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AN ENGINE OIL LIFE ALGORITHM

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by

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ABSTRACT

An oil-life algorithm to calculate the remaining percentage of oil life is presented as a means to determine the right time to change the oil in an engine. The algorithm accounts for major factors that affect the engine oil life and is intended to provide a simple balance between human interference and automation to improve the reliability of oil-life prediction without affecting the engine components and their performance. The algorithm can be implemented as a simple and robust system that can be updated through timely field tests and applied to any type of engine or engine oil.

The proposed oil-life algorithm takes into account, the nominal engine oil life (based on the oil grade and engine type used) and monitors engine oil temperature, coolant temperature, engine load, engine speed, engine cranking, and oil aging. The algorithm also accounts for driving in desert or dusty environment. The development of correction factors for each of these operating conditions is presented. Implementation of the oil-life algorithm as a system and its capabilities are also discussed.

To evaluate the oil-life algorithm, an oil-life simulator is developed using MATLAB. Various driving conditions are simulated by generating data from the heavy duty diesel engine test data and by controlling the operating conditions according to the driving condition being simulated. The simulation results and multiple evaluations of the oil-life algorithm are broadly discussed. Comparisons with the existing practice, manufacturer’s manuals, and experimental research are also presented in order to validate the oil-life algorithm.

The features and advantages of the oil-life algorithm over the existing practice are presented along with the conclusions and key results. Finally, the scope for improvement and further development is suggested.

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Chapter 1

Introduction

In recent years, the cost of inappropriate oil drain intervals to the economy, to the environment, to car and truck owners has received closer inspection by major car manufacturers. In the United States, a vehicle owner, on an average, changes the oil at just less than 5,000 miles [1]. Conversely, the average oil change intervals of more than 10,000 miles were reported in Europe [1]. Assuming 10,000 miles is a more optimum interval, approximately additional 300 million to 400 million gallons of engine oil (worth about $1.5 billion, not including labor) [2] in the United States are consumed. Extended oil drain intervals are beneficial to the environmental conditions and lessen the cost of waste oil disposal or reclamation. With increasing environmental and economic pressures, the potential waste can no longer be easily glossed over.

There are, however, negative consequences to overextended oil drains. For example, a user may drive a station wagon automobile towing a 22 foot trailer with a boat for 16 hours and only cover 800 miles, yet the sufficiently high engine temperature and heavy engine load will have degraded the engine oil to the point that it will have to be changed at the end of those 16 hours. Continued use of that engine without changing the oil can adversely affect the performance and durability of the engine long before the mileage suggested by manufacturer for changing the oil is reached [3]. In diesel engines, over extended oil drain intervals have been shown to increase engine wear by more than 20 percent with a corresponding reduction in horsepower and fuel consumption [2]. One could safely project that over extended drains in passenger car applications would have a similar negative outcome. This of course presents a real dilemma to the vehicle owner. What exactly is the correct interval? In the quest for optimum lubrication, the vehicle owners often receive conflicting advice from the vehicle manufacturer's manuals, mechanics, quick-lube operators and auto parts merchants. As a practical matter, we must consider a range for an oil change from around 3,000 miles to well over 10,000 miles [4, 5]. Although, in general vehicle owners change the engine oil in less than 5,000 miles, most car makers recommend changing the oil for automobiles and light trucks burning gasoline once a year or every 7,500 miles, whichever occurs first [6]. For diesel engines and turbocharged gasoline engines, the recommendation is typically a more accelerated 5,000 miles or six months

[6]. In some cases (highway driving), GM and DaimlerChrysler have suggested more than 10,000 miles [4, 7].

