance, the machine manufacturer approach considers the type of equipment, operation, environment, and diagnostic trouble codes (DTCs) (Van Rensselar, 2016). From the oil blender or manufacturer, oil sampling wear limits are related to physical state of the oil such as viscosity, oxidation, or nitration (Van Rensselar, 2016). Laboratories will focus on translating oil analysis into maintenance recommendations. The construction machine owners might set oil wear limits based on component cost and importance within the system, machine life cycle, machine warranty cost, and machine downtime and its impact in the construction project.

This section describes the methodology undertaken to review oil samples in Latin America. It was conducted by: (1) creating wear tables of construction machines, (2) establishing statistical significance and medium values, (3) evaluating average values with median values, (4) determining measurements that do not fall within one standard deviations (5) determining low, upper, abnormal, and critical values, and (6) determining when values need to be adjusted.

Diesel engines in construction equipment vary greatly. Thus, it is important to understand the metal wear values of each engine to be evaluated and their limits under certain hours. Table 2.1 shows two examples for an Isuzu engine and a John Deere engine. These tables are important to answer the question about how much metal PPM is normal for different operating hours.

Table 2.1: Machine specific wear metals range

	Engine Isuzu			John Deere Engine		
Filtered System	Normal	Abnormal	Critical	Normal	Abnormal	Critical
Fe	<58	58	>89	<50	50	>75
Pb	<15	15	>25	<15	15	>25
Cu	<17	17	>30	<31	31	>61
Cr	<5	5	>10	<5	5	>10
Al	<50	50	>65	<25	25	>35
Ni (Report Only)	<5	5	>10	<10	10	>17
Ag (Report Only)	<2	2	>3	<2	2	>3
Sn (Report Only)	<5	5	>10	<5	5	>10
Na	<31	31	>50	<70	70	>134
K	<30	30	>50	<30	30	>50
Ti	<5	5	>10	<5	5	>10
Si	<14	14	>21	<11	11	>16

The wear tables can be established by reviewing oil analysis results, evaluating its statistical deviation, understanding the machine application, and adjusting and compensating for its operating hours. An example of oil analysis on a John Deere 544K loader is presented in Figure 2.5. A database of oil sample results for target Latin America countries will be utilized to determine such parameters.

To analyze oil samples results in Latin America, a multistep process was followed:

1) Oil results from the oil laboratories database were exported to an Excel database.
2) A refining process was completed to eliminate the outlier values caused by unusual situations and inappropriate maintenance.
3) The average values, median values, and standard deviation for wear level ranges were determined.
4) ASTM D7720-11 (American Society for Testing and Materials, 2011) oil sample evaluation standard was used to measure distribution.

a. Values within the first standard distribution were considered normal. The critical values would be considered after the second standard deviation. A bell-shaped curve is typical for measuring wear metals.

b. The cumulative distribution would have two-tails.

c. The common distribution of TBN usually lower with usage. Thus, it is represented by a cumulative distribution of one tail.

d. In the case of TAN, the typical distribution increases with usage. Thus, there is a cumulative distribution of one tail.

5) Metal wear must be normalized to engine hours. For instance, not all metals wear shows results at specific time. Thus, it is common to normalize wear metals in machine hour intervals. For instance, Fe is a metal that time dependent and should be normalized.

NIBOL
Análisis de Lubricantes

Compañía:	003133SERGUT	**Ciudad:**	SANTA CRUZ
Dirección:	AV. CRISTO REDENTOR KM	**Estado:**	BOLIVIA
Número de teléfono:	°	**Código postal:**	
Correo electrónico:		**Fax:**	

John Deere Santa Cruz — **Número de teléfono:** — **Fax:**

Marca de máquina:	JOHN DEERE	**Identificación de unidad:**	797614	**Identificación de máquina:**	631832
Modelo de máquina:	670G	**Ubicación de la unidad**	REAR	**Fecha de prueba:**	07/11/2011
Capacidad del cárter:	24 Litros			**Equipo:**	Motor Diesel Off-road

Fecha tomada:	07/11/2011
Identificación de muestra:	66
Marca de aceite:	JOHN DEERE
Tipo de aceite:	JOHN DEERE PLUS 50 II
Peso del aceite:	15W40
Horas del unidad:	535
Horas del aceite:	1

Metales del Desgaste (partes por millón):

Hierro	Cromo	Plomo	Cobre	Estaño	Aluminio	Níquel	Titanio	Vanadio
3	<2	<2	10	<2	<2	0	0	13
N	N	N	N	N	N	N	N	N

ADITIVOS

Sedio	Magnesio	Calcio	Bario	Fósforo	Cinc	Molibdeno	Boro
<2	215	911	0	298	946	95	176
N	N	N	N	N	N	N	N

CONTAMINACIÓN

Aluminio	Silicio	Sedio	Potasio	Agua	Glicol	Combust:	Hollín	Nitración
<2	<2	<2	<2	<0.1	-	-	0.3	<2.0
N	N	N	N	N	ND	ND	N	N

PROPIEDADES FÍSICAS (V40 92 - 124; V100 12.5 - 16.3)

TBN	Oxidación	V40C	V100C	Vindex
9.8	4.2	117	15.2	135
N	N	N	N	N

EL POCO TIEMPO DEL ACEITE LIMITA LA PRECISIÓN DE LA PRUEBA. El desgaste del motor TARIFAS PARA BREAK-IN/OVERHAUL PERIODO NORMAL. LA MUESTRA PARECE ESTAR LIBRE DE CONTAMINACIÓN EXTERNA. EL ANÁLISIS INDICA UN RENDIMIENTO ADECUADO DEL LUBRICANTE Y LA UNIDAD. VUELVA A TOMAR UNA MUESTRA EN EL PRÓXIMO INTERVALO ENTRE DRENAJES DE ACEITE.

Figure 2.5: Fluid analysis sample report

2.6.2. Other Engineering Data

Diagnostic Trouble Codes (DTCs): A principle of system engineering is to evaluate impact of the environment to the desired system outputs. In construction equipment, this is possible by evaluating the engine control units (ECUs) system error messages (diagnostic trouble codes) when engines do not perform as intended in a specific environment. By tracking the system alert, possible root-causes leading to system disturbances can be identified and mitigated. Telematics systems such as Care Track (Volvo), JDLink (John Deere), Vision Link (Caterpillar), and Komtrax (Komatsu) have been in the market for over a decade and can provide important indicators of non-conforming engine performance. Telematics systems installed in construction machines allow the transfer of operational data via cell phone tower or satellite for remote monitoring worldwide. Thus, an important data point to analyze is the diagnostic trouble codes (DTCs) provided by telematics. The diagnostic trouble codes (DTCs) in Latin America could point to relationships among the operating environment, machine maintenance, engine oil degradation or contamination, and engine performance. After reviewing 4,969 machine alerts in Latin America, the most repetitive DTCs identify were: (1) water in fuel, (2) extreme low coolant levels, (3) low oil pressure, (4) extremely high exhaust manifold temperatures, (5) engine coolant temperature measuring extremely high, (6) extremely restricted engine air filters, and (6) fuel filter restrictions. The data showed that fuel quality is a major concern. For instance, the water in fuel alerts could be triggered by fuel refining processes, bio-diesel content, storage practices, local climate, fuel adulteration, and fuel in-tank contamination.

ECU Data: Engine Control Unit (ECU) data was extracted from engines working in Latin America countries that have low lands and high humidity conditions such as Panama and Mexico. Also, data was collected from countries with high elevation such as Chile, Bolivia, and Ecuador. Engine data will help to further determine engine-operating characteristics by evaluating operating air, ambient, coolant, fuel, and manifold temperatures.

2.7. Results

In this study involves the review of 7,561 engine oil samples from different manufacturers in Latin America from December 2010 to March 2015. The equipment utilized was the OSA3 microlabs in the target countries. The microlab is compliant with ASTM D7417 "Standard Test Method Analysis of In-Service Lubricants Using Particular Four-Part Integrated Tester (Atomic Emission Spectroscopy, Infrared Spectroscopy, Viscosity, and Laser Particle Counter)" (Spectro Scientific, 2013). By utilizing an infrared spectrometer, the microlab measures of TBN, oxidation, soot, water, and glycol. The microlab also has a kinematic viscometer to test engine oil viscosity at 40°C and 100°C. A particle count is measured by a laser that, by blocking light, identifies particle number and size. A spectrometer identifies 20 wear metals. The output results are elemental analysis in ppm for iron (Fe), chromium (Cr), aluminum (Al), copper (Cu), lead (Pb), tin (Sn), vanadium (V), silicon (Si), sodium (Na), potassium (K), titanium (Ti), molybdenum (Mo), nickel (Ni), manganese (Mn), boron (B), magnesium (Mg), calcium (Ca), barium (Ba), phosphorus (P), and zinc (Zn). The fluid chemistry measures were soot (% by weight), water (% by weight), glycol (% by weight), oxidation (Abs./cm), nitration (Abs./cm), and TBN (mg KOH/g). Kinematic viscosity was analyzed (up to 680 cSt) at 40°C and 100°C. The particle count studied were particle counts > 4µm [per mL] categorized in 7 particle size ranges.

The data show that 43% of oil sample results resulted in abnormal readings. Abnormal readings were triggered by dirt contamination, coolant leak, oil degradation, water, fuel dilution, and abnormal wear metal results. As a comparison, in an analysis conducted by Fitch (2011) with close to 100,000 oil samples, it was identified that 23% of the oil samples in the US had abnormal results. Table 2.2 quantifies abnormal and normal oil samples as a percentage of total oil samples in the target countries.

Table 2.2: Abnormal engine oil samples results

Countries	Abnormal	Normal
Bolivia	40%	60%
Colombia	46%	54%
Costa Rica	39%	61%
Dominican Republic	18%	82%
Ecuador	53%	47%
Guatemala	34%	66%
Honduras	22%	78%
Mexico	33%	67%
Paraguay	40%	60%
Peru	51%	49%
Uruguay	77%	23%

Fitch (2011) states that abnormal oils analysis readings are usually associated with water contamination, fuel dilution, combustion problems, dirt contamination, coolant leak, oil degradation, overheating, abnormal wear, and large wear particles. The standard testing procedures focus on the measurement of the following groups: (1) wear metals (iron, chromium, aluminum, copper, tin, and lead),

(2) measurement of contaminants (silicon, sodium, potassium, and boron), (3) and oil additives (magnesium, calcium, barium, phosphorous, and zinc). When analyzing diesel engine wear metals, Fitch (2011) suggests focusing on iron (Fe), copper (Cu), lead (Pb), and tin (Sn). For external contaminants, the focus should be silicone (Si), sodium (Na), and potassium (K) (Fitch, 2011). Table 2.3 defines the average percentage of wear metals that were found. Iron and tin abnormal levels were very high. Iron particulates in diesel engines point to wear of cylinder liners, gears, or crankshaft due to erosion or abrasive type of wear (Flitch, 2011). Tin wear is related to bearing wear and solder from the cooling system. Also, according to Flitch (2011) chromium points to engine ring or cylinder wear. Copper particulates are a result of wrist pin bushing, bearing, and thrust washer (Flitch, 2011) wear. Lead particulates are related with engine bushings and bearings wear. Aluminum particulates are related to piston, bearings, bushings, and ground contamination.

Table 2.3: Wear metals results

	Fe	Cr	Cu	Pb	Al	Sn
Normal	65.67%	69.49%	77.16%	92.99%	93.25%	57.27%
Abnormal	34.33%	30.51%	22.84%	7.01%	6.75%	42.73%

Table 2.4 shows the average levels of contaminants. The results point to the environment dirt contamination or cross system contamination such as coolant contamination. For instance, the presence of silicon is associated with dirt contamination or residue of manufacturing material such as silicone. Potassium is associated with coolant contamination as part of glycol. Sodium particles are associated with dirt contamination.

Table 2.4: Contaminants results

	Si	Na	K
Normal	67%	77%	62%
Abnormal	33%	23%	38%

Correlation coefficients were evaluated for metals and contaminants. The Equation 2.1 is the Person's Correlation Coefficient linear formula. It is noted where n is the number of pair scores or the number of oil samples results, x and y are the results of wear metals. The following statistical equation 2.1 determines the strength relationship between two variables.

Equation 2.1: Person's Correlation Coefficient linear formula

$$r = \frac{n\,(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}$$

A cross comparison of each sample result was conducted with two variables at a time on the average oil analysis. Table 2.5 shows the r-values when correlating two variables. For instance, Fe and Cr, the r-value is 0.47. For the purpose of this study, values over 0.70 represent a very strong positive correlation, 0.40 to 0.69 a strong positive correlation, 0.30 to 0.39 a moderate positive correlation, 0.20 to 0.29 a week positive relationship, and 0.01 to 0.19 negligible relationship. Negative values covey inverse relationships. The most significant relationships in Table 2.5 are identified in red. It is important to note the level of relationship exposed between aluminum, silicon, and sodium. All three share a characteristic of dirt contamination.

Table 2.5: Correlation analysis of particles

	Fe	Cr	Pb	Cu	Sn	Al	Ni	Si	Na	Fuel	Soot	Water	TBN
Fe	N/A	0.47	0.21	0.22	0.44	0.23	0.40	0.24	0.15	0.23	-0.05	0.23	0.27
Cr	N/A	N/A	0.60	0.40	0.43	0.64	0.03	0.48	0.44	0.10	-0.07	0.09	0.12
Pb	N/A	N/A	N/A	0.42	0.43	0.80	0.02	0.51	0.54	-0.03	-0.17	0.00	0.08
Cu	N/A	N/A	N/A	N/A	0.32	0.44	0.07	0.41	0.39	0.06	-0.06	0.00	0.01
Sn	N/A	N/A	N/A	N/A	N/A	0.43	0.06	0.36	0.31	0.07	-0.04	0.10	0.09
Al	N/A	N/A	N/A	N/A	N/A	N/A	0.05	0.58	0.58	0.00	-0.18	-0.04	0.09
Ni	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.00	-0.01	0.12	-0.06	0.00	0.23
Si	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.47	-0.02	-0.15	-0.01	0.04
Na	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.03	-0.17	-0.03	0.05
Fuel	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.08	0.36	-0.10
Soot	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.12	-0.42
Water	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-0.04
TBN	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

2.8. Conclusion

The Latin America region has a high potential to build and grow its infrastructure. The region is a global source of raw material such as copper and iron. Thus, Latin America is an important territory for construction machine manufacturers. However, due to testing cost and logistical complexity, machine are not tested locally; rather, it is assumed that system performance in the manufacturer's home market is applicable in Latin America. Furthermore, testing construction equipment in Latin America is very complex and costly. There are 33 countries in the Latin America region with different geographies, climates, fuel standards, and maintenance practices.

Latin America oil samples showed significantly higher abnormal oil analysis readings compared with the United States. Countries with the highest elevation presented significant more abnormal results than the countries with low elevations. For instance, Peru, Ecuador and Colombia had more abnormal oil readings than Mexico, Honduras, and Dominican Republic. High altitude increases particulate matter. Particulate matter increases engine oil viscosity, leading to low oil flow rate resulting in low lubricity. Low lubricity increases engine component wear and reduces engine cooling capability.

Also, by analyzing and comparing oil analysis chemistry, there is the evidence of environmental (dirt or cross-system) contamination. Because the DTCs associated with the cooling system are very prevalent in the Latin America region, particles from the cooler and water pump might be leading to accelerated wear in internal engine components such as engine bearings. When combined with the high inverse correlation of water and TBN, the results indicate that contamination of a failing cooling system could be a significant contributor to oil degradation. Furthermore, the high correlation of sodium, silicone, and aluminum indicates dirt environmental contamination. Because there are high numbers DTCs related with air intake restriction, dust is likely passing into engine combustion chamber leading to excessive wear of engine pistons and rings. Thus, to improve engine durability, manufacturers should implement design changes in the machine conceptual design and details development phases of the system engineering process. For instance, a fuel filtering mechanism should be installed in the fuel tank. Additionally, a water-in-fuel sensor programing should inform the operator to stop the machine and replace the fuel. An engine oil sensor to measure levels of iron wear should also be added.

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CHAPTER 3: SYSTEM ENGINEERING RISK ANALYSIS OF DIESEL ENGINE DURABILITY IN LATIN AMERICA[2]

3.1. Introduction

Engine durability risk analysis is a critical part of engine development, but oil analysis (a leading metric in determining engine durability) has not been explored for construction equipment operating in Latin America. Oil analysis makes it possible to determine the role the operating environment and diesel fuel quality play in engine oil contamination, a key factor in the reduction of engine durability in Latin America. During the system life cycle, the system needs analysis is the first step in the concept development phase (Kossiakoff et al., 2011). When determining system needs, system engineers expect the implementation of system operational deficiencies and system technology improvements. Kossiakoff et al. (2011) state, “the output of this phase is a description of the capabilities and operational effectiveness needed.” During this first step of the concept developmental phase, heavy equipment manufacturers establish engine durability expectations. However, there are unknown risks related to operating diesel engine equipment outside of the United States for example, Latin America. Testing the engines of construction equipment for all foreign markets is cost-prohibitive. Consequently, manufacturers perform system needs analyses, identify system requirements, and test their equipment in established high-volume markets. Traditionally, product development programs concentrate on previously accumulated knowledge and experience regarding machine operation, laboratory subcomponent testing, and computer modeling to bring products to market.

The lack of testing and the inability or failure to identify system risks in foreign-market applications has led to premature system failure. To bridge the knowledge gap of engine operation durability in the Latin America region, this paper addresses the following research questions: (1) What are risks leading to reduced engine durability in Latin America? (2) How can the risk drivers be quantified? The research is based on

[2] Paper published in the Journal of System Engineering.

engine oil analysis as a leading indicator for engine durability. The risk and risk drivers identified by answering these research questions will decrease system development time as they are included in the system needs analysis and the cause-effect risk modeling. During the system operation and support phases of the system life cycle, system engineers will understand the risks affecting the durability of construction equipment diesel engines operating in Latin America and will be able to implement mitigation strategies to meet customer-user durability expectations and will reduce warranty costs.

The purpose of this research is to determine and quantify the fuel and environmental risks for construction machines powered by diesel engines operating in Latin America. The research academically addresses motivation, current literature review, and engine studied. Furthermore, the paper defines the research method composed of the following steps: (1) it identifies all possible root-causes leading to engine oil abnormalities, (2) filters the root-causes, (3) statistically compares the root-causes with oil analysis results to identify cause-effect relationships, and (4) applies the Standard Risk Model to determine the system expected loss.

3.2. Motivation

Kossiakoff et al. (2011) states that risk assessment should be performed at each phase of the system engineering life cycle, including the prototype development and development testing phases. However, it is cost-prohibitive to perform such testing for a product in each geography in which it will operate. The construction equipment market in Latin America (excluding Brazil) consisted of approximately 14,000 units between 2007 and 2013 (Construction Machine Import Data, 2017). The scope of this research includes the following Latin America countries: Bolivia, Colombia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Honduras, Mexico, Paraguay, Peru, and Uruguay. These countries represent 70% of the units operating in Latin America. Thus, failures experienced in these countries provide a significant statistical representation of failures throughout the Latin America geographies. From the customer's (and user's) perspective, premature engine failure results in significant financial cost and loss due to: (1) cost to repair equipment, (2) costs associated with idle work crews and operators, (3) contractual delay penalties, and (4) the potential loss of construction projects. From the manufacturers' perspective, premature engine failure increases the cost of doing business due to increased warranty claims and potential loss of equipment sales.

Backhoes and excavators represent the highest number of construction units in Latin America. Based on the authors' work, during the period between 2010 to 2015, a high percentage of diesel engines employed in backhoes and excavators operating in Latin America failed prematurely. Field maintenance and failure data indicate that engine oil viscosity increased, preventing the oil to perform its primary functions of lubrication and cooling. Figure 3.1 shows an engine oil pan of a 200DLC John Deere excavator with 200 hours of operation in Colombia. The image shows oil thickening and sludge accumulation that led to catastrophic engine failure. This type of failure is avoided by knowing the risk drivers common to the region in which the equipment is operating. The risk drivers are identified using oil sample analysis. The analysis of 7,561 engine oil samples from the period of 2010 and 2015 determined that 63% of the excavators and 59% of the backhoes yielded abnormal results. The oil sample analysis indicates that these units have a greater level of risk of engine failure compared to bulldozers, loaders, and graders, whose abnormal result rates are 34%, 31%, and 16%, respectfully.

Figure 3.1: John Deere 200D excavator engine oil pan

3.3. Literature Review

Engine durability is defined by Xin (2011) as an attribute of engine endurance. Citing the Advanced Product Quality manual developed by Chrysler Corporation, Ford Motor Company, and General Motors (SAE J1739), Xin states that engine durability is defined as "the probability that an item will continue to function at customer expectation levels, for the useful life without requiring overhaul or rebuild due to wear-out" (Xin, 2011, p.42). Southwest Research Institute (U.SA.) is one of the leading authorities in engine testing. This organization provides independent laboratory testing, including "16 flexible and well-equipped test cells that evaluate a wide spectrum" (Engine Durability and Reliability Testing, n.d.) to manufacturers such as Cummins, John Deere, and Caterpillar (Diesel Engine Lubrication Testing, n.d.) on various aspects of Latin America operations such as altitude simulation. However, these tests isolate a specific risk factor of engine operation. When a machine is operating in the field, a combination of risk factors interacts simultaneously with the engine.

Academic Search Premier, Web of Science, Southwest Research Institute Technical Publications, and Google Scholar databases were utilized to determine the availability and quality of peer-reviewed literature related to the durability of diesel engines operating in Latin America geographies. It was determined that limited peer-reviewed research exists related to the risks that affect the durability of diesel engines operating in Latin America. Thus, the focus of this research was broadened to include academic information related to key risk drivers, including: diesel fuel quality, biodiesel, sulfur, altitude, and humidity.

Diesel fuel quality: The quality of diesel fuel is a critical risk factor throughout Latin America geographies. While no specific research addresses the quality of diesel fuel found in the 11 Latin America countries targeted in this research, several peer-reviewed papers describe the characteristics of fuel blending, an important factor when dealing with diesel fuel quality. For instance, while evaluating the use of alcohol-blends with biodiesel, Peer et al. (2017) determined that mixing alcohol, biodiesel, and fossil diesel fuels is common in developing Latin American countries to deal with diesel fuel shortages. Research indicates that in various Latin American countries, ethanol from sugar cane and corn is often mixed with biodiesel sourced from different feed stocks such as palm and soybeans (Ludena, Razo, and Saucedo, 2007). Fuel mixing adversely affects storage oxidation stability, an important criterion in determining the quality of biodiesel (Peer et al., 2017). Peer et al. (2017) determined that a mixture of over 15% of pentanol in biodiesel blends showed a decline in storage ability as "more concentration of pentanol weakens the hydrophilic and hydrophobic clusters formed between pentanol/diesel/biodiesel compounds" (Peer et al., 2017, p.455). Research conducted by Bermudez et al. (2016) determined "how much HDCD could be blended before diesel engine operation becomes problematic." This research concluded that the increase of HDCD blended higher than 30% led to considerably longer engine start times (Bermudez et al, 2016).

Biofuel sources: A key issue is that Latin America biofuel is produced from a wide variety of sources, depending on the country or geography. Ludena, Razo, Saucedo (2007) state that biofuels in Latin America are often produced from soybeans, sugar cane, palm oil, corn, and cassava roots. Soybean-based biodiesel is common in Argentina, Brazil, and Uruguay (Timilsina and Shrestha, 2010). Biodiesel produced from palm oil is common in Colombia. This is problematic for diesel engine design because each biodiesel fuel source has different properties, such as kinematics viscosity, that affect engine durability. Singh and Signgh (2010) described the different sources of biodiesel and their respective operating characteristics. For instance, palm oil exhibits significantly lower combustion values compared with conventional diesel fuel: 32.4 MJ/kg versus 43.8 MJ/kg (Singh and Singh, 2010). Also, soybean and palm biodiesels exhibit significantly higher flash points compared with conventional diesel fuel: soybean 178°C, palm 164°C, and diesel 78°C (Singh and Singh, 2010). Unfortunately, the relationship of biofuel sources and their adverse effect on diesel engines operating in Latin America is not commonly included in engine durability testing. For instance, biofuel sources correlated with environmental operating characteristics such as ambient temperature, humidity, and altitude applied to diesel engines have not been tested or determined.

Biodiesel degradation caused by long storage periods: Another important factor in diesel fuel quality is biodiesel fuel degradation caused by long storage periods. Linhares et al. (2017, p.130) state, "Biodiesel can be degraded easier and faster than petroleum diesel through oxidation during storage because of its low stability and therefore is considered more corrosive than petroleum diesel." Each biofuel formulation will provide a different shelf life and will perform differently in a diesel engine. Storage time and temperature affect the biofuel oxidative stability and viscosity. Amaral et al. (2016) studied total particulate matter (TPM) generated on B5 biodiesel, pure soybean biodiesel (B100), biodiesel with additives (B100 adt), and ethanol. The research determined that TPM was higher with B100 biodiesel than B5 and ethanol. Amaral et al. (2016, p.156) determined that, "the chemical nature of biodiesel, a mixture of unsaturated fatty acid, facilitates the oxidation processes" thus, leading to high levels of TPM. Also, Dos Reis Albuquerque (2009) suggests that factors such as temperature, air humidity, metals, and mixture of unsaturated fatty acids are drivers in the storage effects, leading to an acceleration of the diesel oxidation. Finally, Singh and Singh (2010) determined that the disadvantages of biodiesel are: (1) higher kinematic viscosity leading to poor atomization of fuel during injection, (2) higher NOx, (3) lower oxidation stability during storage, (4) hygroscopic when makes contact with humid air, (5) non-standardized production processes, and (6) the quality is highly dependent on the respective refinery and its infrastructure.