Manufacturer's manual will show the 5,000- or 7,500-mile oil change interval for vehicles driven under normal or ideal conditions. This is where the problem lies. What exactly are these ideal conditions and what are the consequences of non-ideal conditions with respect to engine oil condition and engine wear? A few might perceive frequent short trip driving (especially during cold weather) to be normal service driving, but it is actually severe service driving from the standpoint of the oil. Other examples of severe service driving are stop-and-go driving, driving in dusty conditions (gravel roads, etc.), high-temperature and high-load (HTHL) conditions. Under such conditions, the general recommendation found in manufacturer's manuals is to change the oil every 3,000 miles or six months [8].

The real problem rests in the attempt to generalize. Whether or not the general recommendation is applicable to different engine designs and types of engine oils can only be justified by conducting laboratory and field experiments. But before reviewing the experiments conducted, the latest developments in engine designs and engine lubricant formulations that might affect the oil drain intervals, are presented. The following section gives a brief review of a few advancements in engine designs and engine lubricants.

1.1 Advancements in Engine Designs and Engine Oils

Engines have many moving parts that require lubrication and engine durability is directly related to the ability of engine oil to lubricate these moving parts. In the past few years, there have been a few changes in the diesel engine designs that have the potential to affect the oil-change intervals. To meet the Heavy-Duty Diesel Emission Standards, more and more diesel engines have been incorporating exhaust gas recirculation (EGR) to reduce NOx levels [9]. Adding EGR to a diesel engine increases the engine's efficiency [10] by:

- Reducing heat rejection and dissociation
- Reducing the amount of power that can be extracted by the piston
- Reducing the amount of fuel burned in the power stroke

EGR has a few disadvantages as well. EGR increases the amount of particulate matter (mainly carbon), that is not burned in the power stroke, which accounts for a form of wasted energy [10]. To compensate for the particulate matter emissions introduced by EGR, the most common is the use of particulate filters in the exhaust system, which reduce the fuel efficiency. Not only can EGR bring some of the exhausted soot into the lubricating oil, but it will also diminish the soot oxidation process within the combustion chamber and increase the amount of the freshly formed soot inter-mixing with the oil.

Another recent development is the use of intensified fuel injection systems that alter the mass flow rate of fuel. More and more diesel engines are released into the market equipped with post injection regeneration of diesel particulate filters (DPF) [11]. DPF is a device designed to remove diesel particulate matter or soot from the exhaust gas of a diesel engine. Wall-flow diesel particulate filters usually remove 85% or more of the soot, and can at times (heavily loaded condition) attain soot removal efficiencies of close to 100%. Also, a diesel-powered vehicle equipped with functioning filter will emit no visible smoke from its exhaust pipe. However, during regeneration of a DPF using a post injection strategy, fuel is accumulated in the engine oil, which degrades the ability of the engine oil to properly lubricate the engine.

There have also been significant changes in the engine lubricant formulations. Modern engine lubricants are required to serve several important functions that are important for engine performance and longevity. These functions include separation of moving parts in order to reduce friction and wear, improving fuel economy, cooling the piston, sealing the piston, piston-ring and cylinder against combustion gases, and protecting and cleaning engine components for proper engine operation. They also need to accommodate for higher soot and acid loadings expected to result from the use of EGR. Engine lubricants must perform these functions for periods of hundreds of hours between oil changes under a variety of operating conditions. Therefore, it is essential to formulate engine lubricants using high quality base oils and performance enhancing additives.

Engine oil performance levels can be broadly based on their classifications and specifications [12] as determined by technical societies and Original Equipment Manufacturers (OEMs). American Petroleum Institute (API) and the International Lubricant Standardization and Approval Committee (ILSAC) implement engine oil performance specifications for much of the industry. In addition, some OEMs implement their own testing and performance specifications for their engines.

To evaluate and predict the performance of engines and engine lubricants under various operating conditions, research organizations have been conducting extensive laboratory experiments and field tests. Three such benchmarking and performance evaluating tests are reviewed in the next section.