Sulfur content: The combination of biofuels and high sulfur diesel is a key risk factor. Linhares et al. (2017, p.130) state, "Despite the similarities and advantages between biodiesel and petroleum diesel, they possess significant chemical differences, which has raised concerns about material compatibility, especially with respect to their use in the automotive industry." When analyzing microbial growth in biodiesel in different parts per million (PPM) level of sulfur (Ultra High Sulfur Diesel UHSD <= 1800 PPM sulfur; High Sulfur Diesel HSD <= 500 PPM sulfur; Low Sulfur Diesel LSD <= 50 PPM sulfur and Ultra Low Sulfur Diesel ULSD <= 10 PPM sulfur), de Azambuja et al. (2017, p.343) state, "the greatest microbial biomass was formed in UHSD at all times and it was statistically significant compared to controls." Thus, the researchers determined that "at 40 days, the sulfur content in diesel fuel was directly proportional to biomass production" (Azambuja et al, 2017, p.343).

Effects caused by altitude: The effects of altitude on combustion is a risk factor that should be considered. Kan et al. (2017) determined that "altitude has a significant effect on combustion of heavy-duty diesel engines, especially during cold start." The authors evaluated heavy-duty diesel engines at several altitudes including 0, 1000, 3000, and 4000 meters above sea level. As altitude increased, engine combustion instability became more noticeable and engine start-up times increased. Also, Kan et al. (2017) determined that with increased altitude, "the cycle-to-cycle variation of the peak pressure and speed fluctuation increased during the idle, the ignition and CA50 were delayed and the combustion duration was shortened." In Colombia, where machine operators commonly run palm oil-based biodiesel, Benjumea, Agudelo, and Agudelo (2009) determined that when comparing palm biodiesel (B100) and conventional diesel fuel (B0) at altitudes of 500 and 2400 meters above sea level, palm biodiesel demonstrated the adverse effect of a shorter combustion duration. Also, the authors determined that altitude decreased fuel thermal efficiency and fuel consumption increased (Benjumea, Agudelo, and Agudelo, 2009). While testing the effect of altitude on engines operating in Chile, Lapuerta, Armas, Agudelo, and Sanchez (2006) determined that altitude considerably reduced engine performance in naturally aspirated engines (non-turbocharged engines) by modifying the thermodynamic cycle and increasing the generation of soot.

Water contamination**:** Water contamination in diesel fuel is common in Latin America. Li et al. (2017, p.313) stated, "Water and other water-based fuel impurities can cause fuel filter plugging, fuel starvation, damage of engine components, and promotion of microbiological growth." Regarding biofuels, de Azambuja et al. (2017) determined that the presence of water contributed to the growth of microbial such as Niastella, Acineto, Bacillus, Rhodotorula and Mycosphaerella. Also, Azambuja et al. (2017) determined that compared to ultra low sulfur diesel (ULSD) and high sulfur diesel (HSD), B100 (100% biodiesel) produced the highest level of microbial growth leading to corrosion of carbon steel (Azambuja et al, 2017).

3.4. Diesel Engines Studied

During the period of 2010 to 2015, Tier 3 engines deployed in Latin America increased. Tier 3 is a U.S. Environmental Protection Agency (EPA) engine classification that states the maximum levels of particulate matter, nitrogen oxides, hydrocarbons, and carbon monoxide an engine can emit (Understanding Emission Regulation, n.d.). Remarkably, most construction equipment sold in Latin America employed the same Tier 3 technologies adopted to meet emissions certification in the United States.

A John Deere 6068 Engine - 6.8 litres with six cylinders was used in the research of this paper. Several engine design changes were implemented to achieve Tier 3 EPA certification. When comparing the engines side-by-side and comparing the changes implemented from Tier 2 to Tier 3, the fixed geometry turbocharger was replaced by a variable geometry turbocharger. Also, the engine valve heads increased from 2-valves per cylinder to 4-valves. An exhaust gas recirculation (EGR) valve was added. The air intake manifold design was redesigned. An EGR cooler was added; a portion of the engine exhaust gases are cooled and routed back to the engine intake manifold. These engines are the primary focus of this paper.

Maintaining engine lubrication uniform across different operational environments was a challenge as the engine design changed. According to Southwest Research Institute (Diesel Engine Lubricant Testing, n.d.), lubricants and lubrication procedures are continuously evolving as a result of diesel engine design changes such as "high exhaust gas recirculation (EGR) and exhaust after-treatment systems along with improved combustion systems and higher cylinder pressures, place increased demands on crankcase lubricants."

3.5. Research Method

According to the Rebovich and White, risks are defined in terms of probability ranging from 0 to less than 1 related to the undesired event and the created impact that it might occur (Rebovich and White, 2011). In the engineering discipline, Modarres, Kaminsky, Krivtsov, (2017, p.13) state that risk can be "viewed both quantitatively and qualitatively." Kossiakoff et al. (2011) further defines risk in system engineering as "the degree of the likelihood that the system will fail to meets its design goals." In its most basic concept, the process of risk analysis is composed of risk identification and risk assessment (Kossiakoff et al., 2011). A multi-step research method process was created for this paper. The risk method utilized for this paper consists of the following steps: (1) identify possible root-causes leading to engine oil abnormalities, (2) filtering the root-causes, (3) statistically compare the root-causes with oil analysis results to find cause-effect relationships, and (4) apply the Standard Risk Model to determine the system expected loss.

3.5.1. Root-Cause Analysis

There are several techniques available to determine risk. The most commonly industry used techniques include: (1) work groups, (2) risk lists from lessons learned, (3) interviews, (4) brainstorming, (5) experimental and documented knowledge and data, (6) surveys, (7) output from risk-oriented analysis, (8) historical information, (9) engineering templates, (10) critical paths, (11) Delphi technique, (12) cause and effect diagram, and (13) decision tree analysis. This paper applies a combination of Experimental and Documented Knowledge and Data (EDKD) and Output from Risk-Oriented Analysis (OROA) methodologies. The EDKD addresses the "the collection of information or data that has been documented about a particular subject" (Sweeting, 2017) and OROA is a "top-down analysis approach that attempts to determine what events, conditions, or faults could lead to a specific top-level risk event" (Mahfuz, 2016, p.176).

When applying the EDKD and OROA, the first step is to determine the root-causes leading to engine function loss. According to Ayyub (2003, p.60), "causes of failure are sources of process variations that cause the failure mode to occur." For instance, poor combustion is a common cause of engine failure. It leads to soot generation, corrosion of fuel injectors, and plug fuel filtration systems. Thus, it is essential to mathematically define the causes and effects of poor combustion. Air-to-fuel ratio is the first and most basic factor to be analyzed. Jääskeläinen and Khair (2016) state that the primary factors for an efficient diesel combustion process are the inducted charged air and injected fuel atomization. The inducted charge air is affected by the engine external environment such as altitude, humidity, and temperature (Jääskeläinen and Khair, 2016). The injected fuel atomization is affected by diesel chemical characteristics (Jääskeläinen and Khair, 2016). Gupta (2013, p.27) states, "when a certain mass of fuel is introduced into the engine cylinder, the combustion of fuel takes place in the presence of air. The rate of heat energy release which is contained in the fuel and may liberate during the combustion process may be termed as fuel power." Gupta (2013, p.27) defines the Fuel Power equation as the following:

Equation 3.1: Fuel power equation

$$\text{Fuel power} = m_f \times \text{CV (kW)}$$

Where:

m_f = mass flow rate of fuel (kg/s)

CV = calorific value of heating value of fuel (kJ/kg)

Besides the fuel, the operating environment of air, humidity, and temperature greatly influence engine combustion and its adverse effects. Known as combustion efficiency, Gupta (2013, p.30) states, "all fuel molecules may not find oxygen molecules, or the local temperature may not favor the reaction." Gupta (2013, p.27) defines the Combustion Efficiency equation as following the:

Equation 3.2: Combustion efficiency equation

$$n_{\boldsymbol{c}} = \frac{Q_s}{m_f \times \text{CV}}$$

Where:

Q_s = heat supply to the gas per unit time

An imbalance of mass flow rate of fuel (mf) and heating value of fuel (CV) causes poor combustion. Thus, the first step in the methodology of this paper is to identify the possible leading factors of engine oil degradation. Based on interviews of machine owners in Latin America, the primary users' defined top-level groups leading to abnormalities in oil samples are classified under the following categories: the fuel utilized, operating environment, maintenance practices, user operation practices, and the effects caused by the engine software and hardware changes when transitioning from Tier 2 to Tier 3. The top-level groups are shown in Figure 3.2.

Kossiakoff et al. (2011) suggest four potential areas for system performance risk: (1) failure due to deviation of component tolerances, (2) component material variation, (3) component durability in extreme or untested environment conditions, and (4) risks associated with component interfaces. While, this paper recognizes all four areas of concern in the root-cause analysis (refer to Figure 3.2), it focuses on the analysis of two groups leading to engine oil abnormalities: fuel and environmental conditions. For instance, after reviewing local fuel characteristics in the focus countries, it was determined that fuel quality is affected by its biodiesel content, diesel sulfur content, and storage duration. Environment conditions that affect engine performance include: altitude, humidity, and the ambient temperature. Figure 3.2 displays the different root-causes leading to engine oil abnormalities in Latin America. Marked in red are the major group focus of this paper.

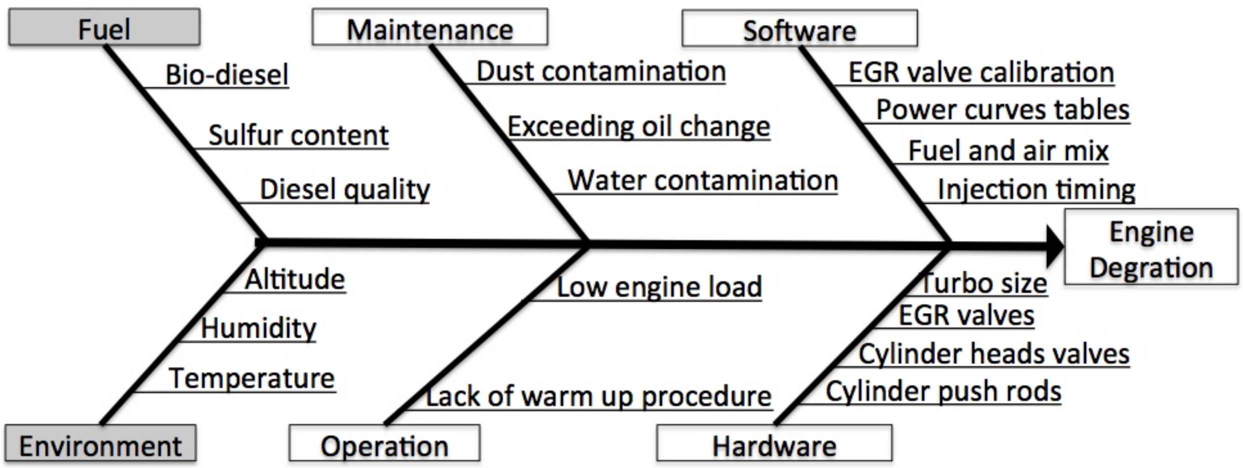

Figure 3.2: Possible causes for engine degradation in Latin America

3.5.2. System Engineering Standard Risk Model

This research employed the System Engineering Standard Risk Model to evaluate the risk in the Ishikawa Diagram, Figure 3.2. The Standard Risk Model provides the methodology to quantify, qualify, calculate, and graph each risk probability of impact, probability of event, and the total expected system loss. Thus, it provides a systematic approach to address risk. According to Smith and Merritt (2002), the Standard Risk Model addresses two important objectives or outcomes: (1) it quantifies the magnitude of a risk so it can be compared and managed, and (2) since it points to the risk root-cause, risks can be mitigated, avoided, or eliminated. Furthermore, the Standard Risk Model was chosen because: (1) the output of the model is verifiable, (2) independent researchers can develop similar outcomes when using similar input records, (3) it supports cause and effect relationships, and (4) the model is universally accepted (Smith and Merritt, 2002). Figure 3.3 represents the Standard Risk Model applied in this paper.

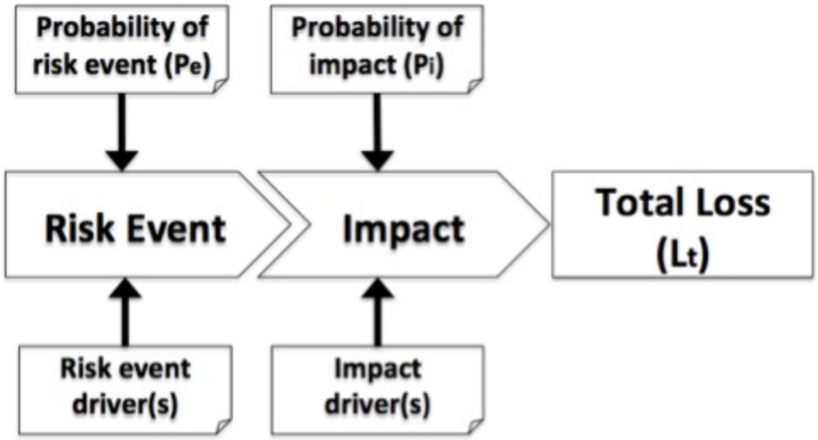

Figure 3.3: Standard risk model

According to Kossiakoff et al. (2011) system engineering makes common use of risk assessment tools to determine the source, probability, and criticality of risks. The following is an application of this definition to the research, as provided by Smith and Merritt (2002):

1) The risk event is the action that prompts an engine system loss.
    a. The risk event drivers are the inherent factors of the engine environment or fuel, leading to the conclusion that a loss of engine function might be realized.
    b. The probability of the risk event is the statistical possibility that the risk might be realized.
2) The impact is the potential system operational loss that could result if the risk might be realized.
    a. The impact drivers that are inherent factors in the fuel or operational environment leading one to believe that an impact might be realized.
    b. The probability of an impact is the statistical possibility that it will happen if the event realizes.
3) The total loss is the magnitude of machine operational actual loss value accumulated when a risk event realized.

When analyzing each risk, the following calculation in Figure 3.4 is employed:

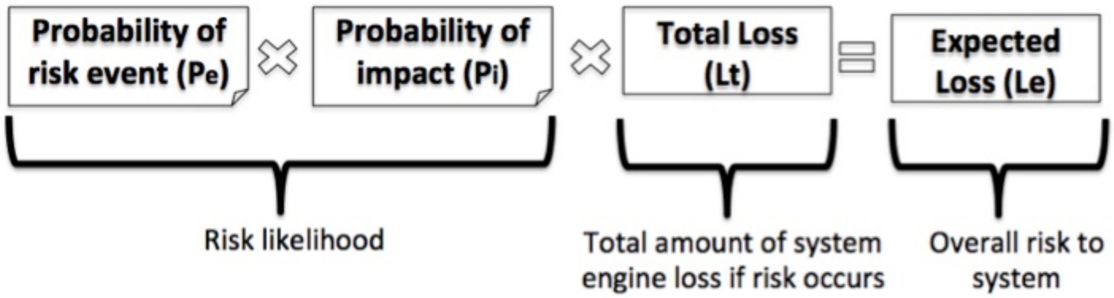

Figure 3.4: Risk calculation

3.6. Results

The risk qualification process followed in this paper is to (1) identify the risks, (2) analyze the risks, (3) prioritize the risks, and (4) map the risks. The following sections describe each of theses process steps. Also, statistical analysis will determine the relationship between a risk and engine durability in construction equipment operating in Latin America.

3.6.1. Risk Identification

The first step is risk identification. The risks were first cataloged under two groups: fuel and environment. The research classified the following risks within the fuel group: biodiesel, sulfur content, and diesel quality. Also, the research determined the following risks under the environmental group: altitude, humidity, and temperature. Based on these six risks, this paper identifies the following risk statements:

- Given the use of biodiesel, it is possible that diesel fuel degradation can occur, leading engine oil oxidation.
- Given the presence of high sulfur in fuel, it is possible that low mass flow rate of fuel can occur, leading to the increase of engine oil viscosity.
- Given the use of poor quality diesel fuel, it is possible that low heating value of fuel (CV) can occur, leading fuel and engine oil mixing.
- Given the machine operation at high altitude, it is possible that low heat supply to the gas per unit time levels can occur, leading to engine soot generation.

- Given the machine operation in high humidity environments, it is that possible internal fuel tank condensation contamination can occur, leading to high levels of water-in-fuel in oil analysis.
- Given the machine operation in high temperature, it is possible that engine overheating can occur, leading to engine oil oxidation.

The previously mentioned risks are intermediate risks that will be traced between the problematic condition (e.g., increased engine oil viscosity) and the resulting cost effect. Ultimately, the total expected cost of each risk is the most important factor for the user when considering engine durability. The cost effect of the risk is determined as the last step of the risk analysis and is summarized in Table 3.

3.6.2. Risk Analysis

Blau (2016) suggests to approach risk analysis by first implementing a consistent terminology to catalog the risks drivers leading to engine wear. The benefits determined are: improved definition of durability problems, consistent documentation of engine wear failures, aid in the compilation of root cause databases, and filter problem resolution strategies related to engine wear (Blau, 2016, p.31). Thus, for the second step, risk analysis, a database containing 7,561 engine oil sample analysis results is used to correlate the possible risk factors with the abnormal results. The oil analysis results were obtained from the previously stated target countries. The risk levels (biodiesel, sulfur, diesel quality, altitude, humidity, and ambient temperature) were applied to the oil sample database for each engine oil sample on a country-level basis. For instance, the percentage of biodiesel of each country was researched and added to the database. Sulfur parts per million (PPM) was determined for each country based on the United Nations Environment Programme (UNEP) diesel sulfur PPM content for Latin America. By interviewing John Deere dealer service managers in each target country, a user-defined diesel quality level was determined. Average altitude, humidity, and ambient temperature of operating location were determined by telematics geo-location data obtained from John Deere construction equipment operating in each target country.

Oil analyses are obtained from OSA3 microlabs in the target countries. The oil lab is equipped with atomic emission spectroscopy, infrared spectroscopy, viscometer, and a laser particle counter. Abnormal engine oil sample results are quantified based on engine oil contaminates and engine internal wear metals, engine oil viscosity, and engine oil chemistry variation. The ASTM D7417-17 (2017) is used as the standard method of oil analysis and ASTM D7720-11 (2011) is used as the standard to determine the median, average, and standard deviation. Thus, by qualifying each oil sample, abnormal results can correlate with each risk qualifier. Table 3.1 shows a qualification and quantification of each risk.

Table 3.1: Summary of magnitude and scope of the data risk qualifier

	Sulfur (PPM)	Diesel Quality for Off-Road Equipment	Engine Operating Altitude (meter above sea level)	Average annual Precipitation (millimeters)	Average operating annual temperature (Celsius)	Biodiesel Content
Bolivia	3714	Low	> 2500	851.8	17.2	B0
Colombia	1514	Mid	1000-2500	1781.8	23.4	B20
Costa Rica	179	High	< 1000	1529	24.7	B20
Dominican Republic	7500	Low	< 1000	1363.4	24.8	B0
Ecuador	6143	Low	> 2500	1034.9	19.5	B0
Guatemala	5000	Low	1000-2500	1585.7	20.7	B0
Honduras	5000	High	< 1000	1861.6	25.5	B0
Mexico	500	Mid	1000-2500	943.6	20.6	B0
Paraguay	3829	Low	< 1000	1575.6	22.3	B5
Peru	5000	Mid	> 2500	621.5	15.8	B20
Uruguay	5443	Low	< 1000	1132.6	16.7	B2

3.6.2.1. Fuel factors as leading causes of engine function loss

1) The research determines that the mixture of biodiesel in several target countries was high and production of biodiesel might not meet international standards. Furthermore, there are different sources of biodiesel. Figure 3.5 shows the abnormal oil sample results for different biodiesel blends. The y-axis represents the percentage of engine oil results with an abnormal reading. The x-axis represents the biodiesel blends where B2 means biodiesel with 2%, B5 represents 5%, and B20 represents a 20% blend of biodiesel mixture to fossil diesel fuel. When comparing the percentage of abnormal engine oil sample results and the biodiesel implementation in Latin America, it is evident in Figure 3.5 that there is a direct correlation between an increase in the percentage of biodiesel mixture and the increase in the percentage of abnormal oil sample results. The research found that six percent of abnormal oil samples are related to B2 biodiesel levels (2%

of biodiesel mix with fossil diesel), 14% to B5 biodiesel levels, and 50% to B20 biodiesel levels. Given the use of biodiesel, it is possible that diesel fuel degradation can occur as the percentage of bio-diesel increase, leading engine oil oxidation.

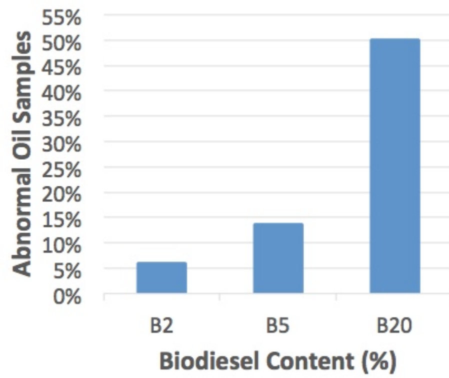

Figure 3.5: Percentage of biodiesel and abnormal results

2) Sulfur content in diesel fuel exceeding the manufacturer's recommendation leads to a high percentage of abnormal engine oil readings. Since 2011, governments in Latin America have been reducing the sulfur content (measured in parts per million - PPM) in fossil diesel fuel (unep.org). Figure 3.6 depicts a comparison of sulfur PPM levels and the respective impact on oil sample readings. The data indicates that there is an important decrease in the number of abnormal oil results as sulfur PPM levels decrease. Figure 3.6 shows that 84% of the abnormal engine oil results are related to sulfur content in fuel diesel over 4,000 PPM, 10% related to PPMs levels between 1,000 to 4,000, and 6% related to 50 to 1,000 sulfur PPM. Given the presence of high sulfur in fuel, it is possible that low mass flow rate of fuel can occur as soot enters the engine carter, leading to the increase of engine oil viscosity.

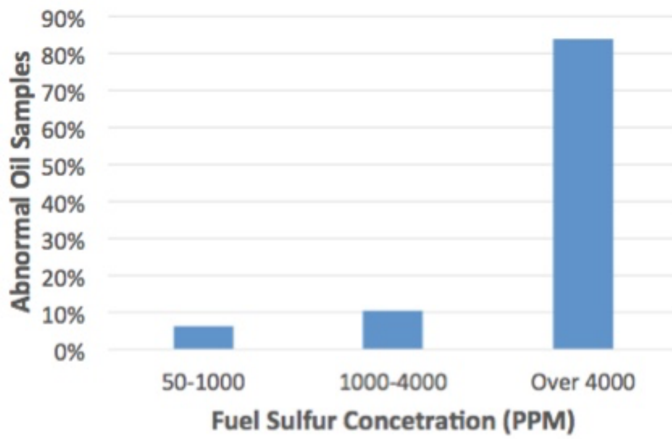

Figure 3.6: Abnormal oil samples readings as a result of change of sulfur PPM levels on diesel

3) Diesel fuel quality is an important driver that leads to engine function loss. It is common in Latin America to encounter diesel fuel that includes other chemicals or water. Furthermore, diesel fuel storage best practices are not universally followed in Latin America. For this research, the fuel quality is user defined. Low fuel quality is defined by a combination of sulfur PPM levels, quality of the fuel source, and user defined fuel storage practices. The user defined fuel qualification scores ranged as follows: 1 to 2 for low quality, 3 to 4 for average quality, and 5 for high quality on their fuel storage practices. When comparing the fuel quality of each country, it was determined that countries with better in-market diesel quality (lower sulfur PPM levels, low biodiesel mix in fuel, and better customer fuel storage practices) had fewer abnormal oil sample results. Figure 3.7 shows that 11% of the abnormal oil samples are attributed to countries with high diesel quality, 27% are related to countries that had an average level of diesel fuel quality, and 62% are related to low quality diesel fuel. Given the use of poor quality diesel fuel, it is possible that low heating value of fuel (CV) can occur as diesel fuel can't burn completely, leading fuel and engine oil mixing.

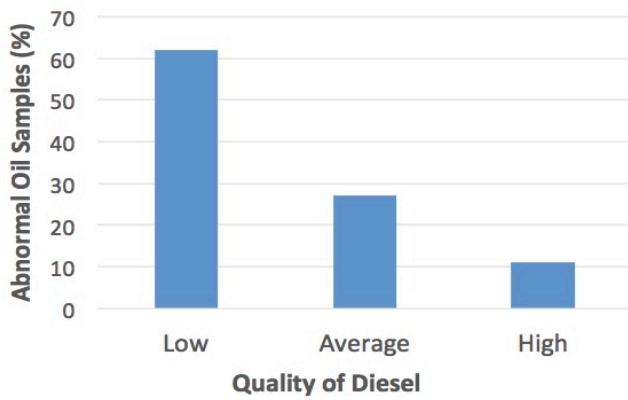

Figure 3.7: Quality of diesel versus abnormal oil samples

3.6.2.2. Environment factors as leading causes of engine function loss

The second group of risks factors leading to engine function loss is related to environmental factors. Under this group, the most prevalent environmental condition risk factors in Latin America are altitude, humidity, and operating temperature.

1) The impact of engine operating altitude is the first variable analyzed. Locations were separated in three independent data subset. As depicted in Figure 3.8, 36% of abnormal engine oil results relate to operational elevations less than 1000 meters above sea level (MSL). In comparison, for locations between 1000 and 2500 MSL, 40% of oils samples were determined as abnormal. For locations with over 2500 MSL, 52% of the sub-data set showed abnormal oil sample results. Given the machine operation at high altitude, it is possible that low heat supply to the gas per unit time levels can occur, leading to engine soot generation.

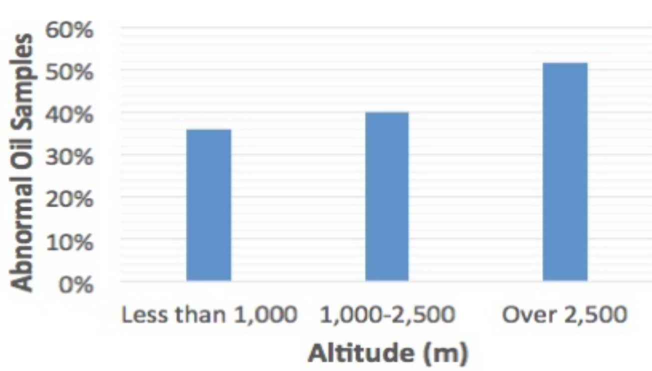

Figure 3.8: Abnormal oil results by altitude

2) Construction equipment operating in the Latin America region are exposed to a widely variable levels of humidity. Humidity leads to the contamination of diesel fuel resulting in decreased combustion efficiency

and fuel power (see Equation 2: Combustion Efficiency equation). Table 3.1 indicates the average annual precipitation (millimeters) per country. A statistical correlation was accomplished by comparing the geo-location of the construction equipment with the average annual precipitation of that region. Low humidity operating conditions are areas below 893 mm of precipitation. Areas from 894 mm to 1298 mm are considered average humidity. High humidity are areas with over 1299 mm of annual precipitation. The data in Figure 3.9 indicates that 43% of abnormal oil results relate to countries with higher levels of humidity, 33% with average levels of humidity, and 24% with lower levels of humidity. The high correlation between abnormal oil samples indicates that humidity is a risk factor leading to oil degradation. Given the machine operation in high humidity environments, it is possible that internal fuel tank condensation contamination can occur, leading to high levels of water-in-fuel in oil analysis. Figure 3.9 shows the relationship of precipitation and abnormal oil samples.

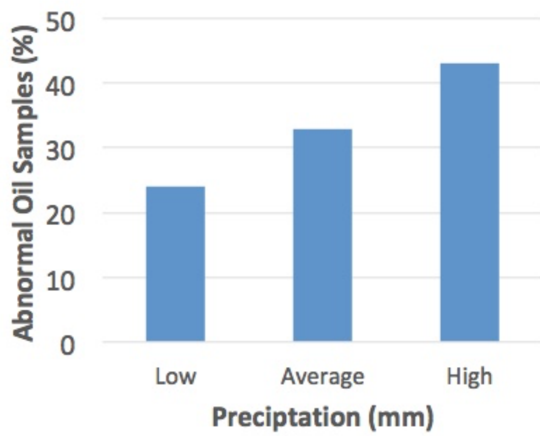

Figure 3.9: Abnormal oil Results by country humidity level

3) The final risk analyzed was the yearly average ambient operating temperature levels of each region and the impact they have on abnormal oil results. Figure 10 shows the relationship between engine operating temperature and abnormal oil samples results. First, the research determined the average operating temperature for each country. Secondly, the research determined that the operating mean temperature was 21°C. The ambient operating temperature of countries with abnormal oil sample results were qualified as follows: one standard deviation falls between 18°C and 24°C, and temperatures below 18°C and over 24°C falls over two standard deviations. Each country in these temperature rages were independently grouped,

thus each column in Figure 10 is an independent data subset. When analyzing the abnormal oil sample results with the specific operating environmental data temperature range of each independent subset group locations, it is determined that 55% of the abnormal oil results are related to locations over 24°C. In comparison, 49% of abnormal oil samples were related to locations from 18°C to 24°C. Also, locations with temperature below 18°C showed 32% abnormal oil sample. Given the machine operation in high temperature, it is possible that engine overheating can occur, leading to engine oil oxidation. However, the research indicates that temperature is not a critical risk driver.

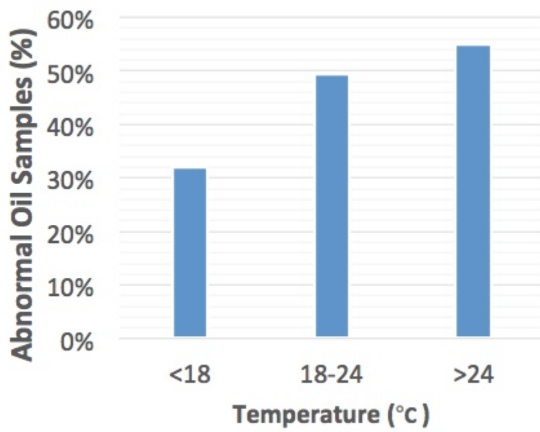

Figure 3.10: Abnormal oil by regional operating temperature

3.6.3. Risk Prioritization

The risk prioritization step identifies the most critical risk factor affecting system loss. Smith and Merritt (2002) suggest that the expected loss is the most important gauge for selecting or disregarding a risk because it determines the expected risk damage. Risk prioritization calculations are used to create the risk map and serve as input for creating the Total Cost Models for Expected Risk.

Risk prioritization is composed of a multi-step process. First, each risk is qualified in the oil sample database for each country based on interviews with John Deere dealership service managers, in-country diesel engine technical data, sulfur content history from the United Nations Environment Programme (unep.org), local operating temperature information, and altitude information based on machine geo-location data. Then, the data is correlated with abnormal oil sample readings. Probabilities of risk events are based on the identified highest percentages of abnormal oil analyses. Probabilities of risk impact are representations of the percentage of countries that display a relationship of risks and abnormal engine oil analysis results. Total system operation losses are based on the expected hourly repair rates or the loss of productivity caused by machine downtime.

The expected system loss formula in Figure 3.4 (Risk Calculation) is applied to Table 3.2 to determine the risks with the greatest impact affecting diesel engine durability of construction equipment operating in Latin America. The probability of risk event (Pe) is based on the determined highest percentages of abnormal oil analysis results.

- The probability of risk impact (Pi) of sulfur is based on the percentage of countries with high levels of sulfur content in abnormal oil analysis results. For instance, according to Table 3.1, there are six countries with sulfur content over 4000 PPM; thus, the calculation is 6 divided by 11 countries, 0.55.
- The probability of risk impact of diesel fuel quality is based on abnormal oil analysis results from countries with low diesel fuel quality.
- The probability of risk impact of humidity is based on abnormal oil analysis results from countries with high humidity levels.
- The probability of risk impact of biodiesel is based on abnormal oil analysis results from countries with high biodiesel levels.
- The probability of impact of machine operating temperature is based on abnormal oil analysis results from countries with high ambient operating temperatures, average over 24C. According to Table 3.1, 3 out 11 countries fall in this category, 0.27.
- The probability of risk of impact of altitude is based on abnormal oil analysis results from countries with high altitude.

The total system operation loss (Lt) is based on the expected engine service labor time published in the John Deere Standard Service Time Guide. For instance, for removing sulfur contamination, the standard service labor time is 8 hours. After determining the probability of risk event (Pe) and the probability of risk impact (Pi) based on the engine oil laboratory results, the likelihoods are calculated by multiplying Pe by Pi. The final expected system losses are determined by multiplying risk likelihoods by total system operation losses. Risks with the highest expected system losses (Le) are deemed to be the most critical risks to be addressed. Smith and Merritt (2002) suggest that it is not completely possible to eliminate environmental risks. Furthermore, system engineering should avoid employing risk mitigation strategies leading to diminishing returns.

Table 3.2: Risk prioritization

Risk	Probability of Risk Event (Pe)	Probability of Risk Impact (Pi)	Likelihood (Pe x Pi)	Total system operation loss (Lt) in hours per day	Expected System loss (Pe x Pi x Pt = Le)
Sulfur	0.84	0.55	0.46	8	3.70
Diesel Quality	0.62	0.73	0.45	5	2.26
Humidity	0.43	0.45	0.19	4	0.77
Biodiesel	0.50	0.18	0.09	6	0.54
Temperature	0.48	0.27	0.15	1	0.15
Altitude	0.52	0.27	0.14	1	0.14

3.6.4. Risk Mapping

Once the risk prioritization calculations have concluded, the risk coordinates output is mapped. Smith and Merritt (2002) suggest that a benefit of risk mapping is that it balances prioritization by identifying the risk above and below the established threshold curve. Also, the risk map determines catastrophic risks that lead to total loss. These risks can be high value, but low likelihood (Smith and Merritt 2002, p.35). Figure 3.11 depicts the plotting of each risk likelihood for the diesel system engine loss and total system expected loss from Table 3.2, Risk Prioritization.

The Risk Mapping in Figure 3.11 shows that diesel fuel sulfur content and diesel fuel quality are the critical concerns that should be addressed as they are above the threshold curve. The risk threshold is determined by the expected hours of machine down-time for each risk factor. For instance, average cooling time for an overheated engine due high ambient temperature is 1 hour and 10 minutes (John Deere, 2010). This plot is based on the accepted maximum probability of risk event multiplied by the maximum probability risk impact and the total estimated system hourly loss for each identified risk. The logarithm function curve represents the user-defined maximum acceptable system loss in hours for a specific risk likelihood (Pe*Pi). For instance, users expect to spend less than one hour with an unavailable system due to low diesel fuel quality at a likelihood of 0.45. The threshold curve is a logarithmic curve determined by the formula y = -0.096 ln (x) + 0.2021.

Design and field engineers must address the risk factors. Engineers should produce action plans composed of risk avoidance, transfer, or redundancy for risks above the threshold line. For instance, engineers should produce a risk avoidance action to eliminate the exhaust gas recirculation system on engines operating in countries with high sulfur content in diesel fuel. For risks below the threshold line, Smith and Merritt (2002) suggest mitigation actions such as prevention and contingency planning as well as the creation of risk reserve funding. Furthermore, Kossiakoff et al. (2011) suggest that the risks below the curve are low risks. However, a performance correlation must be demonstrated and validated prior to determining whether the low risk should be managed as they could be critical to engine operation.

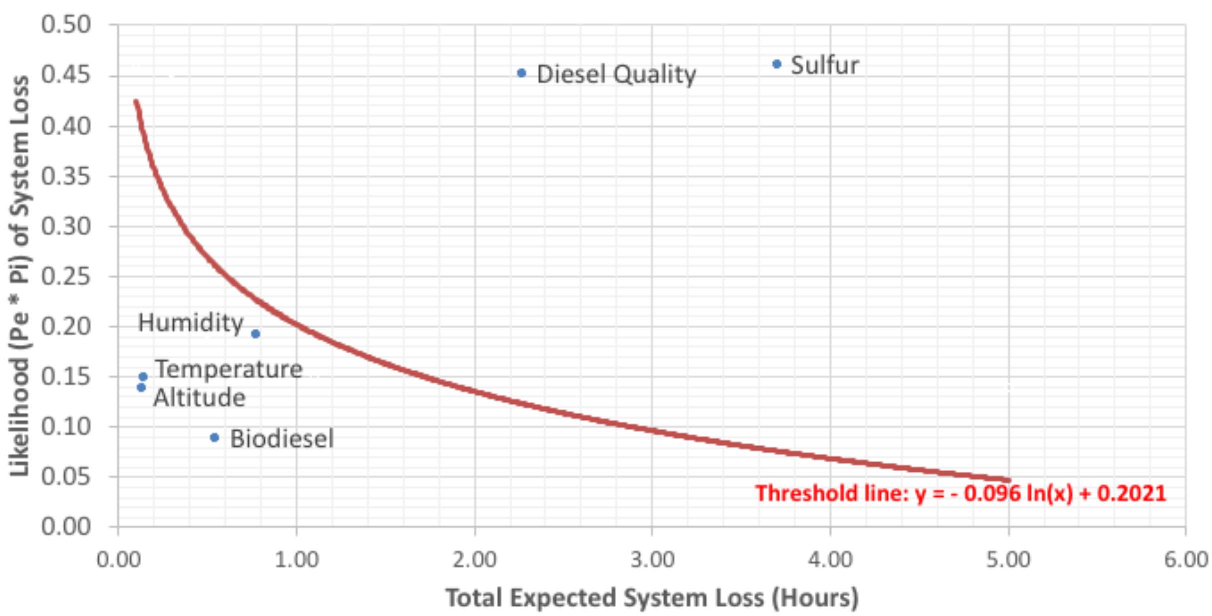

Figure 3.11: Risk mapping

3.6.5. Risk Total Cost Model

The risk total cost model is the last step in the risk analysis application for diesel engine durability of construction equipment operating in Latin America. The model recognizes three conditions for minimum risk (-50% of expected), expected risk, and worst risk (+50% of expected). The cost model is applied to the 20-ton excavator. 20-ton excavators (i.e., John Deere 200GLC or CAT 320D2) are the most popular machine size for large-scale construction projects (e.g., road construction) in Latin America. The formula from Table 3.3 was applied to draw the graphic shown in Figure 3.12. The average monthly rental rate, rental utilization rate, labor cost of repair, and repair hours were determined based on data obtained from John Deere dealers in the target Latin America countries. For instance, in Mexico a 200D John Deere excavator is rented at 161,200 Mexican Pesos per month (Tarifas Promedio de Rentas Mensuales, 2017). By converting the monthly rental rate to USD and dividing by 176 hours of utilization per month, the rate is $49.07 per hour. It is assumed that penalty cost per hours is the same as the average monthly rental rate as the contractors lose a similar rate in contract revenue. Total hours lost is the combination of repair hours and transportation hours to the service center.

Table 3.3: Total risk

Risk	Average Monthly Rental Rate (20 Ton Excavator)	x	Hours of utilization per month	+	Labor for Repair	x	Repair hours	+	Penalty Cost per hour	x	Total hour Lost	=	Total Cost Loss	x	Likelihood	Expected Total Loss
Sulfur	$ 49.09	x	176	+	$ 41.95	x	37	+	$49.09	x	45	=	$ 12,400	x	0.46	$ 5,729
Diesel Quality	$ 49.09	x	176	+	$ 41.95	x	37	+	$49.09	x	45	=	$ 12,400	x	0.45	$ 5,612
Humidity	$ 49.09	x	176	+	$ 41.95	x	3	+	$49.09	x	3	=	$ 8,912	x	0.19	$ 1,725
Biodiesel	$ 49.09	x	176	+	$ 41.95	x	3	+	$49.09	x	3	=	$ 8,912	x	0.09	$ 802
Temperature	$ 49.09	x	176	+	$ 41.95	x	1	+	$49.09	x	1	=	$ 8,730	x	0.15	$ 1,296
Altitude	$ 49.09	x	176	+	$ 41.95	x	1	+	$49.09	x	1	=	$ 8,730	x	0.14	$ 1,226

Kossiakoff et al. (2011) suggests that when dealing with systems durability, technical risk data should be compared with customer risk cost tolerances. These authors suggest to employ a total expected loss curve mathematical formula. This formula determines loss scenarios and sets limits to describe the acceptable levels of risk tolerance. To identify the total expected loss curve for a 20-ton excavator, logarithmic functions are employed for each of the three risk cost conditions from the expected cost in Table 3: minimum (-50%), expected (Last column of Table 3.3), and worst total system lost (+50%). As a result, Figure 3.12 was produced by plotting each risk likelihood from the Table 3.3 (y-axis) and the expected total loss (x-axis). While exponential, linear, or power formulas could be employed, Smith and

Merritt (2002, p.89) advocate that “a logarithmic scale on either or both axis may be better for showing areas of high total loss or low risk likelihood.” As a result, the minimum total cost formula is represented by y = 0.1981 ln (x) – 1.1242, the expected formula is y = 0.1981 ln (x) – 1.2616, and worst total system loss is y = 0.1981 ln (x) – 1.3419. These formulas are based on a worst cost scenario of +50%, best-case scenario of cost -50%, and expected cost for each risk at their respective likelihood.

Figure 3.12: Total cost models for expected risk

3.7. Conclusion

The durability data of diesel engines was gathered from periods of 2010 to 2015. During this period, manufacturers transitioned manufacturing production from Tier 2 to Tier 3 engines. Among the design changes implemented in the transition was the introduction of an exhaust recirculation system and changes to the intake valve design. A common evidence of diminishing engine durability was the increase of abnormal oil sample results. However, peer-reviewed literature does correlate oil sample analysis results with risk drivers for equipment operating in Latin America.

By using the System Engineering Standard Risk Analysis methodology, this paper identifies, quantifies, prioritizes, graphs, and cost associated with the risk drivers. The paper applies data collected from oil laboratories located in eleven Latin American countries. After analyzing 7,561 engine oil samples and correlating local operating conditions, root-causes were catalogued into two groups: fuel quality and environment. This paper recognizes an additional four groups (i.e., maintenance, software, operation, and hardware) that could be studied in future research.

The first group of root-causes relates to fuel factors. The research concludes that (1) countries with high biodiesel (B20) usage have a 50% incidence of abnormal oil samples, (2) 84% of the abnormal engine analysis oil samples relate to diesel fuel sulfur content, and (3) 62% of the abnormal engine oil samples relate to low quality diesel fuel.

The second group of root-causes relate to environmental factors. The research concludes that (1) 52% of the abnormal oil samples were associated with operating altitudes over 2,500 MSL, (2) 43% of the abnormal oil samples were associated with countries with high levels of humidity, and (3) 55% of the abnormal oil samples were associated with geographic locations over 24°C. The data shows that higher operating altitudes have a significant impact on abnormal engine oil analysis results. It leads to the creation of black smoke (particulate matter) by reducing the air-to-fuel mixture due to the lower atmospheric pressure found at higher altitudes.

The risk prioritization determined the following risk priorities: (1) sulfur (Le=3.70), (2) diesel quality (Le=2.26), (3) humidity (Le=0.77), biodiesel (Le=0.54), temperature (Le=0.15), and altitude (Le=0.14). After mapping each risk and determining the threshold formula ($y = -0.096 \ln (x) + 0.2021$), it was determined that the sulfur content in diesel fuel and the quality of diesel fuel pose the greatest impact on the durability of construction equipment diesel engines operating in Latin America. The last step in the risk analysis process was to determine the total cost for each risk. As summarized in Table 3, the expected loss and the priority determined for each risk is as follows: sulfur ($5,729), diesel quality ($5,612), humidity ($1,725), temperature ($1,296), altitude (1,226), and biodiesel ($802). Finally, when applying these risks to the most critical construction equipment units in Latin America, the 20-ton excavator, this paper determines that the expected cost curve is $y = 0.1981\ln (x) – 1.2616$.

The research limits the contribution to determining risks that lead to reduced engine durability in Latin America and how the risk drivers can be quantified. The isolation of the contribution of the individual factors is a subsequent study target of the authors. The lessons learned from Latin America could be applied to countries with similar environmental or diesel fuel conditions. Furthermore, applications could be drawn to trucking industry and stationary diesel engines. Manufactures could benefit by this research by implementing mitigation strategies to meet users' durability expectations and to reduce warranty costs. For instance, manufactures could redesign engines and their subsystems to better cope with these risks and customers could install aftermarket components to improve engine durability.

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CHAPTER 4: ENGINE OIL DEGRADATION ANALYSIS OF CONSTRUCTION EQUIPMENT IN LATIN AMERICA[3]

4.1. Introduction

The Latin American market is an important source of revenue for U.S. construction equipment manufacturers and multinational construction companies. However, the operating conditions can adversely affect construction equipment engine durability. Previous research has shown significant abnormalities in oil samples obtained from diesel engines operating in Latin America versus oil samples taken from equipment operating in the United States. Thus, the objective of this paper is to determine the impact of oil degradation on the durability of a diesel engine powering a 20-ton class excavator. This will be accomplished by answering the following research questions: (1) What are the engine abnormal reading distributions per wear metal at 500 hours for 20-ton excavators operating in Latin American geographies? (2) Is there a relationship between wear metals and the environmental conditions particular to Latin America? (3) Do wear metals present in oil samples indicate that a change to the scheduled maintenance frequency is necessary for environments such as Latin America? To answer these question, these research parameters were followed: (1) a John Deere PowerTech Plus 6068 diesel engines that powers the 20-ton class excavator was studied, (2) OSA3 oil analysis laboratory equipment in eleven target countries in Latin America was employed to analyze oil samples, and (3) the same sampling scope and method were followed for each oil sample. Results of the research can be applied globally to countries with similar operating conditions.

4.2. Motivation

Latin America has become an important source for annual revenue for U.S. construction equipment manufactures. The Caterpillar Annual Financial Report informs that during the year 2016, construction equipment sales in Latin America surpassed $1 billion USD (Caterpillar 2016 Annual Report, 2016). In

[3] Paper in press in the Journal of Quality in Maintenance Engineering.

2016, the Latin America market represented 14% (Caterpillar 2016 Annual Report, 2016) of CAT's total America's sales. CAT's presence and success in Latin America extends to employment as Caterpillar currently maintains a workforce of 11,400 employees in the region (Caterpillar 2016 Annual Report, 2016).

U.S. construction equipment manufacturers plan to expand manufacturing in Latin American countries to improve manufacturing utilization, the return on asset, and incremental profitability. For example, the John Deere Construction Equipment division announced in 2014 the inauguration of two new factories in Idaiatuba, Brazil to build backhoes, loaders, and excavators (John Deere Inaugurates Two New Manufacturing Facilities in Brazil, 2014). Furthermore, numerous construction, infrastructure project management, and civil engineering multinationals have operations in Latin America. For instance, in 2016 Bechtel managed four multi-year projects in Peru, Chile, and Brazil (The Bechtel Report, 2016).

However, the construction industry is challenged by machine downtime due to pre-mature engine failure. Caterpillar experienced $1.26 billion USD in machine warranty liability, representing 8% of total sales in 2016 (Caterpillar 2016 Annual Report, 2016). The previous research targeted 7,561 oil samples from 11 Latin American countries to determine whether such samples could be used to identify possible improvements to engine durability that would reduce manufacturing warranty costs.

When researching engine oil samples, it was determined that 43% of the samples taken from machinery operating in Latin America showed abnormalities. Previous research determined the following percentages of abnormal oil results varied by country: Bolivia 40%, Colombia 46%, Costa Rica 39%, Dominican Republic 39%, Ecuador 53%, Guatemala 34%, Honduras 22%, Mexico 33%, Paraguay 40%, Peru 51%, and Uruguay 77%. Furthermore, their research determined a high statistical relationship among the following particles: sodium and lead (0.54), aluminum and chromium (0.64) aluminum and copper (0.44), aluminum and lead (0.80), silicon and lead (0.51), and silicon and aluminum (0.58). Also, there was an important negative correlation between soot and TBN (-0.42).

In a separate paper, it was determined that environmental factors led to the engine durability issues in Latin America. By applying the System Engineering Standard Risk Analysis, the risks leading to engine failure was cataloged in two groups: fuel quality (i.e., biodiesel level, sulfur level, and low-quality diesel) and local operating conditions (i.e., operating altitude, temperature, and precipitation).

Thus, this paper determines the specific impact of oil degradation in Latin America to the 20-ton construction excavator. The research goal is to answer the following questions: (1) What are the engine abnormal reading distributions per wear metal at 500 hours, typical maintenance of engine oil change interval, for 20-ton excavators operating in Latin American geographies? (2) Is there a relationship between wear metals and the environmental conditions particular to Latin America? (3) Do wear metals present in oil samples indicate that a change to the scheduled maintenance frequency is necessary for environments such as Latin America?

4.3. Literature Review on Construction Equipment Oil Degradation

The study of engine oil degradation should begin with the determination of the oil base and additives. The oil base is composed of mineral or synthetic content. For U.S. formulated oil, the base oil can represent as much 70% of the oil content while the remaining 30% represent the additives (The Lowdown on Oil Breakdown, 2017). While Bowman and Stachowiak (1998) determined that mineral base oil oxidation with carboxylic acids have a positive impact on reducing metal scuffing, Glavatskih and Simmons (2011) determined that synthetic-based lubricants are superior than mineral-based lubricants because they offer a higher viscosity index. Furthermore, synthetic lubricants have the following advantages when compared to mineral-based oils: (1) temperature range performance (alkylbenzenes and polyalphaolefins), (2) low volatility (diesters), (3) fire resistance (phosphate esters), (4) hydrolytic stability and friction properties (polyalkylene glycos), and (5) low pour point (polyolesters) (Marine Lubricants Information Bulletin 8 - Synthetic Oils, 2013).

The level of additives in engine oil utilized in the construction equipment industry is higher than automotive because heavy equipment operates at higher temperatures and loads. Additives are formulated to increase lubrication, transfer heat, or to suppress undesired oil characteristics and contaminants. According to Gupta (2013), the most common additives are: (1) detergent-dispersant, (2) oiliness and film-strength agents, (3) antioxidants and anti-corrosive, (4) rust inhibitors, (5) extreme-pressure additives, (6) pour-point depressors, (7) antifoam agents, and (8) viscosity-index improvers. Spikes (2015) determined that additives with friction reduction modifiers are classified as (1) organic friction modifiers, (2) functionalized polymers, (3) soluble organo-molybdenum, and (4) nanoparticles dispensers. The friction modifier additives are important because they protect engine internal wear.

Construction equipment diesel engine durability can be traced to improper lubrication. According to Gupta (2013), engine oil has multiple functions, including: (1) carries away heat, (2) seals components such as cylinder walls, (3) cleans carbon deposits from piston surfaces, (4) reduces noise, and (5) protects against engine internal corrosion and wear. Gupta (2013) states that when engine oil fails to perform its function, the most common signs include: (1) scored cylinders, (2) damaged bearings, (3) stuck pistons rings, and (4) the presence of engine deposits and sludge. Thus, the source of oil degradation must be determined and it is commonly recognized as a leading factor to improve engine durability. The three most common causes of oil degradation include: thermal failure, oxidation, and compressive heating (The Lowdown on Oil Breakdown, 2017). Thermal failure is determined by the presence of lacquer and carbonaceous deposits. Oxidation degradation leads to the creation of sludge. Compressive heating leads to the creation of varnish, coke, tars, resins, and soot deposits (The Lowdown on Oil Breakdown, 2017).

The most prevalent method of oil degradation is determined as oil oxidation (The Lowdown on Oil Breakdown, 2017). It can be measured by the changes of Total Acid Number (TAN). Oil oxidation is defined as “the chemical reaction of an oil molecule with oxygen, which is present from either the ambient or entrained air” (The Lowdown on Oil Breakdown, 2017). The chemical reaction with oxygen leads to the creation of alcohols, hydroperoxides, ketones, aldehydes, carboxylic acids, esters, and lactones (Mangolini, Rossi, and Spencer, 2010). Among these chemical reactions, carboxylic acids represent the compound with the potential for the greatest damage. The polymerization process from carboxylic and hydroperoxides acids leads to the increase of oil viscosity (The Lowdown on Oil Breakdown, 2017). Also, the process of polymerization, carboxylic and hydroperoxides forms varnish and sludge in the engine’s oil galleries and oil filter (Westbrook and Shah, 2003). According to Westbrook and Shah (2003, p.204), “in diesel-fuel engines, soot from the combustion chamber is the key component of carbon and lacquer deposits that occur on pistons, and sludge". This is commonly seen when the engine oil dispersants additive is depleted.

Thermal degradation affects the rate that oxygen bonds with base oil. The degradation of the base oil is due to high temperatures leading to the creation of gums and varnish as carbonyl groups undergo a polycondensation process (Gresham and Totten, 2010). For instance, mineral base oil will double the rate of oxidation for every 10°C increase of temperature over 75°C (The Lowdown on Oil Breakdown, 2017). This is also known as the Arrehenius rate rule. Because construction equipment diesel engines operate at high temperature, synthetic-based oil is commonly used to reduce the rate of oxidation. The temperature stability of synthetic oils is due to fewer refining impurities such as unsaturated aromatic compounds and paraffinic molecules (The Lowdown on Oil Breakdown, 2017). Any impurity (mainly unsaturated impurity) in oil will result in an oxidation chain reaction. According to Noria Corporation, "By carefully controlling the chemical structure of the base oil molecules, synthetic-based oil manufacturers can limit the number of reactive hydrogen and carbons atoms, and hence improve the overall oxidative resistance of the base oil" (The Lowdown on Oil Breakdown, 2017).

Extreme temperatures due to high compression can also lead to oil degradation. Stationary construction equipment with diesel engines such as 20-ton class excavators with high-pressure common rail configurations can reach extremely high temperatures as there is limited airflow through the engine cooling system. Engine oil in a pressurized system over 250 psi can increase temperature up to 200°C at which oil thermal failure occurs (The Lowdown on Oil Breakdown, 2017). However, in comparison with oxidation, oil degradation due to thermal or compressive heating is more difficult to diagnose because fewer carboxylic acids are formed, and thus, the acid numbers typically do not vary noticeably. Thus, practitioners look for an early change of oil color to determine thermal or compressive heating problems. An earlier change in oil color conveys the information that there is a break-down of the base oil as a result of oxide insoluble (The Lowdown on Oil Breakdown, 2017). When oil temperature exceeds 200°C, oil thermal cracking occurs; thus, cutting carbon oil molecules. This effect is identified by the unexpected reduction of oil viscosity (The Lowdown on Oil Breakdown, 2017).

Soot generated and trapped inside of the engine affects engine oil properties. Yamaguchi and Ryason (2007) have studied how soot affects oil in diesel engines. The authors determined that "both wear and viscosity increase depend on the degree of agglomeration of soot suspended in the crankcase oil" (Yamaguchi and Ryason, 2007, p.517) Thus, engine oil is formulated with dispersant to avoid the agglomeration of soot. While soot generation is associated with exhaust gas recirculation (ERG) equipment installed in engines, it can be also associated with inefficient combustion process, due to low quality diesel, reduced combustion temperature, and inefficient or depleted soot dispersants in engine oil formulation (Yamaguchi and Ryason, 2007). According to Plumley, Wong, and Martin (2017) soot is the largest contributor to engine wear due to increasing lubricant viscosity, leading to the reduction of oil lubrication properties and increasing engine surface friction.

4.4. Research Method

4.4.1. Engine Studied

The research is based on the analysis of John Deere 20-ton excavators operating in Latin America. This class of excavator is the most important across Latin America as it is deployed in infrastructure projects, construction, the petroleum industry, and small mining operations. The John Deere PowerTech Plus 6068 diesel engine powers this excavator (John Deere, 2010). The 6068 John Deere engine underwent several modifications to meet the U.S. Environmental Protection Agency (EPA) Tier III regulations (Off-Highway Diesel Engines Ratings Tier 3 / State III A, 2003). The following components were added to reduce emissions: an EGR valve, a variable geometry turbocharger, 4-valve head, an EGR cooler, and a high pressure common rail fuel injection system (John Deere, 2010). Some of these new sub-components were added to re-route exhaust gases to the engine, a key strategy to reduce exhaust gases and particulate matter. According to the Operating Manual for the 200D and 200DLC Excavators (John Deere, 2010), the engines studied have a Tier 3/Stage IIIA emissions classification in the U.S. The engine type is a turbocharged 4-stroke power plant, with a charger air-to-air cooler (John Deere, 2010). The bore and stroke is 106 mm x

127 mm (John Deere, 2010). The engine has six cylinders with a displacement of 6.8 Liters (John Deere, 2010). The net torque at 1400 RPM is 702 N-m and the compression ratio is 19:1 (John Deere, 2010). The maximum power at 2000 RPM is 122 kW and 164 HP Net SAE (John Deere, 2010). The lubrication system is classified as a pressured system with full-flow filter. Also, the engine has a fan force air to cool the lubrication system. The oil pan size capacity is 0.16 L/kW (John Deere, 2010).

4.4.2. Measuring Equipment

The third generation of On-Site Oil Analysis (OSA3) micro laboratories was employed to perform the oil and chemical analysis. The micro laboratories are equipped with a laser particle counter, infrared and atomic spectroscopy, and a viscometer. The oil fluid micro laboratories utilize the Standard Test Method Analysis of In-Service Lubricants Using Particular Four-Part Integrated Tester, ASTM D7417, for methodology and repeatability (White Paper - MicroLab Series Fully Automated Oil Analyzer, 2017). The laser particle counter measures particles over 4μm [per mL] of aluminum (Al), iron (Fe), lead (Pb), copper (Cu), chromium (Cr), tin (Sn), titanium (Ti), nickel (Ni), barium (Ba), magnesium (Mg), vanadium (V), potassium (K), molybdenum (Mo), silicon (Si), calcium (Ca) , zinc (Zn), boron (B), manganese (Mn), sodium (Na), and phosphorus (P) (White Paper - MicroLab Series Fully Automated Oil Analyzer, 2017). The kinematic viscometer measures viscosity of oil at the temperatures of 40°C and 100°C up to 680 cSt (White Paper - MicroLab Series Fully Automated Oil Analyzer, 2017). The infrared spectrometer determines oil oxidation by measuring absorbance by centimeter (Abs./cm), TBN is measure by potassium hydroxide per gram (mg KOH/g), nitration (Abs./cm), levels of soot (% by weight), water (% by weight), and glycol (% by weight). According to Nora Corporation, "infrared spectroscopy, which measures the degree of infrared absorption in different parts of the infrared spectrum, can be an excellent tool for pinpointing base oil oxidation" (The Lowdown on Oil Breakdown, 2017). Also, the infrared spectroscopy can determine oil degradation due to thermal or compressive heating measure the levels of nitration (The Lowdown on Oil Breakdown, 2017).

4.4.3. Sampling Scope

The research focused on 11 of the 33 countries in Latin America. The target countries were: Bolivia, Colombia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Honduras, Mexico, Paraguay, Peru, and Uruguay. To eliminate measurement variation, the oil samples of each of the 11 countries were analyzed using the same equipment type and analysis method: OSA3 Micro Laboratories. Furthermore, the identically structured database format was obtained from each oil laboratory. A total of 1064 oil sample results were analyzed, making it the most comprehensive study of its kind for Latin America to date. Oil samples were narrowed to 20-ton excavators with engine oil hours less of 250 hours. Subsequently, the data was organized into the following groups: (1) engine oil contaminants, (2) engine wear metals parts per million counts, and (3) engine oil signature measurement. The following is how each group of subsets of data was grouped:

1) Engine oil contaminants were composed of the measurement of boron, potassium, sodium, and silicon.
2) Engine wear metal part per million counts (PPM) were determined for iron, aluminum, lead, copper, chromium, and tin.
3) The engine oil additive signature measurements were calculated by determining the levels in parts per million of oil additives such as zinc, calcium, magnesium, phosphorus, and barium.

The paper focuses on engine oil contaminants and engine wear metal statistical analysis groups. To narrow root-cause correlation to specific wear and risk factors, the paper analyses copper, iron, aluminum, and lead for wear metals and potassium, sodium, silicone for engine oil contaminants. Engine oil signature is not included in this research as there is a level of uncertainty where different oil brands were mixed.

4.4.4. Sampling Limits Method Definition

There are several methods one may choose to define the sampling limits methodology. The methods vary by user needs. There is the oil laboratory, oil manufacturer, engine maker, and user sampling limit method definition (Van Rensselar, 2016). These user groups have not determined a common approach for setting sampling limits. For instance, oil blenders analysis of oil degradation might be based on oil signature degradation while an end-user might be based on the standard variation of specific particle count. According to Van Rensselar (2016), the most common methods utilized for oil analysis limits are: (1) trend base analysis, (2) statistical distribution, (3) user defined, and (4) industry standards. This paper approaches on the manufacturer statistical definition of engine subcomponent wear. This method emphasizes the importance of tracing abnormal oil sample results to operational and environmental risk factors. Furthermore, it permits a system approach for component and subcomponent wear as defined by Blau (2006) as tribosystem. Finally, the manufacturer metal wear approach allows correlation of oil degradation to engine system life cycle, engine warranty, and engine condition based maintenance.

The approach taken in this research is based on Blau's (2006) view of tribology, tribosystem. Blau (2006, p.7) defines tribosystem analysis as "a process to dissect and organize the mechanical, chemical, thermal, and materials-related aspects of a wear-related and/or friction-related condition." It is based on the systematic interaction of triboelements leading to a tribological behavior. This approach advocates the identification of internal and external factors leading to component wear in the assembly or component (subsystem) and part or unit level. Furthermore, Blau (2006) determined that a combustion engine has open and closed subsystems characteristics. Thus, while engine oil recirculation inside the engine is a closed system by design, it is greatly impacted by external input factors such as fuel and air that serve as carriers for contamination. These external factors can cause excessive and premature component wear due to the degradation of engine oil. Thus, resulting in a negative impact on the system life-cycle.

There are two ways to identify component wear in tribology, direct and indirect analysis (Blau, 2006). While Gonçalves, Cunha and Lago (2006) advocates oils analysis combined engine vibration, this research analyzes the direct indication of wear provided by oil sample analysis. Furthermore, Blau (2006) determined that oil analysis can be divided in two major areas of analysis, chemical and particle analysis. The by-products of component wear will be determined by analyzing oil sample results. The particle count found in the engine oil samples will indicate the level of contamination. While there are qualitative observations to identify engine oil degradation and contamination, such as oil smell and appearance (discoloration and thickness), this research will focus on quantitative methods such of wear metals parts per million (PPM) count and acid base number identified in oil analysis.

Oil guidelines for lower, upper, abnormal, and critical ranges are not determined in peer-reviewed literature for construction equipment. There could be wide variation depending of type of industry, engine size, and engine utilization. It is common practice to employ industry guidelines. However, manufacturer-specific guidelines are more precise. Addressing oil analysis, Blau (2006, p.15) states that it can be subdivided into "(a) fluid composition and thermophysical properties (e.g., room temperature viscosity, volatility, thermal conductivity, temperature-viscosity coefficient), (b) external contamination level, and (c) tribosystem-generated wear debris."

Regarding physical properties or chemical analysis, the viscosity levels in the oil samples will be analyzed in centistokes (cSt), measured at 100° Celsius. The viscosity levels with variation exceeding 10% to 15% will be subject of concern. Oil viscosity is the most important property of oil because it reduces friction. According to Luzuriaga (2017), the predominant oil graders (over 50%) are the conventional multi-grade 15Ws oil. However, low-quality performance oil and non-synthetic oil are widely used (Luzuriaga, 2017).

Changes in the physical properties of engine oil are related to oxidation, reduction of viscosity, Total Acid Number (TAN), and Total Base Number (TBN). Oil life is measured in relation to its oxidation levels to determine anti-oxidants additive levels. Additives are used to reduce oxidation. However, it is depleted with oil hours. Depletion is accelerated with increased temperature and contaminants. The TBN will provide inferences of additive depletion by measuring the alkaline levels in the oil, which neutralize acids. For the purpose of this research, normal TBN for engine oil will be greater than 5, abnormal between 2.6 and 4.9, and critical will be less than 2.5. The TAN is the opposite of TBN as it represents the acidic level in the oil. The normal levels are considered to be equal to or less than 25, abnormal will be over 25 but less than or equal to 39, and critical will be over 40. A normal oxidation level is less than 20 (Abs./cm), abnormal level is 20 to 25 abs per cm, and critical is over 25 abs per cm.

Regarding engine oil signature, it important to understand the key ingredients, which are the following: boron, barium, calcium, magnesium molybdenum, sodium, phosphorus, sulfur, and zinc. Boron is an additive employed for engines that operate in extreme pressure environments. Barium is an additive used to prevent corrosion. Calcium is a detergent that helps to clean carbon deposits, reduce corrosion, and is a dispersant. Magnesium is a detergent that helps to reduce varnish and sludge. Molybdenum is an anti-wear agent. Phosphorus is employed in high compression engines by delivering anti-wear (by reducing friction) and anti-oxidant properties. Sulfur is an additive used in engines that employ high-pressure fuels systems. Zinc is an additive that reduces wear, corrosion, and oxidation.

In operation (in the field), the engine oil used for lubricating a machine is often a mixture of oils from different manufactures. Research by Yang et al. (2015) provides guidance on how to identify tampered oil. The benefits of fingerprinting or finding the oil signature will help "(i) to better understand the physical and chemical change of used lube oil; (ii) to determine and to track the source of spilled oil; (iii) to determine the contamination source; and (iv) to differentiate oils that do not meet the specification and used lube products from virgin and compliant oils" (Yang et al., 2015, p.272)

4.5. Results

This research focuses on answering the following questions: (1) What are the engine abnormal reading distributions per wear metal at 500 hours for 20-ton excavators operating in Latin American geographies? (2) Is there a relationship between wear metals and the environmental conditions particular to Latin America? (3) Do wear metals present in oil samples indicate that a change to the scheduled maintenance frequency is necessary for environments such as Latin America? To answer these research questions, this section provides results for the engine oil sample distribution, plotting particle count over time for the most important metal wear and contaminants, statistical relationships between wear metals and contaminants, the statistical relationships between wear metals and oil age, nitration, oxidation, and TBN, and the relationship of wear metals and environmental risk drivers.

A total of 1064 oil sample lab results were analyzed. Excavators with engine oil life limited to 500 hours were extracted and analyzed. Table 4.1 shows the engine abnormal reading distribution per wear metal below 500 hours of use in Latin America operating conditions for excavators. 73.4% indicated that soot accumulation in diesel engines is a significant problem. It is evident that tin and iron tested at significantly critical levels, 18.5% and 17.6% of the samples respectively. Furthermore, it is important to emphasize that silicon, sodium and potassium are present at the upper-level results classification. The combination of these components at upper level quantities indicates cross-contamination between the lubrication systems and the cooling systems of the respective engines. It also indicates that water, external to the engine, entered the lubrication system of the engine.

Table 4.1: Engine oil results distribution

Contaminants	Low	Upper	Abnormal	Critical
Iron	46.8%	23.2%	12.4%	17.6%
Silicon	64.6%	28.6%	3.3%	3.6%
Aluminum	90.7%	7.1%	1.2%	0.9%
Tin	45.6%	22.3%	13.6%	18.5%
Lead	95.9%	2.2%	1.2%	0.8%
Nickel	92.8%	2.6%	2.8%	1.8%
Copper	76.7%	10.3%	5.6%	7.3%
Sodium	65.7%	28.9%	1.7%	3.8%
Potassium	57.5%	35.3%	3.8%	3.4%
Soot	17.1%	9.5%	0.0%	73.4%

To better assess the increased metal and contaminants over time, the research analysis was narrowed to 250 hours of engine oil utilization. Thus, a subset of the lab results of 694 engine oil samples were evaluated. The most important wear metals considered for the analysis are iron, aluminum, copper, and lead. The most important external contaminants analyzed are potassium, sodium, and silicone. Figures 4.1 through 4.7 depict the metals and contaminates parts per million plotted over time. In these figures, it is important to emphasize the rapid rate of increase of particles over time. At 250 hours, critical levels were achieved, indicating that an immediate change of oil is required to protect the engine from damage.

Understanding the source of a metal present in the oil sample can provide an early indication of which engine components present the highest level of degradation. According to Holloway (n.d.), the presence of iron particles in the oil can be traced to accelerated surface wear of cylinder liners, crankshafts, piston rings, connecting rods, oil pumps, and rocker arms. The presence of lead particles is commonly associated with accelerated surface wear of bearings and connecting rods (Holloway, n.d.). Figures 4.1 and 2 show an increase of iron and lead at 50, 100, 150, 200, and 250 hours. Iron levels above 70 PPM and lead levels above 26 PPM are classified as abnormal and should be addressed to prevent engine damage.

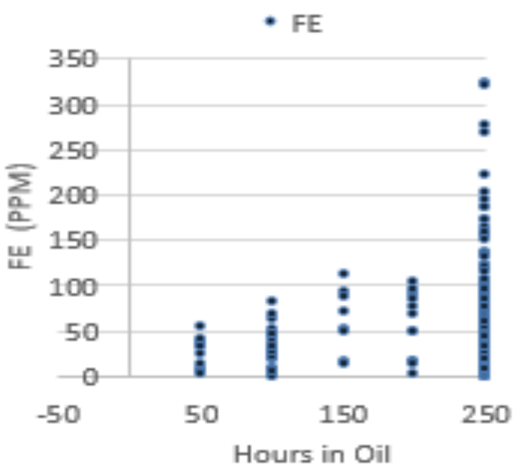

Figure 4.1: Iron

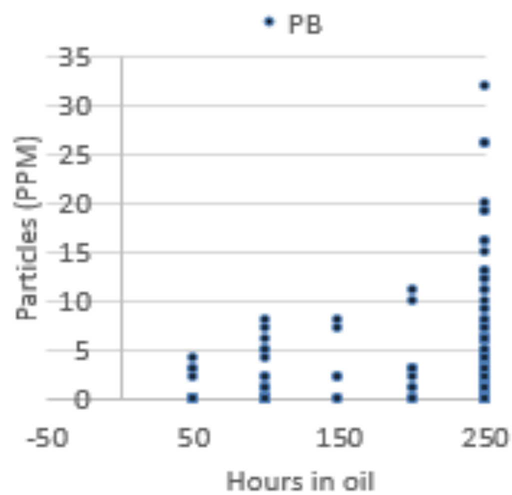

Figure 4.2. Lead

Copper particles in engine oil indicates premature wear to bearing systems and heat exchange systems (Holloway, n.d.), and the presence of aluminum often indicates degradation within the cooling system. Figures 4.3 and 4.4 present the quantity of aluminum and copper in the oil samples. Abnormal readings over 31 PPM for aluminum and 26 PPM for copper should be addressed. Aluminum particles present in oil samples extracted from diesel engines are associated with pistons and oil pump bushings, valve train bushings, oil cooler cores, thrust washers, and connecting rod bearings (Holloway, n.d.).

Figures 4.5, 4.6, and 4.7 show the levels of contamination at 50, 100, 150, 200, and 250 hours. It is important to note that abnormal levels for silicon, potassium, and sodium begin at 21, 31, and 31 PPM, respectively.

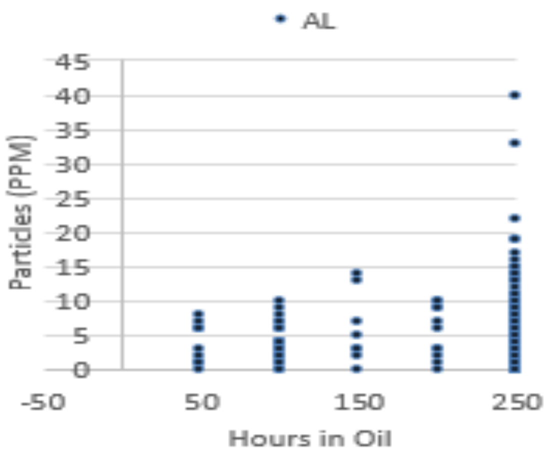

Figure 4.3: Aluminum

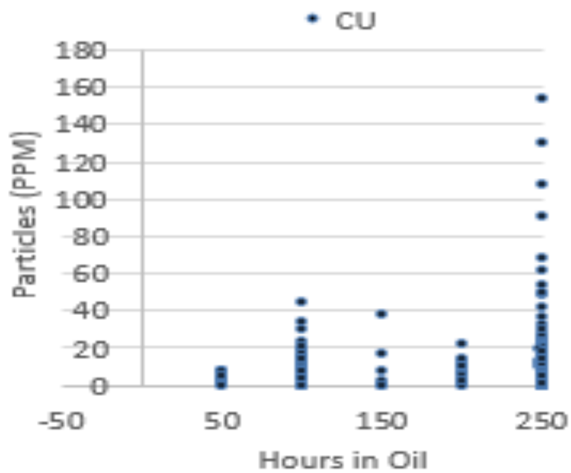

Figure 4.4: Copper

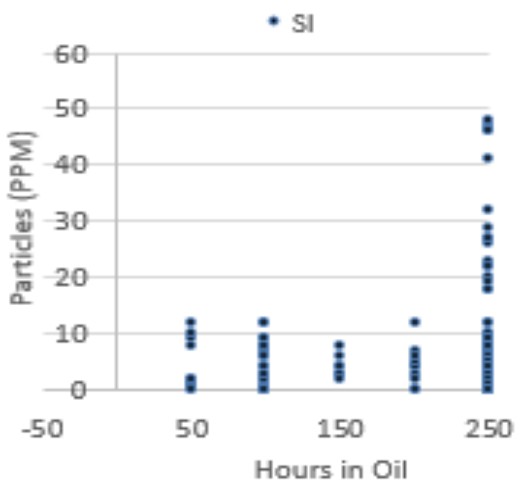

Figure 4.5: Silicon

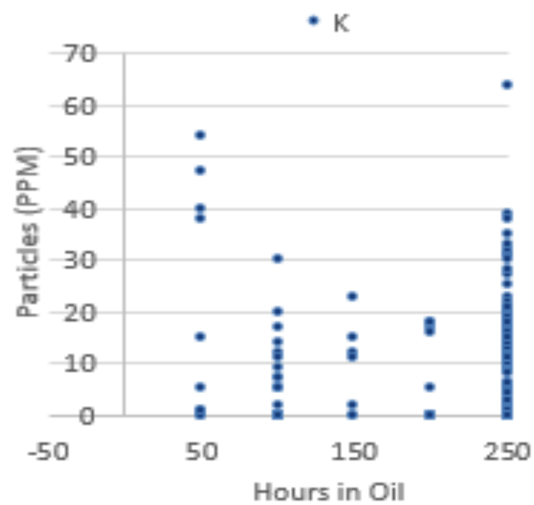

Figure 4.6: Potassium

According to Holloway (n.d.), silicon is the most common contaminant in engine oil. Due to its high molecular density and strength, it is abrasive to the internal components of an engine. Blau (2006) stated that alumina and silicon carbine lead to the highest levels of internal engine damage and wear by scratching the surfaces of internal components. Internal contamination can be traced to the operating environment (e.g. dust and contaminated water) of an engine, engine oil additives such as de-foaming agents, and aluminum engine parts (Holloway, n.d.). The presence of silicon within an engine system is often traced to a failed air filtering system or failed seals and gaskets.

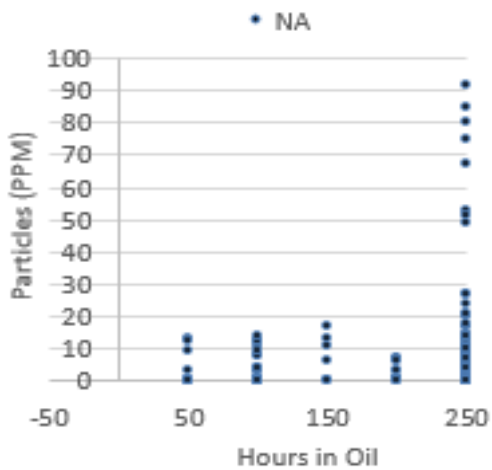

Figure 4.7: Sodium

The presence of potassium often is attributed to the operating environment. Potassium often indicates a coolant leak (Poley, 2017). Higher levels of potassium can be traced to cooling system cross-contamination with the lubrication system. McGuire (2017) stated that “coolant contaminants increase the acidity of a lubricant and they promote corrosion.” Also, it can be traced to a failed air filtering system and seals.

The presence of sodium is also traced to the operating environment. However, sodium particles can also be a lubricant additive (Poley, 2016). According to McGuire (2016, 30), sodium as “polar compounds enhance the ability of the rust preventive to wet the metal surface, giving a more intact and uniform coating.” However, as seen in Figure 4.6 and 4.7, they can increase to critical levels within 250 hours, often introduced from the operating environment of the machine.

4.5.1 Statistical Correlations

Statistical correlations are performed to determine the level of relationship between external and internal contaminants. The Person’s Correlation Coefficient formula is used to compare data sets. For instance, iron is compared with aluminum PPM in the database to determine whether a relationship exists between each oil sample result. The Person’s Correlation Coefficient formula is noted as follows:

$$r = \frac{n\,(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}$$

In this formula notation, n represents the number of oil samples in the database, x and y are compared values of oil sample components, such as iron PPM and aluminum PPM. The higher the absolute value of r, the higher the correlation**.** The positive correlation denotes a progressive relationship between contaminants; a negative correlation indicates an inverse relationship among contaminants. For the purpose of this research, the following correlation considerations were assumed: very strong relationship (abs(r) ≥ 0.70), strong relationship (abs(r) ≥ 0.40 to 0.69), moderate relationship (abs(r) ≥ 0.30 to 0.39), and weak relationship (abs(r) ≥ 0. to 0.29)**.**

Table 4.2 provides a summary of the results achieved by analyzing the statistical relationship of oil sampled at 250 hours. The focus is on strong and very strong relationships.

Table 4.2: Statistical relationships among wear metals and contaminants

Contaminants	Fe	Si	Al	Sn	Pb	Ni	Cu	Na	K	Soot	Water	Fuel
Fe	1											
Si	0.29	1										
Al	0.67	0.46	1									
Sn	0.67	0.27	0.56	1								
Pb	0.7	0.31	0.51	0.54	1							
Ni	0.39	0.14	0.21	0.18	0.25	1						
Cu	0.43	0.31	0.35	0.43	0.49	0.14	1					
Na	0.03	0.15	-0.01	0	0.05	-0.03	0.09	1				
K	-0.05	0.1	0.01	-0.08	-0.02	-0.03	0	0.1	1			
Soot	0.3	0.03	0.14	0.23	0.09	0.08	0.07	-0.09	-0.02	1		
Water	0.28	0.05	0.12	0.23	0.08	0.09	0.07	-0.07	-0.02	0.95	1	
Fuel	0.25	0.05	0.13	0.16	0.14	0.05	0.11	0	-0.08	0.58	0.63	1

Based on the values tabulated in Table 4.2, note the following:

- Very strong correlation between soot, water, and fuel, and the strong correlation between water and fuel.
- Strong correlation between iron and aluminum, tin, and copper.
- Strong correlation between silicon and aluminum.
- Strong correlation between aluminum, tin and lead.
- Strong correlation relationship between tin, lead, and copper.

- Strong correlation between tin, lead and copper.
- Strong correlation between lead and copper.
- Moderate relationship and weak relationship correlation between iron and silicon, soot, water, and fuel.
- Moderate correlation of aluminum with copper was determined.
- Week correlation between tin with soot and water particles.

The appearance of water, aluminum, and silicon with several metals points to that internal contamination point. It is more likely that an internal leak from cooling system or fuel contaminated with water. This is turn leading the accelerated wear of bearings and pistons. Water is also affecting the generating engine soot and oil viscosity.

4.5.2 Engine Oil Oxidation

When engine oil is combined with oxygen molecules, a chemical reaction called oxidation occurs (The importance of Oil Oxidation Stability, 2017). According to Fitch (2015), oxidation is the primary method to determine whether engine oil has been chemically modified or degraded. While oil degradation is a normal process that occurs over a period of time, degradation is accelerated by the depletion of oil additives. The most common enablers of oil chemistry degradation relate to temperature, environmental contaminates (e.g. water and oxygen), and internal engine contaminates (e.g. metal particles) (Fitch, 2015). Because normal oil degradation is expected to be linear in relation to engine oil time (Fitch, 2015), John Deere (2010) recommends that service personnel change the Plus 50-II SAE 10W-30 engine oil at 500 hours for its 200D excavators (Plus-50TM II Premium Engine Oil, 2010). When engine oil is degraded, viscosity tends to increase as varnish and sludge increase in the engine oil. This is a normal chemical process that occurs when engine oil free radical molecules (e.g. hydro peroxide) bond with internal and external contaminants thereby producing a “new” byproduct, engine varnish. Once the oil degradation process begins, these created oil byproducts exponentially accelerate engine oil degradation. Fitch (2015) states that, “the increase in weight of the molecular compounds translates to the formation of sludge, varnish and deposits." As seen in Table 4.3, there is an important statistical correlation of oxidation to iron 0.216, water 0.825, fuel 0.699, and soot 0.778 within engine oil samples collected at 250 hours. The mix of water, soot, and fuel are known ingredients in creating engine varnish and sludge (Fitch, 1999).

4.5.3 Engine Oil Nitration

Nitration is defined as a type of oil degradation when nitrous oxides (NOx) interact with the engine oil (Causes of Nitration in Engine Oil, n.d.). While it is commonly seen in older engines operating at cold temperatures, the sampled 200D excavators working in Latin America were neither old (less than 1000 hours) nor were they working in cold temperatures. The result of the interaction of oil with NOx is the saturation of "soluble and/or insoluble nitrogen-oxide compounds" (Causes of Nitration in Engine Oil, n.d.). The major causes of nitration are: (1) exhaust gas scavenging efficiency, (2) cylinder wall temperature, (3) piston ring efficiently, (4) crankcase ventilation, (5) oil sump temperature, (5) base oil type, (6) rate of oil makeup, (7) spark timing, (8) air and fuel ratio, and (9) engine load (Causes of Nitration in Engine Oil, n.d.). Table 4.3 shows there is a high statistical correlation between engine oil nitration and water (0.825), soot (0.778), fuel (0.699), and iron (0.216). Water is entering the engine through the engine head gasket and falling into engine combustion chamber. It is leading the oxidation top of engine short-block and wears of cylinder heads. When that happens, NOx escapes to engine oil pan, having contact with engine oil.

4.5.4 Engine Oil Total Base Number

The total base number (TBN) is determined by the measurement of alkaline levels in engine oil (White Paper - Guide to Measuring TAN and TBN in Oil, 2016). Alkali is commonly found in engine oil; it is an additive that is formulated to reduce the acid build-up created by oxidation and nitration. Engine oil used in diesel engines tends to have higher levels of alkaline additives (15-30 mg KOH/g) than their gasoline engine counterparts (5-10 mg KOH/g) (White Paper - Guide to Measuring TAN and TBN in Oil, 2016). The alkaline additive is higher in diesel engine because of the higher temperature and engine loads at which they operate. There is an inverse relationship of engine oil TBN number and the increase level of total acid number (TAN). As TBN decreases, acids concentration leads to oil oxidation over time. This result in an increase in engine internal component corrosion, engine sludge, and oil varnish. Tables 4.3

shows the relationship between TBN and wear metals and contaminants. The reduction of TBN is highly correlated with water, soot, and fuel.

Table 4.3: Statistical relationships of wear metals, nitration, oxidation, and TBN at 250 hours

Contaminants	Nitration	Oxidation	TBN
Iron	0.216	0.215	-0.213
Silicon	0.058	0.062	-0.046
Aluminum	0.086	0.079	-0.084
Tin	0.166	0.157	-0.159
Lead	0.097	0.088	-0.092
Nickel	0.085	0.076	-0.08
Copper	0.037	0.031	-0.031
Sodium	-0.089	-0.077	-0.073
Potassium	-0.017	-0.03	-0.018
Soot	0.778	0.831	-0.815
Water	0.825	0.877	-0.863
Fuel	0.699	0.758	-0.714

Systems degradation is rooted in component material variation, improper component interface matching, and extreme environmental conditions (Kossiakoff et al, 2011). In a previous research, engine degradation in Latin America was cataloged in two groups, internal and external factors. Internal factors were composed of fuel and bio-diesel, diesel sulfur content, and diesel quality. The environmental factors impacting engine durability in Latin America was determined to be operating altitude, high precipitation, and temperature variation. Table 4.4 indicates the relationship of wear metals and the environment in Latin America. Based on the values tabulated in Table 4.3, note the following:

- Bio-diesel is significantly correlated with high levels of iron, copper, silicon, and Potassium.
- Diesel fuel sulfur content exceeding 1,800 PPM results in abnormal oil results including high levels of iron. Also, it is associated with the presence of potassium, and silicon. High sulfur diesel is related to abnormal copper levels.
- Low quality diesel has a high impact on iron PPM and a moderate impact on copper. Also, low quality diesel is associated high levels of silicon and potassium.

- Countries with high altitudes (2,500 meters over sea level) showed oil results with high iron PPM levels. Also, engines operating in these conditions show high levels silicon and potassium.
- Countries with precipitation over 600 millimeters/year is associated with very high levels of iron. There is a high level of association with potassium and silicon and moderate association with copper.
- Temperature variation is associating of iron PPM; it is related to silicon and potassium (levels).

Table 4.4: Percentage wear metals and environmental risk drives

Risk Factors	Percentage of oil samples with abnormal results					
Bio-diesel type	Fe	Cu	Pb	SI	Al	K
B2	54%	44%	10%	43%	9%	18%
B5	36%	13%	3%	27%	3%	46%
B20	45%	17%	1%	25%	2%	37%
Diesel Sulfur Level (PPM)						
<1,800	34%	18%	1%	27%	1%	29%
>1,800	62%	26%	6%	39%	13%	49%
Diesel Quality						
Low	70%	30%	5%	44%	16%	49%
Mid	36%	14%	2%	24%	2%	43%
High	31%	21%	5%	34%	1%	16%
Altitude (meters)						
< 1,000	41%	22%	5%	30%	5%	28%
1,000-2,500	42%	17%	2%	32%	3%	34%
>2,500	78%	31%	5%	46%	21%	68%
Precipitation (Millimeters)						
600-900	73%	19%	3%	32%	7%	52%
901-1,200	67%	37%	6%	51%	20%	56%
1,201-1,900	39%	16%	3%	27%	3%	32%
Temperature (Celsius)						
< 18	66%	28%	6%	36%	8%	39%
18-25	59%	28%	4%	39%	16%	59%
>25	42%	17%	4%	32%	4%	30%

4.6. Discussion

There is a growing interest in condition base maintenance (CBM) as diesel engines in construction equipment become more complex and maintenance costs increase. CBM is also gaining popularity because of the environmental factors associated with operating equipment in less than optimal operating conditions (Duchowiski and Mannebach, 2006). CBM is defined by equipment manufacturers as “a maintenance strategy aimed at extending machine life, increasing productivity, and lowering daily operating costs” (Condition Base Maintenance, 2017). According to Edwards, Holt and Harris (1998) “Condition-based monitoring revolves around examination of these wear processes in mechanical components”. Compared with the equipment periodic maintenance, CBM does not rely on the manufacturers’ maintenance schedules. According to John Deere, the machine application, temperature, operating environment, and engine internal wear should be the leading indicators that control machine maintenance intervals (Condition Base Maintenance, 2017). According Tsang et al. (2006), modeling CBM modeling are still premature due the diverse operating conditions, modeling techniques, and data quality. While large fleet equipment owners apply some aspect of CBM, a significant lack of understanding exists in Latin America regarding the principles of CBM. Survey of machine operators in Latin America indicated that they followed the product operating manual recommended intervals for engine maintenance.

It is important to monitor oil analysis results to determine critical levels of wear metals, TAN, and contaminants. When a significant correlation exists between two metals, machinery users can proactively order the parts and schedule downtime without interrupting the construction project. When level of copper and lead reach high levels, it is possible that bearing might fail. If TAN reach high levels, it is important to change engine oil. For instance, John Deere Plus 50-II is the recommended engine oil for the John Deere 200D excavator (John Deere, 2010). It is formulated to allow oil-changes at 500 hour intervals (John Deere, 2010). Furthermore, according to the John Deere 200D operating manual (John Deere, 2010), the recommended oil change interval is also specified at 500 hours. The oil is formulated to tolerate fuel sulfur levels between 15 PPM to 500 PPM (John Deere, 2010). However, as of March 2017, the diesel fuel sulfur levels for key Latin America regions were as follows: Bolivia (>2000 PPM), Colombia (>15-50 PPM), Dominican Republic (>5000-10000 PPM), Ecuador (>500-2000 PPM), Guatemala (>2000-5000 PPM), Honduras (>2000-5000 PPM), Mexico (>50-500 PPM), Paraguay (>15-50 PPM), Peru (>2000-5000), and Uruguay (>15-50 PPM) (Diesel Fuel Sulphur Levels: Latin America and Caribbean Region, 2017). This one simple metric implies that operating equipment in Latin America and other parts of the globe may require more frequent oil-change intervals.

Iron (Fe, 17.6%), tin (Sn, 18,5%), and soot (73,4%) have accumulated in the engine oil at 500 hours. Also, silicon (Si, 28.6%), sodium (Na, 28.9%), and potassium (K, 35,3%) are present. When analyzing the contaminants trends, there is an exponential count of particles as oil-time approaches 250 hours. This indicates that engine oil should be changed at intervals of 250 hours or less. The high levels of silicon, sodium, and potassium indicate that water or coolant is entering the lubrication system and making direct contact with the engine oil. Water contamination leads to (1) fluid breakdown (e.g. oil oxidation), (2) reduced lubricating film thickness, (3) corrosion, and (4) accelerated metal surface fatigue (TestOil, 2017). When water or coolant is exposed to the high temperature and high pressure of the engine combustion chamber, micro explosion occur that erode the cylinder liners and piston rings. This contamination also leads to corrosion and deterioration of rocker arms, thrust washers, connecting rods, and engine block internals walls. Furthermore, Troyer (1999) determined that the presence of water and glycol (from coolant) reduce the lubricant soot dispersant property of engine oil. This commonly identified by the presence of high levels of iron in an oil sample as shown in Table 4.1. High levels of soot confirm that the combustion process of the engine is not efficient. "Soot, comprised 98% of carbon by weight, is formed during the combustion process and enters the crankcase with combustion gas blow-by" (Troyer, 1999).

4.7. Conclusion

Latin America is a key source for a variety of raw materials used world-wide. But, many Latin American countries lack the infrastructure to access and deliver those materials. Consequently, Latin America has become an important source of revenue for U.S. construction equipment manufacturers. However, there is evidence indicating that engine durability of construction equipment operating in Latin American geographies is less than the same or similar equipment operating within the United States. About

43% of oil samples taken from machinery operating in Latin America showed abnormalities whereas oil samples with abnormalities collected in the United States averaged 23%. Academic literature currently does not describe engine oil degradation characteristics of construction equipment operating specifically in Latin America. To scope the project and provide statistical significance, the research focused on John Deere 20-ton excavators powered by the John Deere PowerTech Plus 6068 diesel engine. To provide consistency in the oil analysis measurements and results, OSA3 oil analysis micro laboratories were employed to analyze all oil samples. These oil laboratories are located in 11 Latin America countries: Bolivia, Colombia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Honduras, Mexico, Paraguay, Peru, and Uruguay. Due to diverse machine operating conditions, it is safe to assume that they offer a good global representation. A total of 1064 oil sample results were evaluated at 500 hours of engine oil use. A subset of the data was evaluated at 250 hours of engine oil use.

The results indicated that at 500 hours, 73.4% of the oil samples showed that soot accumulation in diesel engines is a significant problem for 20-ton class excavators operating in Latin America. Also, tin and iron tested at significantly critical levels, 18.5% and 17.6% respectively. Silicon, sodium and potassium are present at an upper-level classification. At 250 hours of engine oil utilization, the wear metals considered for the analysis were iron, aluminum, copper, and lead. Also, the following external contaminants were analyzed: potassium, sodium, and silicone. At 250 hours of use there was a notable increase of the following wear metals and contaminates:

- Iron. The presence of iron particles in the oil can be traced to accelerated surface wear of cylinder liners, crankshafts, piston rings, connecting rods, oil pumps, and rocker arms.
- Lead. The presence of lead particles is commonly associated with accelerated surface wear of bearings and connecting rods.
- Copper. The presence of copper particles indicates premature wear to bearing systems and heat exchange systems.
- Aluminum. The presence of aluminum often indicates degradation within the cooling system.

- Silicon. Silicon is the most common contaminant found in engine oil. Due to its high molecular density and strength, it is abrasive to the internal components of an engine. Silicon is traceable to the environment.
- Potassium. Higher levels of potassium can be traced to cooling system cross-contamination with the lubrication system.
- Sodium. Sodium is often introduced from the operating environment of the machine.

After performing a statistical correlation of the presence and quantity of Fe, Si, Al, Sn, Pb, Ni, Cu, Na, K, soot, water, and fuel, the following are the results of greatest concern:

- There is a very strong ($r \geq \pm 0.70$) correlation between soot, water, and fuel, and a strong correlation between water and fuel.
  - The strong correlation (±0.40 to ±0.69) between iron and aluminum, tin, and copper.
  - The strong correlation between silicon and aluminum
  - The strong correlation between aluminum, tin and lead.
  - The strong correlation relationship between tin, lead, and copper.
  - The strong correlation between tin, lead, and copper.
  - The strong correlation between lead and copper.

The statistical analysis comparing the presence of wear metals and contaminants with evidence of nitration, oxidation, and TBN at 250 hours of engine oil use determined that the presence of water, soot, and fuel in the engine oil are the primary factors leading to oil oxidation, oil nitration, and the reduction of TBN.

As for the relation of wear metals and the operating environment, it was determined that bio-diesel is significantly associated with high levels of iron, copper, silicon, and Potassium. High soot levels critically affect levels of iron. Low quality diesel fuels resulted in high levels of iron PPM and moderately high levels of copper. Furthermore, low quality diesel fuels are associated with high levels of silicon and potassium. Operating at high altitudes is associated with high levels (PPM) of iron. Oil sample results from countries with higher levels of precipitation indicated higher levels of iron, potassium, and silicon. Oil sample results from countries with higher average temperatures indicated an increase of iron, silicon, and potassium.

Users can utilize CBM to perform a root-cause analysis and target the components with excessive wear. It will extend engine durability. Also, users will be able of scheduling machine down time without interrupting the construction project. Given these statistical correlations, when operating diesel engines in Latin American geographies, engine oil change intervals should be reduced below 250 hours to avoid premature wear to vital engine components. The high levels of silicon, sodium, and potassium indicate that water or coolant is entering the lubricating system, making direct contact with the engine oil. Water contamination leads to: (1) fluid breakdown (e.g., oil oxidation), (2) reduced lubrication film thickness, (3) corrosion, and (4) accelerated metal surface fatigue. This research points to the failure of engine gasket or failure of cooling system (e.g. coolant pump).

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CHAPTER 5: CONSTRUCTION EQUIPMENT ENGINE PERFORMANCE DEGRADATION DUE TO ENVIRONMENTAL AND OPERATING FACTORS IN LATIN AMERICA[4]

5.1. Introduction

In large scale global infrastructure projects, construction equipment can move between a variety of countries and even continents. Construction equipment engine performance and durability can be affected by the geography in which it operates. Operating altitude, primarily higher altitudes, is among the key risks faced by maintenance engineers. Latin America is a region where construction equipment is exposed to extreme variance in operating conditions (i.e., altitude, temperature, and humidity). While peer-reviewed literature focuses on engine performance at altitude in a laboratory setting, it lacks analysis targeting construction equipment operating in field conditions. Thus, maintenance engineers are left to use common system maintenance models or the manufacturer's scheduled maintenance charts. By applying a system view to system maintenance, the research utilizes oil analysis, operational data, and engine sensor data to recommend maintenance operations and schedules. Jaw and Merrill (2008) define this practice as CBM+.

At low hours, service engineers experienced premature engine wear when equipment operates at higher altitudes in Latin America. Thus, the objective of this research is to answer the following questions: What are the leading and earliest oil analysis indicators of engine wear on construction equipment working at higher altitude? (2) Does the Engine Control Unit computer (ECU) data identify issues related to the operating altitude?

To answer the research questions, the research analyzed and compared identical John Deere 200D excavators located in La Paz (altitude 3657 meter above sea level - masl) and Santa Cruz (altitude 416 masl). Identical 6.8 liter John Deere PowerTech Plus engines are used in both excavators. Engine oil from several usage time points was analyzed from both excavators to determine engine component wear tendencies. An OSA3 oil micro laboratory with infrared and atomic spectroscopy, viscometer, and laser

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[4] Paper under review in the Journal of Quality in Maintenance Engineering.

particle counter sub-systems was used to perform the following analyses: (1) elemental, (2) viscosity, (3) chemistry, and (4) particle count. Furthermore, operational, diagnostic trouble codes (DTCs) and engine sensor data from both excavators were obtained from the Engine Control Unit (ECU), analyzed, and compared.

5.2. Motivation

Organizations in the Latin America region spent $5 trillion dollars for infrastructure projects between 2000 and 2015 (Bridging global infrastructure gaps, 2016). Between 2016 and 2030, the region needs to spend an additional $7 trillion dollars (Bridging global infrastructure gaps, 2016). Thus, Latin America is an important market for construction equipment manufacturers. For instance, in 2017, Caterpillar retail sales to Latin America was up 55% (Retail Statistics, 2017). Given the importance of the Latin America market, it is remarkable that engine durability analysis for construction equipment operating in Latin America is not covered in the peer-reviewed literature. Unique machine applications in the region are foreign to testing and design engineers in the manufacturers' home markets. Thus, the reliance on customer support data is essential to improve engine design and reduce warranty costs for equipment operating in Latin America. Because 20-ton excavators are among the most popular products employed by equipment fleet owners, this research focuses on the engine durability of this excavator class size operating in Latin America.

The 6.8L John Deere engine is employed in the 200D 20-ton excavator. This specific machine operated at a high altitude in Bolivia. The 6.8L Tier III engine presented high fuel consumption at 100 hours. The engine oil was changed at 350 hours intervals, and presented higher than normal levels of viscosity. Furthermore, the engine oil was consumed at the abnormal rate of 0.94 liters per 379 liters of fuel. The machine operated at an average of 1750 RPM. The engine operated at 8% of its operating hours in Power mode and 92% in Economy mode. Black smoke was observed exiting the exhaust pipes during operation and at various RPM levels. Fuel consumption was also abnormal at an average of 22.7 liters per hour. The air filter did not present signs of contamination. The engine used JD Plus-50-II 15W30 engine oil. The average ambient temperature was 12°C in the region where the equipment was operated. The engine presented failure codes indicating low fuel rail pressure. The engine had been operating at altitudes close to 3660 meters above sea level. At this altitude, the standard barometric pressure is 66 kPa (496 mmHg), meaning that the engine is operating with only 65% of the oxygen available at sea level (Lerner, 1996, p.494). Furthermore, the mechanical compression test was below 410 psi and the cylinder compression differential was larger than 50 psi. The engine turbocharger was the first component to fail due to a lack of lubrication caused by inadequate engine oil viscosity. The engine failed at 1511 hours. The engine blow-by level tests showed levels above 50.8 mm of water. As seen in Figures 5.1 and 5.2, after disassembling the engine, the engine exhibited a high accumulation of engine oil sludge and the pistons exhibited excessive wear. Engine filtering sub-systems failed to absorb the excess soot. Also, the engine lubrication sub-system failed to provide sufficient lubrication as seen in Figure 5.2. Unique operating conditions in Latin America include poor fuel quality and topography. Key concerns include operating altitude, diesel fuel sulfur content, quality of biodiesel fuel, and fuel storage.

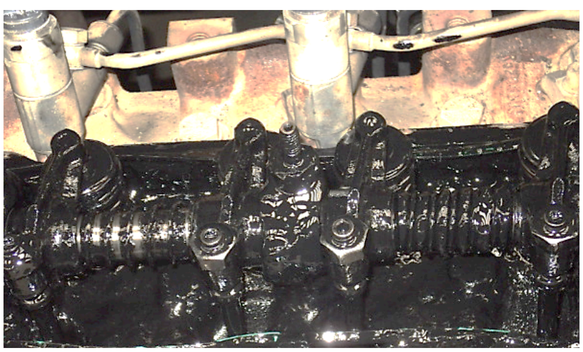

Figure 5.1: Sludge Accumulation

Figure 5.2: Oil Engine Pistons

5.3. Literature Review

Pintelon, Preez, and Puyvelde, (1999), list the following methodologies for maintenance approach: failure-based maintenance, use-based maintenance, condition-base maintenance, opportunity-based maintenance, design-out maintenance, preventative maintenance, mean time to repair, and mean time between failure. Kossiakoff et al (2011) recommend to apply Bayer's Rule to determine system maintenance requirements. It is based on the probability of system failure over the life-cycle of the system, the probability of system maintenance over its life-cycle, and the probability that preventive maintenance will be performed on the system during its life-cycle. Bayer's Rule is based heavily on statistical data and historical analysis for repetitive applications. Associating maintainability practices with reliability is yet another common statistical maintenance model. It is determined by calculating the mean time between failure (MTBF) or mean time between repair (MTBR) (Mobley, 2014). However, for unknown operating environments, it is a common practice for construction equipment manufacturers to determine reliability and durability of machines based on warranty claims, which are only based on a 12-month period. This time period might not be sufficient since the equipment may not be operated an adequate amount during the 12-month period to gather enough data for statistical analysis. Furthermore, construction equipment operating in Latin America is exposed to a wide range of operating conditions such as a variety of climes, terrains, applications, fuel, and fuel quality that could lead to data variability. Also, Wong, Jefferis, and Montgomery (2010) state that many traditional such as Weibull maintenance model "does not take into account environmental or diagnostic data that may be available" (p.146).

According to Mobley (2014), predictive system maintenance begins with the machine operation. Predictive Maintenance (PM) techniques involve (1) process parameters, (2) vibration monitoring, (3) thermography, (4) operational parameters, (5) visual inspections, and (6) tribology (Mobley, 2014) (Pintelon, Preez, and Puyvelde, 1999). A form addressing machine maintenance is to combine PM techniques with operational parameters and tribology analysis. Tsang (2013) defines operating parameters as "process-parameter monitoring" where machine data points such as fluid pressure, temperature, heat generation or loss, are collected and compared with the system expected performance. Thus, to provide a complete assessment of engine systems maintenance, traditional conditional maintenance analysis, such as oil analysis, should be associated with the data gathered by the on-board computer of the engine (Soliman, Rizzoni, and Krishnaswami, 1995). As an example, by collecting data from engine sensors, engineers could assess engine misfire, air and fuel temperature. Jaw and Merrill (2008) define this practice as Condition Base Management Plus (CBM+) where proactive maintenance is associated with on-board monitoring and off-board information analysis. Furthermore, Blau (2006) advocates the study of tribology in the context of the engine system. Blau (2006) states, “tribosystem is any system that contains one or more tribo-elements, including all mechanical, chemical, and environmental factors relevant to tribological behavior” (p.1).

Macian et al (2003) state the following factors should be taken in consideration when evaluating engine wear: (1) wear measurement technique limitation, (2) engine or machine operating conditions, (3) engine oil consumption, (4) filtering effect, and (5) oil composition. Also, Esangbedo, Boehman and Perez (2012) stated that changes in engine design should be considered when evaluating wear. For instance, the addition of exhaust gas recirculation (EGR) sub-systems had contributed to the increase of engine oil degradation by elevating the level of soot, leading to the loss of oil viscosity (Esangbedo, Boehman and Perez, 2012). The cause-effects of this problem are not fully understood (George et al, 2006). However, Esangbedo, Boehman and Perez (2012) suggest the possible causes could be rooted in the operating environment such as operating temperature combined with low oxygen levels (altitude). The consequence of an increased level of soot can be determined by the increase of oil viscosity and scuffing metal wear on engine components such as engine pistons (Ryason, Chan and Gilmore, 1990). This specific wear is caused by the failure of the engine oil to adequately lubricate the cylinder walls (George et al. 2006). Also, George et al (2006) suggest that an early indication of soot generation is the increase of engine fuel consumption.

5.4. Research Method

5.4.1 Diesel Engines Studied

Two 6.8 liter John Deere PowerTech Plus engines were the subjects of this study. The first engine was located in La Paz, Bolivia and operated at an altitude averaging 3657 meters above sea level. The second engine was located in Santa Cruz, Bolivia and operated at an altitude averaging 416 meters above sea level. These engines are used in the 200D 20-ton excavator evaluated in this research. While this engine can be programmed to generate more output, the 6.8L PowerTech Plus in the 200D excavator is rated at 122 kW, or 164 HP, Net SAE at 2000 RPM (Operating Manual for 200D and 200DLC Excavators, 2010). The engine meets the U.S. Environmental Protection Agency (EPA) emission regulation defined as Tier 3. The EPA Tier 3 regulation mandates that the exhaust emission standards for non-road compression-ignition engines between 75 and 130 kW have the following emission limits: NMHC + NOx 4.0 g/kW-hr, particulate matter (PM) 0.30 g/kW-hr, and CO 5.0 g/kW-hr (Non-road Compression-Ignition Engines: Exhaust Emission Standards, 2016). The engine meet these emissions during the machine useful life defined as 8000 hours or 10 years (Highway and Nonroad, Locomotive, and Marine (NRLM) Diesel Fuel Sulfur Standards, 2016). Also, the U.S. EPA regulates the fuel sulfur levels for these engines. Starting in 2010, refineries and importers should not sell fuel in the U.S. market containing sulfur at 500 PPM or higher (Highway and Nonroad, Locomotive, and Marine (NRLM) Diesel Fuel Sulfur Standards, 2016). According to the U.S. EPA, "ULSD (Ultra-Low Sulfur Diesel, less than 15 PPM) is necessary for new advanced emission control technologies and it contributes to particulate matter reductions in the existing fleet of non-road engines and equipment" (Basic Information about the Emission Standards Reference Guide for On-road and Non-road Vehicles and Engines, 2017).

According to John Deere (6.8L Industrial Diesel Engine, 2017) this engine features a 4-valve per cylinder head, a variable geometry turbocharger (VGT), cooled exhaust gas recirculation (EGR), a high pressure common-rail, and an engine control unit. The following are the engine specifications:

- Intermittent rated power and rated speed: 205 kW (275 HP) at 2000 to 2400 RPM.
- Number of cylinders: 6
- Displacement: 6.8 Liters (415 cu in)
- Bore and Stroke: 106 mm x 127 mm (4.17 in x 5.00 in)
- Compression Ratio: 17.0:1
- Engine Type: In-line, 4-Cycle
- Aspiration: Turbocharged and air-to-air after-cooled
- Length: 1161 millimeter or 45.7 inches
- Width: 616 millimeter or 24.3 inches
- Height: 1128 millimeter or 44.4 inches
- Weight: 678 kilograms or 1495 pounds
- The oil pan size capacity: 0.16 L/kW

The engine manufacturer made a significant change to the engine that allows it to meet U.S. EPA regulations. This change includes an engine control unit (ECU) that gathers CAN data from various sensors to determine: crankshaft position, oil pressure, engine coolant temperature, fuel temperature, water-in-fuel, fuel pressure, throttle position, and fuel injector events (6.8L Industrial Diesel Engine, 2017). The system outputs include signals to fuel injector solenoids that specify the quantity of fuel to ignite in the combustion chamber. Fuel quality, bio-diesel, and sulfur levels are important because they impact the combustion process. ECUs must be reprogrammed based on the type of fuel used and its composition. It affects engine combustion strategies such as "the amount of ignition delay, which affects combustion temperatures and pressures, which in turn influences the amount of NOx and PM formation in the exhaust" (Block, 2007).

5.4.2. Measuring Oil Laboratory Equipment

The On-Site Oil Analysis micro laboratory was used to analyze engine oil samples. Made by Spectro Scientific, the laboratory utilizes ASTM D7417 (Standard Test Method Analysis of In-Service Lubricants Using Particular Four-Part Integrated Tester) to perform oil analysis (White Paper - MicroLab Series Fully Automated Oil Analyser, 2017). Once the oil sample is inserted, the laboratory performs the following analysis in this order: (1) elemental analysis, (2) viscosity analysis, (3) chemistry analysis, and (4) particle count. The laboratory is composed of several sub-systems: infrared and atomic spectroscopy, viscometer, and a laser particle counter. The following are the elements analyzed by the oil laboratory: phosphorus (P), molybdenum (Mo), aluminum (Al), lead (Pb), calcium (Ca) , boron (B), tin (Sn), iron (Fe), vanadium (V), barium (Ba), titanium (Ti), copper (Cu), manganese (Mn), potassium (K), nickel (Ni), zinc (Zn), chromium (Cr), sodium (Na), magnesium (Mg), and silicon (Si) (White Paper - MicroLab Series Fully Automated Oil Analyser, 2017). The atomic wavelengths and spectrum of these elements are determined by Optical Emission Spectroscopy (OES). Since each element has a unique atomic structure, the OES can determine the difference among oil additives, mechanical wear, and the source of contamination (White Paper - MicroLab Series Fully Automated Oil Analyser, 2017). To determine the oil chemistry, the oil laboratory utilizes an infrared (IR) spectroscopy sub-system. It is also useful to determine oil degradation and contamination. The IR determines total base number (TBN), oxidation, nitration, soot, water, and glycol.

To measure viscosity up to 680 cSt, a kinematic dual temperature (40°C and 100°C) viscometer sub-system is utilized. A laser particle counter sub-system is utilized to determine particle count and the size of contamination (particles over 4μm [per mL]). This subsystem is composed of a light-blockage sensor (a diode laser and detector). It follows the ISO 11171 standard of light blocking technique.

5.4.3. Sampling Scope

The oil samples were collected at 88, 98, 161, 197, 218, and 250 engine oil hours for the La Paz excavator and at 80, 101, 173, 192, 236, 252 hours for the Santa Cruz excavator. In both cases, the engines used John Deere Plus 50-II 10W30 engine oil. The data was cataloged as engine wear metals parts per million counts (PPM) (lead, iron, tin, copper, chromium, aluminum), engine oil signature measurement (barium, magnesium, phosphorus, zinc, and calcium), and engine oil contaminants (sodium, potassium, boron, silicon, soot, and water). This research sample scope focuses on the engine wear metals and engine oil contaminants. Table 5.1 shows the oil sample ranges for each wear metal and contaminant.

Table 5.1: Sample Ranges Classification in PPM

	Lower		Upper		Abnormal		Critical
	From	To	From	To	From	To	Over
Iron	0	35	36	70	71	100	100
Silicon	0	5	6	20	21	30	30
Aluminum	0	15	16	30	31	45	46
Tin	0	1	2	3	4	5	5
Lead	0	15	16	25	26	40	40
Nickel	0	2	3	4	5	8	8
Copper	0	15	16	25	26	40	40
Sodium	0	5	6	30	31	50	50
Potassium	0	10	11	30	31	50	50
Soot	0.00%	1.50%	1.50%	2.90%	3.00%	4.90%	5.00%
Water	0.00%	0.10%	0.10%	0.20%	0.21%	0.99%	1.00%

5.4.4. Engine Control Unit (ECU) Data.

Engine data was extracted from the ECU by either connecting a laptop directly to the excavator CAN bus terminal or by obtaining the engine diagnostic trouble codes (DTCs) from the machine telematics system. The following DTCs data was extracted remotely from the ECU of each machine via telematics system: (1) water in fuel, (2) extreme low coolant levels, (3) low oil pressure, (4) extremely high exhaust manifold temperatures, (5) engine coolant temperature measuring extremely high, (6) extremely restricted engine air filters, and (7) fuel filter restrictions. The following operating data was extracted remotely from the ECU of each machine via telematics system: (1) engine running hours, (2) non-operating hours, (3) travel hours, (4) excavator swing hours, (5) excavator digging hours, and (6) hours using attachments, (7) engine high power mode hours, (8) engine power mode hours, (9) engine economic mode hours, (10) machine travel hours at high velocity, (11) machine travel hours at low velocity, and (12) machine in auto idle mode hours. Also, by physically connecting a laptop to the excavators with the Service Advisor System, specific sensor data were obtained: (1) actual fuel rail pressure versus actual engine speed (rpm), (2) actual engine speed versus fuel temperature, (3) actual fuel rail pressure versus desired fuel rail pressure, (4) exhaust temperature, (5) variable geometric turbo-charge position, and (6) exhaust recirculation valve position.

5.5. Results

To conduct the research, two 200D John Deere excavators were studied that operate in the Bolivian cities of La Paz and Santa Cruz. Both machines were monitored for a period of 3 months during which they accumulated 250 and 252 hours, respectively. Oil analysis for both machines were analyzed and compared. Also, data was obtained from the ECU (machine utilization data, diagnostic trouble code, and specific sensor readings) of each excavator. It is important to note that the diesel fuel is similar in La Paz and Santa Cruz. The fuel quality is considered to be poor due to a high level of sulfur content, over 2000 parts per million (PPM) (Diesel Fuel Sulphur Levels: Latin America and Caribbean Region, 2017). Also, water-in-fuel is predominant in Bolivia.

The first excavator operated in the city of La Paz at an altitude of 3657 meters above sea level. At this altitude the standard barometric pressure is 66 kPa (496 mmHg), meaning that the engine is operated at 65% of the oxygen available at sea level (Lerner, 1996) over the period of 250 hours. The city of La Paz has annual temperatures ranging from -3°C to 12°C (Climate: Bolivia, n.d.). Precipitation levels range from 7 mm to 115 mm annually (Climate: Bolivia, n.d.). In comparison, the second excavator operated in the city of Santa Cruz, Bolivia with altitude of 416 meters above sea level. At this altitude, the standard barometric pressure is 97 kPa (725 mmHg), meaning that the engine operated at 95% of the oxygen available at sea level (Lerner, 1996) over the period of 252 hours. The city of Santa Cruz has annual average temperatures ranging from 15.9°C to 26°C (Climate: Bolivia, n.d.). Precipitation levels range from 50 mm to 199 mm annually (Climate: Bolivia, n.d.). According to the United Nation Environment Programme the diesel sulfur content is from 500 PPM to 2000 PPM (Diesel Fuel Sulphur Levels: Latin America and Caribbean Region, 2017). Figure 5.3 show locations and elevations of the excavators in Bolivia. The excavator to the left in the map is located in La Paz and the excavator in right is located in Santa Cruz.

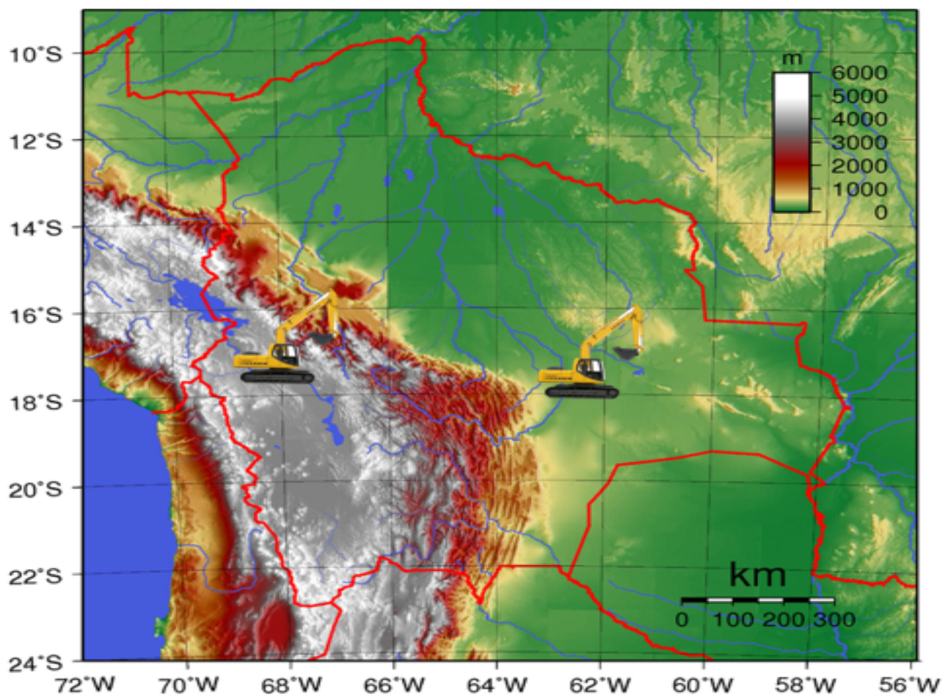

Figure 5.3: Excavators geo-location by altitude

Figure 5.4 shows the excavator operating La Paz and Figure 5.5 shows the excavator operating in Santa Cruz. In these pictures, there is visibly more smoke coming out of the engine operating La Paz versus the engine operating in Santa Cruz. It is important to note that the excavator in La Paz is lifting the boom, thus, with very little engine load. However, excavator in Santa Cruz is excavating, thus, with the highest engine load.

Figure 5.4: Excavator in La Paz

Figure 5.5: Excavator in Santa Cruz

5.5.1. Oil Analysis

Engine oil analysis is the primary set of data analyzed to determine whether there was differences between internal engine wear between these two excavators. The oil samples were collected at 88, 98, 161, 197, 218, and 250 engine oil hours for the excavator in La Paz and 82, 101, 173, 192, 236, 252 hours for the excavator in Santa Cruz. John Deere Plus 50-II 10W30 engine oil was used in both excavators. The following wear particles were analyzed as shown in Table 5.1: lead, iron, tin, copper, chromium, and aluminum. Furthermore, sodium, potassium, glycol, water, and silicon particles were evaluated as contaminants. The oil characteristic such as viscosity, oxidation, and TBN were also assessed.

The results indicated an increase of wear metals, lead, iron, tin, copper, chromium, and aluminum. However, only iron prematurely reached abnormal and critical levels. Particles related to contaminants also had a notable increase over time. Potassium, glycol, soot, and water reached abnormal and critical levels during the period analyzed. In reference to the oil characteristics, viscosity, oxidation and TBN reached alarming levels. The following sections describe the results in greater detail.

Iron was the earliest wear metal to reach upper, abnormal, and critical levels. Figure 5.6 presents the plotted results of the excavator operating in La Paz (represented by the black line) and the excavator operating in Santa Cruz (represented by the gray line). The y-axis represents the wear particle levels measured in parts per million (PPM) and the x-axis represents the engine oil hours. The iron level intervals shown in Table 5.1 are represented by the green, brown, and red lines. Results below the green line are considered normal. Results between the green line and brown line are upper range and are subject of concern. The results between the brown line and red line are abnormal. The results over the red line are classified as critical.

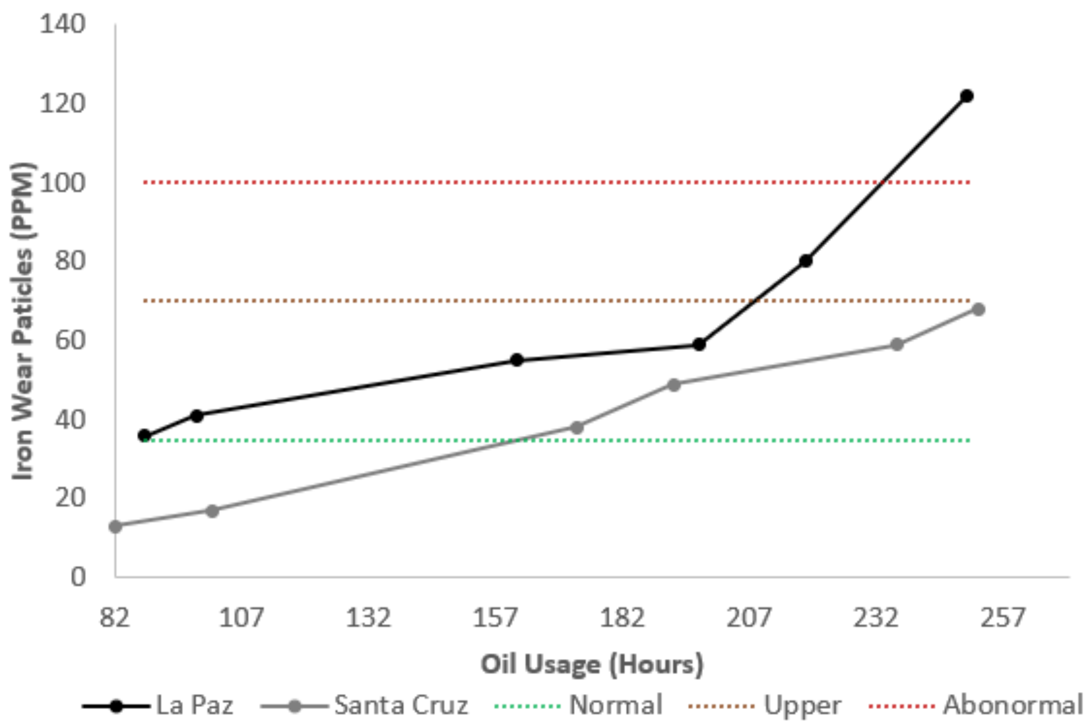

Figure 5.6: Iron

Figure 5.6 indicates that the engine subcomponent is wearing at an alarming rate. The cylinder pistons and cylinder liners were the first components to exhibit visible signs of wear similar of the damage presented in Figure 5.1. Furthermore, the oil pump exhibits scuffing, a sign that a lack of lubrication caused gear surface damage.

Potassium is classified as a contaminant in engine oil analysis. It is commonly found as an engine coolant or antifreeze additive (Holloway, n.d.). As indicated in Figure 5.7, the increase in potassium for the La Paz machine is significantly higher than the Santa Cruz machine. It took 252 hours for the Santa Cruz machine to reach abnormal levels, while the La Paz machine approached a critical level of potassium within that same period of usage.

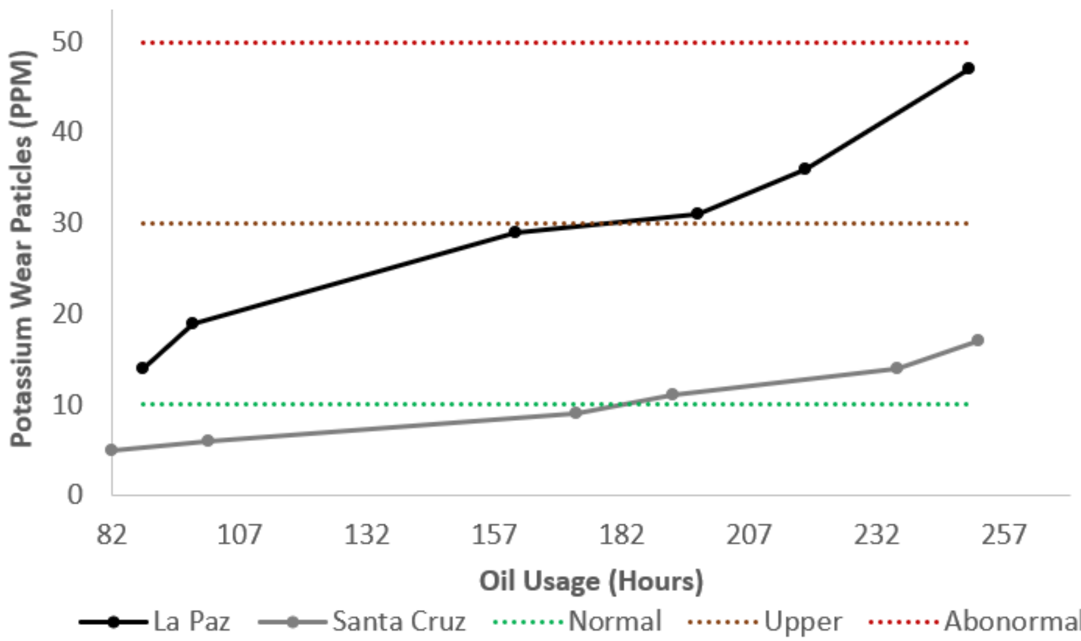

Figure 5.7: Potassium

The presence of this contaminant points to "defective seals, electrochemical erosion, cavitation erosion, corrosion of the liners, a damaged cooler core, a blown head gasket, or a crack in the cylinder head or block" (Root Causes of Sodium and Potassium in Engine Oil, n.d.). Contact of coolant with the engine lubrication system leads to thickening of the engine oil, creation of gels, and emulation in engine oil (Root Causes of Sodium and Potassium in Engine Oil, n.d.).

The glycol contamination is commonly associated with the presence of potassium in the oil analysis. Glycolic acids are often created when glycol is exposed to high temperature. These acids "react with the oil anti-wear and anti-oxidant additives and, along with water, create sludge that plugs filters and cause the oil to lose its lubricity properties, thus increasing abrasive wear" (Guide to Measuring Glycol Contamination in Oil, 2017). The industry has not come to an agreement about the normal, upper, abnormal, or critical levels of glycol. Schiff's reagent method as stated in the ASTM D2982 is commonly used to classify glycol contamination. This method classifies in ranges of 0-50 ppm, 51-100 ppm, 101-500 ppm, and over 1000 ppm. During the time period of oil samples, glycol (measure in percentage by weight) content increased over time. Figure 5.8 shows the progression of glycol content over time in the engine oil. An increase of glycol can significantly decrease engine oil dispersancy performance allowing soot accumulation to increase at greater rates (Troyer, 1999).

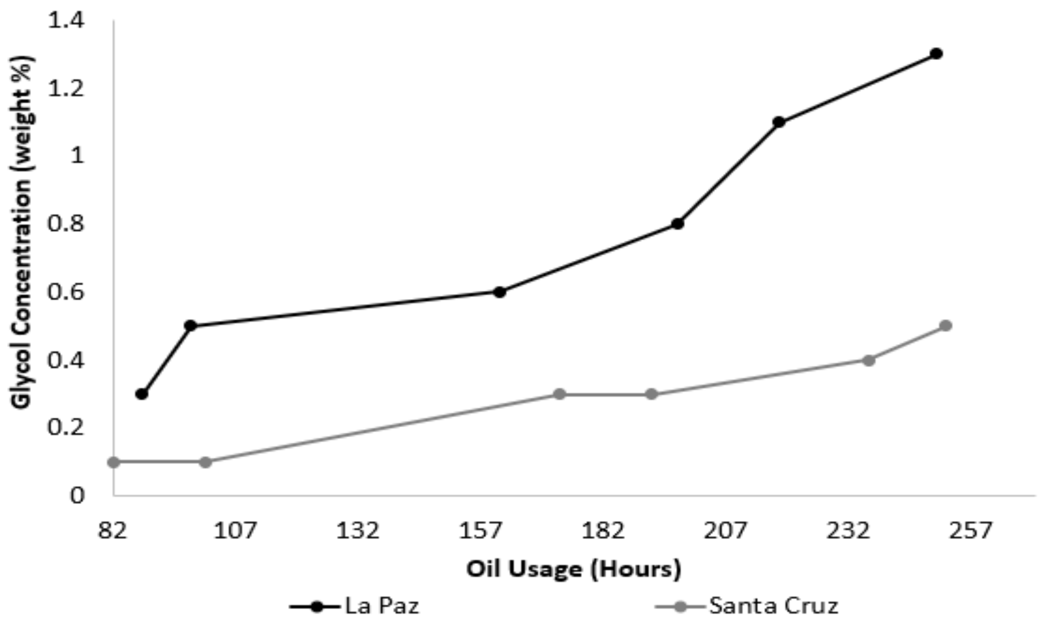

Figure 5.8: Glycol

Water contamination intensifies engine oil degradation by (1) increasing engine internal corrosion, (2) increasing oil oxidation, (3) depleting oil additives, (4) reducing lubrication film thickness, and (5) increasing metal surface fatigue (Testoil, 2017). As indicated in Figure 5.9, the excavator operating in La Paz exhibited a much greater increase of water contamination. The sources of contamination could be rooted in “heat exchanger leaks, seal leaks, condensation of humid air, and inadequate sealed reservoir covers” (Testoil, 2017, p.47). Since La Paz is a city with relatively low humidity and precipitation, the source of water contamination is likely to be caused by an internal leak.

The impact and sources of soot contamination in diesel engines are well-documented in the peer-reviewed literature. However, the results showing the same system operating in two extreme environments should be explored. Figure 5.10 shows that the engine operating at the higher altitude (La Paz) has a significant increase of soot generation compared to the engine operating at the lower altitude (Santa Cruz). The rapid increase of soot indicates inefficient engine combustion. Combined with an EGR system, carbon particles are being introduced back into the engine in greater quantities in the excavator working in La Paz. Because great amounts of soot particles were introduced back into the engine, the dispersant additives in the engine oil failed to contain them.

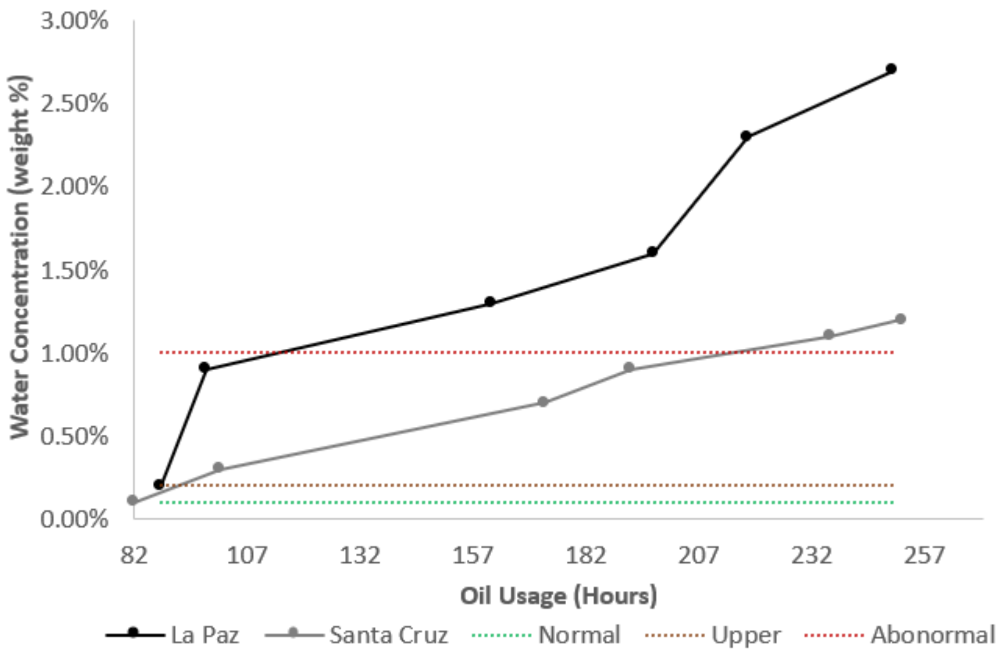

Figure 5.9: Water

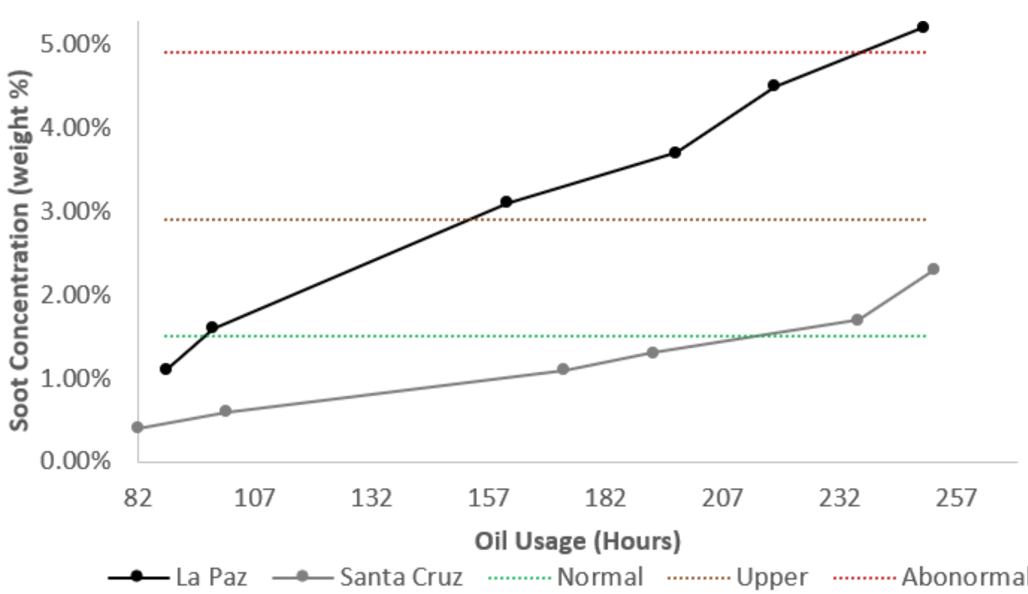

Figure 5.10: Soot

The factors leading to excessive soot levels include: (1) excessive engine idling, (2) worn piston rings, (3) injectors with poor fuel spray patterns, (4) inefficient air to fuel ratio (Soot in Diesel Engines, 2011). The result is: (1) loss of oil dispersancy additives, (2) sludge formation, (3) loss of oil anti-wear performance, (4) increased deposits that block oil passages, (5) increase of oil viscosity, (6) filter plugging, (7) engine overheating, (8) decrease of turbocharger lubrication, and (9) reduced oil flow (Troyer, 1999). For instance, Troyer (1999) states that "the sudden loss of dispersancy leads to rapid agglomeration and deposition of soot onto machine surfaces." The final result is a reduction of engine piston compression, loss of engine power, and an increase of fuel consumption (Soot in Diesel Engines, n.d.).

Engine oil viscosity is defined as a measurement of fluid's resistance to flow (Oiltest, 2017). According to Blau (2006), the change of oil viscosity is an indication of "chemical degradation of the oil, excessive contamination, volatilization of oil components, and mixing or topping-off with other oils" (p. 21). Contaminants such as soot, water, glycol, and potassium have an adverse impact on viscosity. Figure 5.11 shows the engine oil viscosity change of the excavators working in La Paz and Santa Cruz. The oil viscosity is measured in cSt, a kinematic temperature at 100°C. The engine oil viscosity of the excavator working in La Paz reached upper, abnormal, and critical levels at very low usage hours. Figure 5.11 confirms that contaminants (water, glycol, soot, and potassium) impacted the engine oil viscosity.

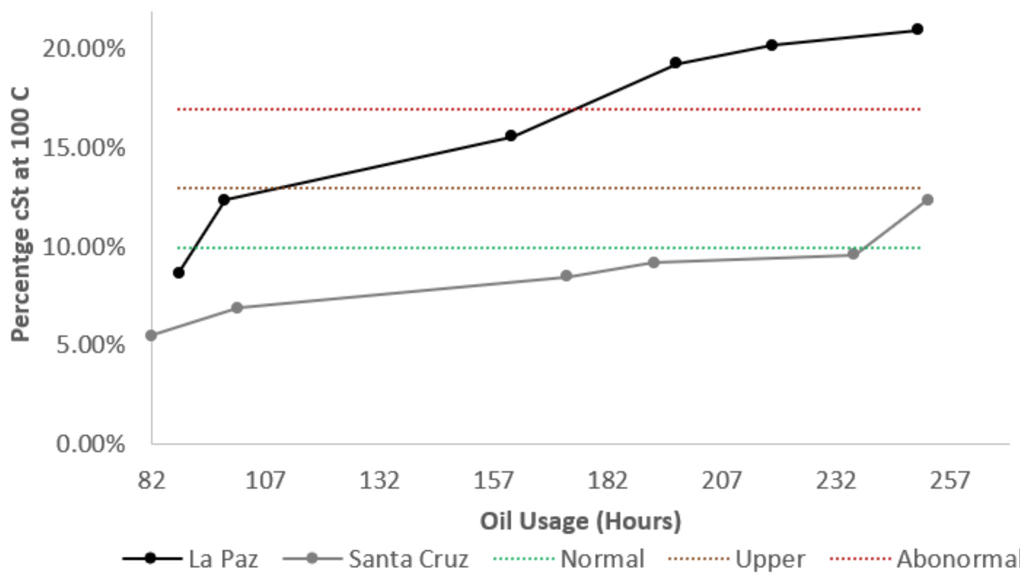

Figure 5.11: Viscosity

The Total Base Number (TBN) is the oil capability to neutralize acids during the combustion process and acid contamination. It can provide information regarding (1) the level of oil alkalinity used to reduce acids, (2) soot contamination, (3) poor combustion, (4) fuel quality, (5) oil oxidation, and (6) engine blow-by (Blau, 2006). Potassium hydroxide is a common additive found in engine oil designed to neutralize acids. It is defined as the "number of milligrams of potassium dydroxided required to neutralize one gram of oil" (Oiltest, 2017). Figure 5.12 shows the TBN depletion over time of the excavators in La Paz and Santa Cruz. The higher the TBN the better. Thus, TBN above the green line is considered normal, between the green and brown line is classified as abnormal, and below the red line is critical.

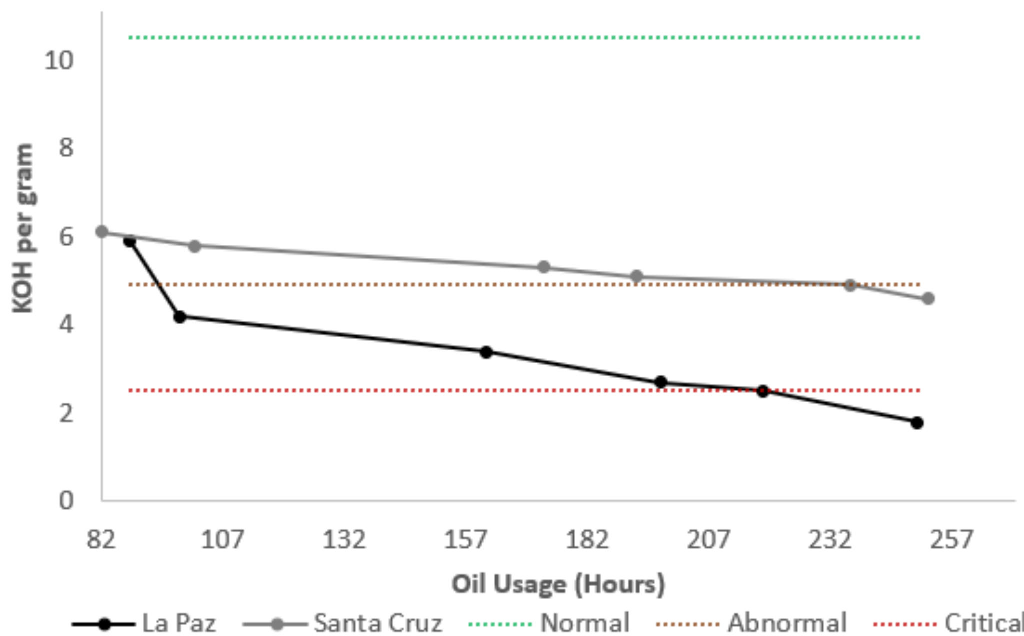

Figure 5.12: TBN

Oxidation is a normal, time-based oil degradation process. Figure 5.13 shows that while both excavators have an alarming increase in oxidation, the excavator in La Paz reached abnormal levels at only 200 hours. According to Fitch (2015), oil oxidation is accelerated when exposed to: (1) oxygen, (2) wear metals such as iron, (3) nitro-oxides, (4) ultraviolet radiation, (5) elevated temperatures, (6) water, and (7) free radicals such as alkyl. When an oxidation chain reaction begins and high temperatures are prevalent, oxygenated compounds lead to the creation of carboxylic acid, ester, sludge, and vanish deposit (Fitch, 2015). Furthermore, according to Fitch (2015), "corrosion will be promoted as water and acids exist on metal surfaces if the corrosion inhibitor additives are depleted."

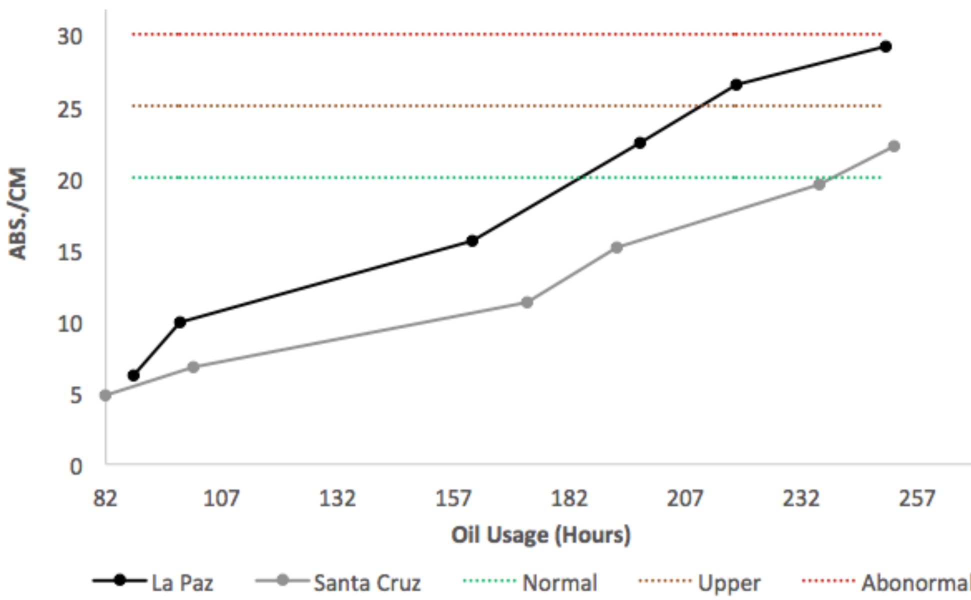

Figure 5.13: Oxidation

5.5.2. Engine ECU Data

Blau (2006) suggests to approach tribology studies from a system perspective so possible cause and effect associations can be drawn. Thus, this section seeks to determine whether there is an impact of the engine wear diagnosed using oil analysis to overall system performance. Therefore, critical ECU data is analyzed. The comparison data points are (1) the machine utilization, (2) diagnostic trouble codes, and (3) ECU readings such as engine revolutions per minute (RPM), fuel temperature, and fuel common rail pressure data.

5.5.2.1 Machine Utilization:

When analyzing engine durability, it is important to first understand machine utilization (how the machine has been used). Machine utilization data can be extracted by connecting a laptop diagnostic computer to the CAN bus of the machine or by remotely accessing the telematics module of the machine. Figure 5.14 shows the ECU operational data for the engines operating in La Paz and Santa Cruz (Bolivia).

The engine of the La Paz excavator spent 93% of its operating time in the Economy Mode while the engine in Santa Cruz was primarily utilized in the Power Mode (56% of operating time) and High Power Mode (35% of operating time). Given the amount of time the Santa Cruz excavator spent in the power mode, combined with the high number of digging operation hours indicates that the engine operated under significant load. Both machines have the auto idle option enabled; thus, when the hydraulic pumps of the machine are not operating or the machine is not traveling, the engine lowers its RPM to the lowest possible range. Low RPMs adversely affect engines working at higher altitudes as fuel is not combusted efficiently. Troyer (1999) states, "at idle, about 70% of the exhaust gas is recirculated, while only about 10-20% is recirculated at full load." The high exhaust gas recirculation injects back black particulate matter to the engine. Thus, improper machine utilization can lead to accelerated internal engine wear. To optimize system performance excavators are designed and should work at the RPM recommended by the manufacturer. The designed system performance results in optimum combustion, engine power, and reduced wear. The gathered data indicates that the engine operating in Santa Cruz better fits this description.

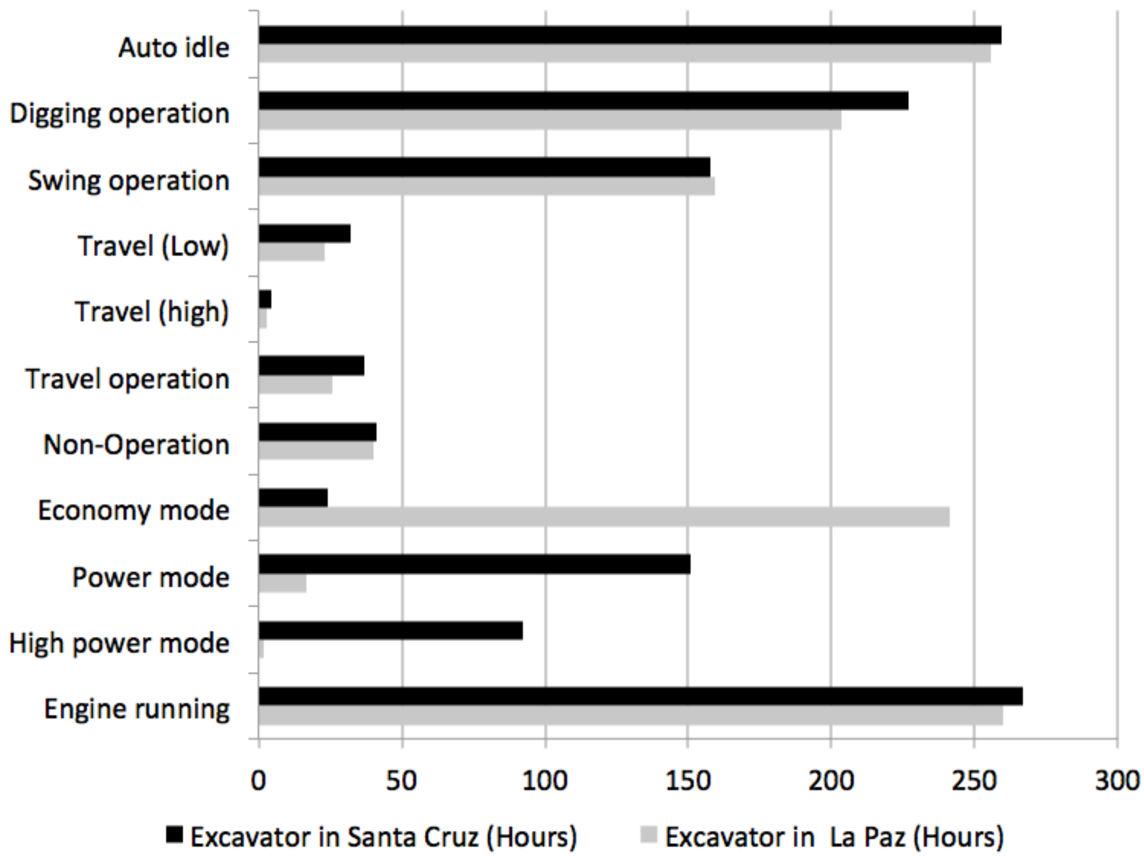

Figure 5.14: Machine Operating Data in Santa Cruz and La Paz

5.5.2.2 Diagnostic Trouble Codes (DTCs) Results:

During the research, DTC data was extracted from the ECU of both engines. A total of 27 DTCs from various sensors recorded the following engine alerts: extremely low coolant levels, water in fuel, and extremely high exhaust manifold temperatures. Table 5.2 shows the percentage of DTC alerts for each category and for each machine.

Table 5.2: Percentage of Diagnostic Trouble Codes

Diagnostic Trouble Codes	Excavator in La Paz	Excavator in Santa Cruz
Extreme low coolant levels	39%	34%
Water in fuel	35%	57%
Extreme high exhaust manifold temperatures	26%	9%

The extremely low coolant levels and extremely high exhaust manifold temperature are related. Technicians visiting the machines reported that it was common for operators to add contaminated water to the radiator (cooling system) instead of the manufacturer's recommended Cool-Gard coolant. Water can cause internal oxidation of the engine internal components, lead to accumulation of deposits (minerals) in the radiator and engine galleys, cause micro explosions when exposed to high temperature, cause cavitation of the coolant pump, and lead to high exhaust manifold temperatures.

The water in fuel alert is a clear indicator of contaminated fuel. Water can pass through the primary and secondary fuel filters and sent to the high-pressure injector nozzles and finally the combustion chamber. Water in fuel causes inefficient combustion, erodes cylinder liners, and leads to premature wear of the injector nozzles.

5.5.2.3 ECU Sensor Data:

Engine Control Unit data was extracted from the excavators located in Santa Cruz and La Paz. Data was obtained from sensors for the variable geometry turbo (VGT), exhaust gas recirculation (EGR), exhaust temperature, engine RPM, engine fuel temperature, and engine rail pressure.

Table 5.3 shows the position percentage open of the VGT actuators, position percentage open of EGR valve, and average temperature of exhaust manifold. Also, noted in Table 5.3 is the target and observed values. As determined in Table 5.3, despite of the much higher altitude, the VGT position for the engine operating in La Paz opened below target and below Santa Cruz engine. The EGR on the other hand was much open when compared with target and Santa Cruz. The engine in La Paz was operating hotter than the engine in Santa Cruz.

Table 5.3: VGT actuators, position of EGR valve, and average temperature of exhaust manifold

Sensors	La Paz	Santa Cruz
VGT Open - Target	53.00%	50.00%
VGT Open - Observed	47.70%	50.30%
EGR Open - Target	47.40%	61.70%
EGR Open - Observed	70.70%	61.90%
Exhaust Temperature	513.3C°	298C°

Each excavator engine RPM was analyzed and compared to fuel temperature. Figure 5.15 shows in the left y-axis the engine RPM of the machine located in La Paz. The right y-axis represents fuel temperature of the same excavator. The x-axis represents the time period in hours, minutes, and seconds (HH.MM.SS). The red line represents the engine RPM and the blue line represents the fuel temperature. It is important to note that this data was extracted while the machine was operating at 3657 meters above sea level, at an ambient temperature of 3°C. As shown in the graphics, when the engine started cold, it is programmed to reach a minimum of 1400 RPM. However, at 200 to 600 RPM, the engine cylinders misfired which caused it to lose RPM, showing a loss of power. At the 2 minute and 30 second mark, the engine started to reduce RPM. At the 3-minute mark, the engine settled at 700 RPM and tried to recover after 30 seconds, and then shut down at 4 minutes.

The engine common rail pressure system, measured in Megapascal (MPa), was compared with engine RPM. The engine common rail pressure is represented by the left y-axis and the engine RPM is presented by the right y-axis. The x-axis represents the time period in hours, minutes, and seconds (HH.MM.SS). The red line represents the fuel pressure and the blue line represents the engine RPM. Figure 5.16 shows that for the time period of 25-30 seconds recorded, engine RPM decrease and the fuel system lost pressure. Furthermore, inconsistent pressure is noted throughout the entire period. In this graphic, the engine RPM drop follows the same pattern of common fuel rail. The drop at specific intervals leads to believe that a specific cylinder is misfiring.

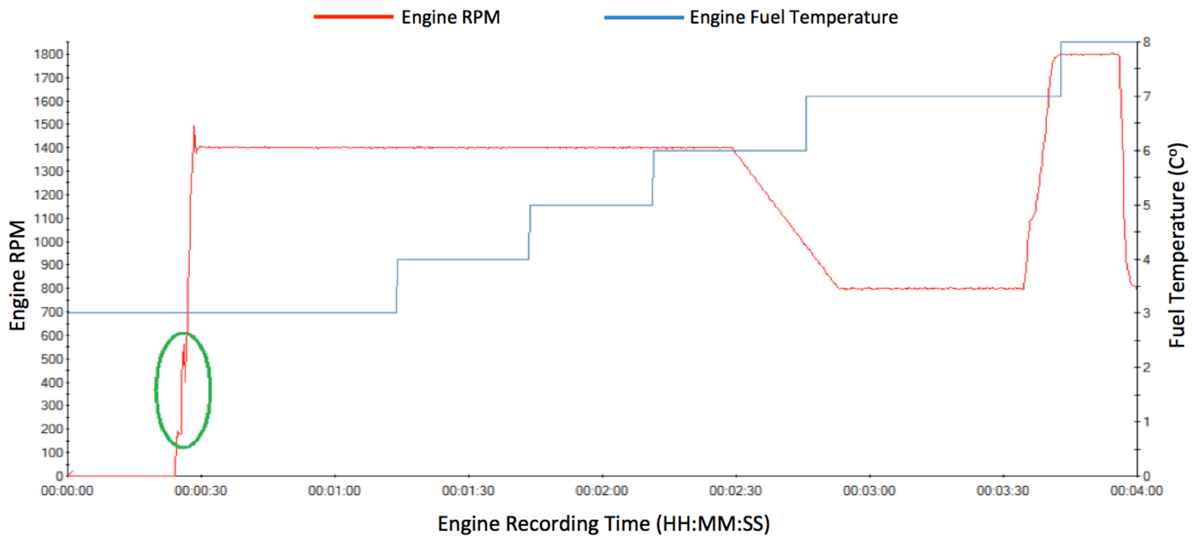

Figure 5.15: RPM versus fuel temperature in La Paz

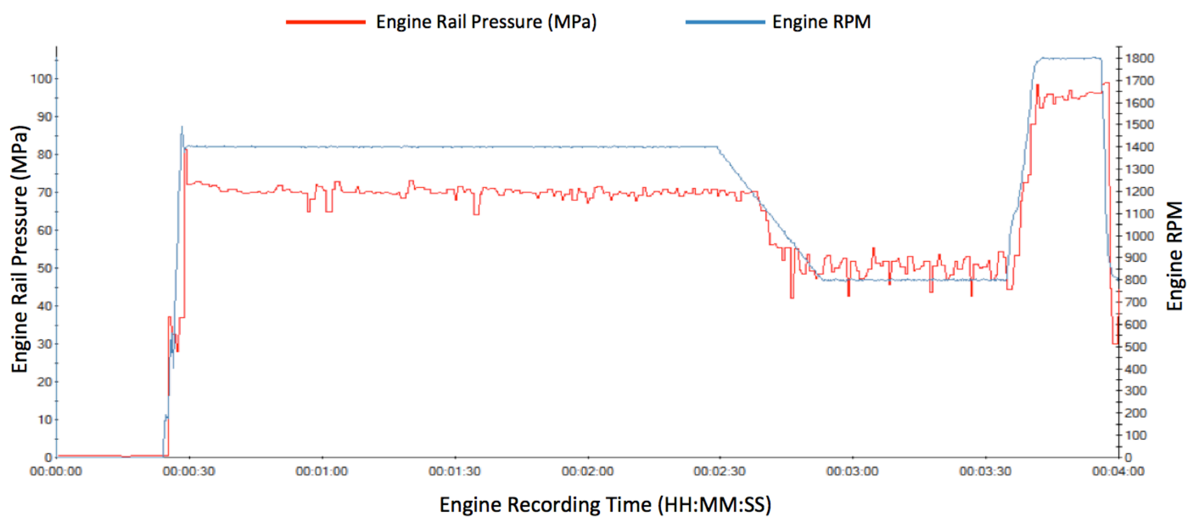

Figure 5.16: Rail pressure versus engine RPM in La Paz

Engine loss of power was not observed in the excavator operating in Santa Cruz with an altitude of 416 meters above sea level. However, for comparison, ECU data was obtained to compare the fuel temperature with the engine RPM. The Figure 5.17 left y-axis represents the fuel temperature and the right y-axis represents the engine RPM. The x-axis represents the time period of the ECU recording in hours, minutes, and seconds (HH.MM.SS). The red line represents the fuel temperature and the blue line represents the engine RPM. In contrast to the La Paz engine, the Santa Cruz engine speed is constant at 1900 RPM while the fuel temperature averages 40°C.

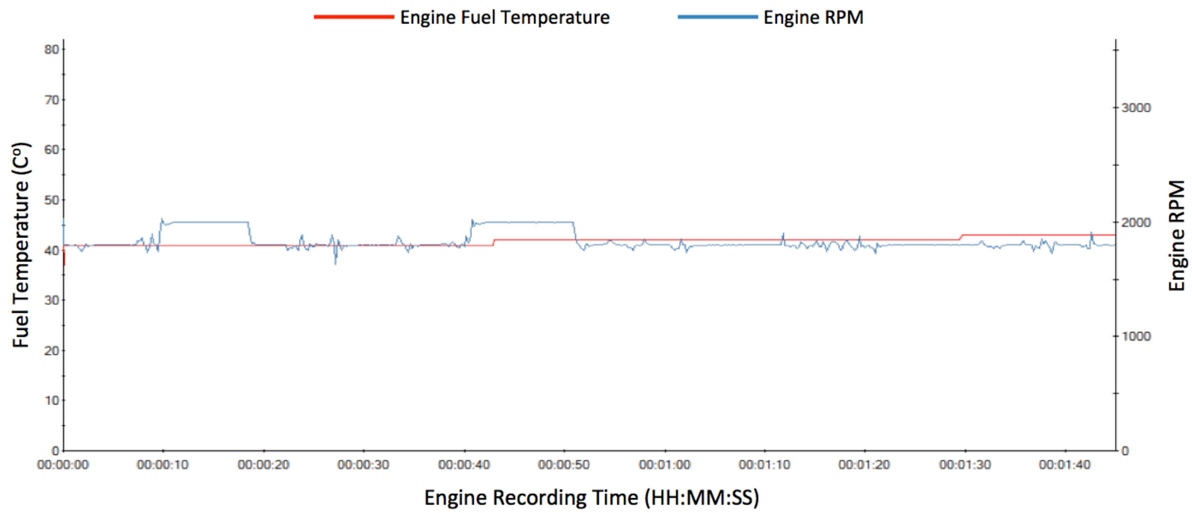

Figure 5.17: Fuel temperature vs engine RPM in Santa Cruz

A comparison of the fuel common rail pressure of the La Paz and Santa Cruz excavators was performed. Figure 5.18 represents the desired fuel common rail pressure measure in MPa versus the observed the fuel pressure in La Paz. The desired fuel common rail pressure (Santa Cruz) is represented by the blue line while the observed pressure in La Paz is represented by the red line. The red line (La Paz engine) graphic shows the engine loss of power at 25 seconds of operation and an unstable fuel pressure throughout the recording period while the engine Santa Cruz had a normal fuel pressure.

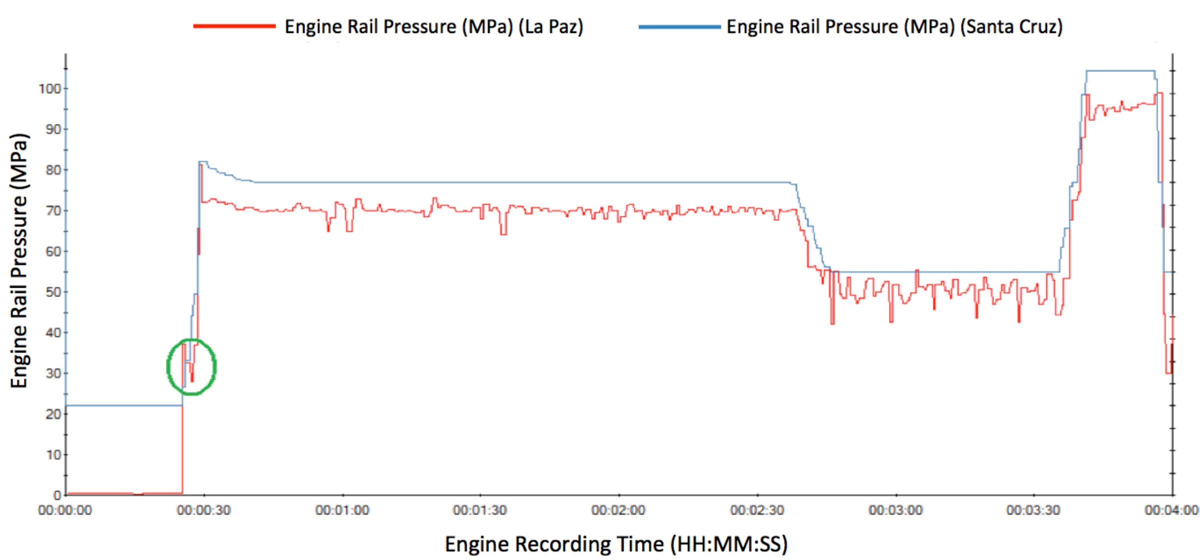

Figure 5.18: Fuel common rail pressure comparison La Paz versus Santa Cruz

The ECU data leads to the conclusion that the engine combustion and fuel system is affected by altitude. The engine loss of power is noticed at start up while the fuel temperature is low. Also, a relationship between engine loss of power and the engine common rail system is noted. Higher altitudes combined with low fuel temperature and low common rail system pressure is leading to engine de-rating. This could be exacerbated by fuel contamination such as water in fuel. Engine function loss is often attributed to poor combustion. According to Jääskeläinen and Khair (2016), air-to-fuel and fuel atomization could be affected by altitude, fuel quality, fuel temperature, and humidity in the intake air. According to Gupta (2013, 30), "all fuel molecules may not find oxygen molecules, or the local temperature may not favor the reaction." This imbalance leads to poor combustion as verified in the mass flow rate of fuel (mf) and heating value of fuel (CV) as calculated using the following equation:

Equation 1: Combustion Efficiency Equation

$$n_{\boldsymbol{c}} = \frac{Q_s}{m_f \times \text{CV}}$$

Where:

Q_s = heat supply to the gas per unit time

5.5.2.4 Compression Testing:

The La Paz engine that operated at the higher elevations presented considerable rail pressure abnormalities; consequently, a compression test was performed. The compression test quantifies the level of pressure in each combustion chamber to determine which cylinder is not functioning correctly. The following Figures 5.19 to 5.24 show the compression pressure readings for each cylinder. Cylinders 2 and 5 showed normal pressures, close to 300 psi, and indicate some degradation in cylinders 3, 4, and 6. The cylinder 1 reading indicates an abnormal psi, below the acceptable range for this engine.

Figure 5.19: Cylinder #1

Figure 5.20: Cylinder #2

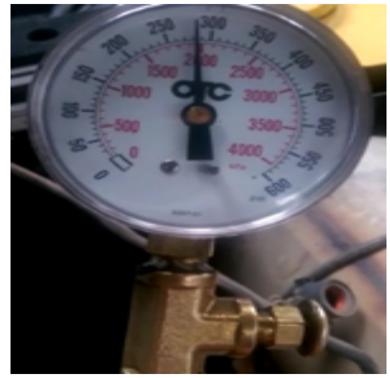

Figure 5.21: Cylinder #3

Figure 5.22: Cylinder #4

Figure 5.23: Cylinder #5

Figure 5.24: Cylinder #6

5.5.2.5 Engine Damage:

The research started with excavators with relatively low engine hours. The excavator in La Paz had 729 hours while the excavator in Santa Cruz had 891 hours. After this study was concluded, the status of the two engines involved in the study was requested. The engine from the La Paz excavator needed to be replaced at 1781 hours. The engine from the Santa Cruz excavator was replaced at 3973 hours. The Figures 5.25 to 5.28 show the extent of the damages to the La Paz engine. The Figures 5.25 to 5.28 Figures 5.25 to 5.28 show issues related to cylinder #1, the cylinder mentioned in the compression test. Figure 5.25 shows erosion due to micro water explosions on the outer wall of the cylinder sleeve caused by using the improper coolant. It confirms the maintenance practice of adding contaminated water to the cooling system. Figure 5.26 shows a coolant leak between the engine block and the combustion chamber of cylinder #1. This confirms the failure of the cylinder head gasket. Figure 5.27 shows the extent of the damage in the fuel injector of cylinder #1. Figure 5.28 shows scuffing and material loss in the thrust-bearing sleeve.

Figure 5.25: Cylinder

Figure 5.26: Cylinder

Figure 5.27: Injector

Figure 5.28: Thrust-bearing sleeve

5.5.2.6 Possible improvements to the engine:

The generation of engine soot is a result of inefficient combustion. Assuming that there are no general quality issues with the engines, the following suggestions could improve engine durability for equipment operating in Latin America:

- To reduce the amount of soot reintroduced back to the engine, the exhaust recirculation (EGR) system could be removed as long as emission control regulations are not violated.
- To improve cylinder ignition and fuel combustion, a turbocharger with higher airflow could be installed.
- Fuel quality should be evaluated to determine its heating value (CV) as high levels of water in the fuel was indicated in the diagnostic trouble codes.
- The oil change maintenance intervals should be set to 100 hours for construction equipment operating at altitudes of 3000 feet or greater.
- Only factory authorized coolant designed for heavy-duty construction equipment applications should be employed in the cooling system.
- Program the engine control unit (ECU) to de-rate (a reduction of maximum engine load, speed time torque) the engine progressively as the barometric sensor identifies an increase in altitude.
- Reduce sulfur content in the diesel fuel for engines operating at high elevations.
- Install additional water-in-fuel filters.

- Equip the engine with a Puradyne engine oil filter to assist in the filtering of soot and to introduce oil additives, thus reducing oxidation and improving the engine oil TBN.
- Develop sensors in the engine to warn of abnormal engine oil viscosity, TBN, and oxidation levels.

6. Conclusion

Maintenance engineers working in large-scale global infrastructure projects maintain construction equipment operating in extreme conditions. Construction equipment is shipped from project to project, often across countries and continents. Construction equipment designed for developed countries and less extreme operating environments exhibit reduced durability when operated in Latin America.

The research has concluded that the engine of the excavator working in altitude showed signs of alarming degradation. Lead, iron, tin, copper, chromium, and aluminum particles increased. Iron was the earliest wear metal to reach upper, abnormal, and critical levels. The research indicates that the cylinder pistons and cylinder liners were the first components to exhibit visible signs of wear. Furthermore, the oil pump exhibited scuffing, a sign that a lack of lubrication caused gear surface damage. Contaminants such as soot, water, glycol, and potassium have an adverse impact on oil viscosity. The viscosity of the excavator working in La Paz had greater degradation of oil viscosity. The reduction of TBN is attributed to soot and coolant contamination, oil oxidation, and poor combustion. TBN was depleted faster in altitude. Coolant and iron are the primary causes of higher oxidation levels as seen in the excavator working in altitude.

Potassium, considered an engine oil contaminant, is commonly found in engine coolant or antifreeze as an additive. The presence of potassium in oil could the lead to corrosion of cylinder liners, erosion by cavitation, and electrochemical erosion. Coolant came into contact with engine oil through a blown head gasket. Since the excavator operating at higher altitude was exposed to low humidity, the contamination is likely the result of an internal engine leak. Also, glycol was also found at higher levels in the engine working at the higher altitude. It is also points to coolant contamination. By interacting with the oil additives, glycol caused sludge build-up which causes blockage of oil filters.

The rapid increase of soot to critical levels points to inefficient combustion of the engine working at the higher altitude. Combined with an EGR system, carbon particles are being introduced back into the engine in greater quantities in the La Paz excavator. Sources of excess of soot include: (1) excessive engine idling, (2) worn piston rings, (3) injectors with poor fuel spray patterns, and (4) inefficient air to fuel ratio.

The ECU data confirms that extended engine idling is the primary operating characteristic that is leading to the premature engine wear of the La Paz excavator. The DTCs shows coolant levels are extremely low, thus, confirming an internal leak. It is important to note that the water in fuel DTC is pointing to fuel contamination, which caused poor combustion and internal contamination. The ECU sensor data indicates a cylinder misfire and inconsistent rail pressure, which are early indicators of engine internal wear. The incorrect fuel and air mixture is leading to a low heat support to gas per unit time. The water in fuel is also likely affecting the heating value of the fuel. Thus, the combustion efficiently is reduced which can lead to soot generation.

The fact that the VGT position for the engine operating in La Paz opened below target, and as comparison below Santa Cruz engine, could lead the engine in La Paz to have air starvation. Engine air starvation leads to lower combustion and higher generation of particulate matter. The EGR of the engine in La Paz was much open than the programmed target. Also, as comparison, the EGR valve of La Paz engine was open with greater frequency than the engine in Santa Cruz. This would lead higher level of exhaust particular mater of inefficient combustion been reintroduced back to the engine.

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CHAPTER 6 - CONCLUSION

The primary objective of this dissertation was to employ system engineering theory and tools to determine the correlations between reduced engine durability in construction equipment operating in Latin America and the environmental factors common to that region. This research contributes to the system engineering field of knowledge with the focus on system maintainability.

This dissertation adopted an interdisciplinary approach of system engineering. Specifically, system engineering concepts such as system life-cycle, system environment analysis, system risk analysis, and system maintainability provided the framework for this dissertation. Furthermore, concepts were drawn from tribology, the construction industry, and mechanical engineering.

Data analyzed in this research was obtained from a wide variety of sources. A large scale and multinational data set was obtained from oil laboratories located in eleven Latin American countries, making this research the broadest to date in regards to addressing engine durability through oil analysis. The data also includes inputs from interviews with Latin American equipment users and service managers. Furthermore, operating condition data obtained from machine telematics and machine engine control unit (ECU) computers were analyzed. Specific data from two 20-ton excavators operating in contrasting working environments was evaluated. Finally, the research leveraged 11 years of the author's industry-specific experience, as the author logged over 1,000,000 air miles visiting customers, technicians, service managers, and service centers, and observed on-site machine applications throughout Latin America. The result of this research provides scholastic and practical value to system engineers, mechanical engineers, field maintenance engineers, and equipment end-users.

Several methods were employed to answer the research questions. The research applied sophisticated oil analysis technology to derive a consistent analysis of wear metal, oil contaminants, and oil chemical degradation. A database of 7,561 engine oil analysis were utilized to determine trends that could lead to premature engine failure. These results were obtained from oil analysis laboratories located in the following Latin American countries: Bolivia, Colombia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Honduras, Mexico, Paraguay, Peru, and Uruguay. By applying the system engineering Standards Risk Model, detail risks were identified, defined, mapped, quantified, prioritized, and cost-evaluated. Extensive use of correlations among wear metals, oil contaminants, oil degradation, and environmental factors was performed. The research also includes evaluations of field-specific equipment. Finally, the research provides an extensive review of peer-reviewed and industry-related literature.

Chapter 2 included a system engineering analysis for construction equipment operating in Latin America. The region is a global resource for mined products such as copper and iron and thus, is an important market for construction equipment manufacturers such as Caterpillar, John Deere, Komatsu, Volvo, and CNH. However, it is not financially feasible for these manufactures to test their construction machine products in all 33 countries and their diverse operating conditions. Consequently, a significant lack of understanding exists regarding engine system performance and durability for the region. Chapter 2 provided a system engineering analysis of how diesel engine durability is affected by environmental factors such as elevation and fuel quality. The examination of engine oil sample results shows that oil condition provides a leading indicator of premature internal engine wear and possible causes. The study also correlated the environmental factors to machine diagnostic trouble codes. The following research questions were answered in this chapter:

1) What are the engine oil contamination characteristics of diesel engines deployed in Latin America? Countries with the highest operating elevations presented a significantly greater number of abnormal results than the countries with low elevations. High altitude operation was correlated to increased particulate matter. Particulate matter increases engine oil viscosity, leading to lower oil flow rates resulting in low lubricity. Low lubricity increases engine component wear and reduces engine cooling efficiency.
2) How does engine oil contamination relate to the environmental factors in Latin America? Engine oil contamination is directly related to environmental factors. When combined with the high inverse correlation of water and TBN, the results indicate that contamination of a failing cooling system could be a significant contributor to oil degradation. Furthermore, the high correlation of sodium, silicone,

and aluminum indicates dust contamination. Because there were a significant number of diagnostic trouble codes (DTCs) related to air intake restriction, dust is likely passing into the engine combustion chamber leading to excessive wear of engine pistons and rings.

The system engineering risk analysis of diesel engine durability for equipment operating in Latin America is performed in Chapter 3. Between 2010 and 2015, engines in 20-ton excavators operating in Latin America failed with a relatively low hours of usage. System maintenance data such as engine oil samples is critical to address engine durability issues seen in equipment operating in the Latin America region. Risk analysis addressing premature engine wear in the Latin America region has not been described in peer-reviewed literature. Thus, the primary objective of this chapter was to apply a system engineering Standard Risk Model evaluation to identify, quantify, and prioritize cost risks associated with diesel engine durability in Latin America. This research applied the Standard Risk Model and cataloged the root-causes of risks under two groups: fuel and environment. Identified in this chapter was a cause and effect correlation between risk drivers and abnormal oil sample analysis results. After calculating, prioritizing, and mapping each risk, the research concludes that diesel sulfur content and diesel fuel quality are the primary risks that should be addressed in machinery operating in Latin America. Risk and cost threshold formulas are presented in this research to support the conclusions. The following research questions were answered in this chapter:

1) What are the risks leading to reduced engine durability in Latin America? Fuel-related risks for equipment operating in Latin America are: bio-diesel fuel, fuel sulfur content, and diesel fuel quality. The environment risks for equipment operating in Latin America that lead to abnormal oil sample analysis results are: altitude, humidity, and temperature.
2) How can the risk drivers be quantified? The research concludes that (1) countries with high bio-diesel fuel (B20) usage have a 50% incidence of abnormal oil samples, (2) 84% of the abnormal engine analysis oil samples relate to diesel fuel sulfur content, and (3) 62% of the abnormal engine oil samples relate to low quality diesel fuel. The research concludes that (1) 52% of the abnormal oil samples were associated with operating altitudes over 2,500 MSL, (2) 43% of the abnormal oil samples were

associated with countries with high levels of humidity, and (3) 55% of the abnormal oil samples were associated with geographic locations with temperatures above 24°C. The data shows that higher operating altitudes have a significant impact on abnormal engine oil analysis results. The risk prioritization determined the following risk priorities: (1) sulfur (Le=3.70), (2) diesel quality (Le=2.26), (3) humidity (Le=0.77), biodiesel (Le=0.54), temperature (Le=0.15), and altitude (Le=0.14).

The engine oil degradation analysis of construction equipment operating in Latin America is performed in Chapter 4. The purpose of this chapter was to determine and describe the effect of oil degradation for the diesel engine of 20-ton class excavators operating in Latin America. The research parameters included: (1) a specific engine class and equipment, the John Deere PowerTech Plus 6068 Tier 3 diesel engine that powers the 20-ton class excavator, (2) identical OSA3 oil analysis laboratory equipment in eleven Latin American countries was employed to analyze oil samples, and (3) the same sampling scope and method were followed for each oil sample. The following research questions were answered in this chapter:

1) What are the engine abnormal reading distributions per wear metal at 500 hours for 20-ton excavators operating in Latin American geographies? The research results indicated that at 500 hours of use, 73.4% of the oil sample results indicated that soot accumulation was a significant problem.
2) Is there a relationship between wear metals and the environmental conditions particular to Latin America? When associating the engine oil contamination with the environment risk drivers: (1) altitude and diesel fuel quality have the greatest impact on iron readings, (2) the use of bio-diesel fuel impacts copper, (3) precipitation and poor diesel fuel quality are associated with high silicon levels.
3) Do wear metals present in oil samples indicate that a change to the scheduled maintenance frequency is necessary for operating environments such as Latin America? Because there is an exponential increase in the count of particles in the oil as oil use approaches 250 hours, the interval of engine maintenance (oil change) for machinery operating under similar conditions should not exceed 250 hours of use.

Construction equipment engine performance degradation due to environmental and operating factors in Latin America are evaluated in Chapter 5. The research in this chapter focused to determine whether the altitude at which construction equipment operates affects or contributes to increased engine wear. The research parameters include: (1) the evaluation of two John Deere PowerTech Plus 6068 Tier 3 diesel engines, (2) utilization of OSA3 oil analysis laboratory equipment, (3) employment of standard sampling scope and methods, and (4) analysis of key Engine Control Unit (ECU) data points, including: the machine utilization, diagnostic trouble codes, and engine sensor data. Thus, research answered the following questions:

1) What are the leading and earliest oil analysis indicators of engine wear on construction equipment working at higher altitudes? The research results indicated that at 250 hours of use, the engine operating at 3657 meters above sea level had considerable more wear than the engine operating at 416 meters above sea level. The leading and earliest indicator of engine wear was a high level of iron particles in the engine oil, reaching abnormal levels at 218 engine oil hours. The following engine oil contaminants were more prevalent in the engine operating at the higher altitude: potassium, glycol, water, and soot. Furthermore, the engine operating at higher altitude also presented abnormal and critical levels of oil viscosity, TBN, and oxidation.
2) Does the Engine Control Unit computer (ECU) data identify issues related to the operating altitude? When comparing the oil sample analysis with the engine ECU data, it was determined that extended engine idling contributes to soot accumulation in the engine operating at the higher altitude. The most prevalent Diagnostic Trouble Codes (DTCs) were water-in-fuel, extremely low coolant levels, and extremely high exhaust manifold temperatures. The ECU operating data demonstrated that operating at a higher altitude caused the engine to miss-fire and the rail pressure was irregular.

This dissertation provides a foundation where future work can be performed. Further research could explore the relationship between engine subsystem durability (e.g., turbo-chargers and exhaust gas recirculation valves) and component design in extreme field applications. The risks identified by this research could be explored individually in the context of hardware and software design. The properties of fuel contamination could be evaluated in relationship with machine performance and specific component degradation while operating machinery at higher altitudes.

The contribution of this dissertation expands the understanding of diesel engine durability globally. While the chosen engine application for this research was construction, researchers can apply these concepts and applications to off-road, on-road, marine, and stationary diesel engine deployments. Construction equipment users, system, mechanical, and service engineers can implement mitigation strategies to improve engine durability for countries with operating conditions similar to those described in this research. For instance, service engineers can implement maintenance strategies to minimize internal engine wear for equipment operating at higher altitudes. Fluid engineers could create engine oils or oil additives to protect diesel engines operating in regions where higher altitudes and fuel contamination are common. Mechanical, electrical, software, and system engineers could create sensors to better evaluate the air-to-fuel mixture for engines operating at higher altitudes. Artificial intelligence could be employed for machine learning (e.g., ECU fuel delivery table adaptation) and fuel delivery mappings adjusted as the equipment is moved to different operating altitudes or when fuel contamination is detected. Maintenance and system engineers could create systems to further protect against fuel contamination. Thus, the research lays the foundation where a global and interdisciplinary collaborative effort among system engineering, tribology, mechanical, software, and maintainability disciplines can be deployed to solve the problems experienced in actual use of the product.