1.2 Experimental Research on Engines and Engine Oils

1.2.1 Southwest Research Institute (SwRI) [13]

SwRI initiated a Heavy-Duty Engine Benchmarking Program to evaluate the performance of seven engines between 5.9L and 15.2L capacity that included engines with and without cooled EGR. The performance and longevity of a typical mineral-based CI-4 diesel engine lubricant with these new engine designs was also evaluated. The work was based upon testing one engine of each kind, a single oil, and one unique test procedure and the objectives of the test were to:s

- Determine how quickly CI-4 oil deteriorates when tested under “normal warm” operating conditions in engines with and without EGR.
- Determine if there is any unusual engine wear due to EGR or engine design changes.
- Discover any short term durability issues with the engines, particularly with the new features and systems.
- Determine if there are any differences in the oil deterioration rates between these engines.

The AVL 8-mode cycle, a heavy-duty steady-state engine test procedure, was used. SwRI operated the engine at each of the eight modes (1 close to idle, 3 at low speed under medium-load, 3 at near rated speed under medium-load and 1 at near rated power) for 1 hour each, 38 times to yield a 304-hour durability test. The CI-4 lubricant passed all required tests which apply very high power settings, over fueling, and aggressive EGR (up to 15%), to accelerate the soot generation and accumulation in the lubricant oil. The 8-hour cycle tests were performed at lower power settings, without over fueling, and applying less EGR than the CI-4 lubricant certification tests. The following test results answer the questions posed above as objectives:

- The test oil thinned by a maximum of 20% for all the engines including the engines equipped with EGR and those equipped with hydraulically intensified injection systems. The decrease was attributed to the viscosity index improver shearing. In real world, high-power and high-temperature applications, soot generation and lubricant oxidation and nitration can easily offset this lubricant thinning.
- Due to EGR and engine design changes, no unusual engine wear was exhibited. Only International 6.0L engine exhibited relatively high iron accumulation rates, which may be explained in part by the engine having much smaller oil sump when compared to other engines.
- None of the engines had short term engine durability issues.
- The engines (with and without EGR) in the range of 12L to 15.2L capacity exhibited similar soot accumulations, fuel dilution (zero) and TBN depletion. Although, the engines equipped with cooled EGR exhibited higher iron accumulation. The engines (with and without EGR) in the range of 5.9L to 12L capacity also exhibited similar soot accumulations, fuel dilution and TBN depletion. The Caterpillar C9 engine, having no EGR and two times larger size of oil sump than other engines in the group, exhibited higher oxidation rate.

From the 308-hour durability test on CI-4 lubricant used in seven different modern engines, SwRI predicted an engine oil life of over 850 hours under normal warm conditions and conclude that cooled EGR does not majorly affect the performance characteristics of the lubricant and heavy duty diesel engines.

1.2.2 Shell Global Solutions and Automotive Maintenance & Repair Association [12]

Real world engine oil samples representing several brands and laboratory scale tests were tested to monitor engine oil quality in today's vehicle population. The test samples included current engine oils, which meet the latest ILSAC and API classification, API/ILSAC GF-4. The oil samples were collected from a variety of vehicles, driving conditions, climates and locations, representing a variety of engine oil base stocks (mineral, synthetic blend and synthetic), engine oil brands and oil drain intervals. The viscosity grades for the samples consisted of either SAE 5W-30 or SAE 10W-30 (with different base stocks) to reflect the majority of SAE viscosity grades used today (about 90% of manufacturers recommend these grades). In addition to these, 82 used engine oil samples and 8 fresh engine oil samples (to represent zero miles on the engine oil) of API/ILSAC GF-4 SAE 5W-30 (with different base stocks) were analyzed. To monitor engine oil degradation over the oil drain interval period, properties like the used engine oil's phosphorus levels, viscosity stability, oxidation resistance, and acid control were measured. The following test results were observed:

- Phosphorus – Most of the used oil samples and all of the fresh oil samples were within the API/ILSAC GF-4 phosphorus limits of 600 to 800 ppm, in contrast to the 1000 ppm limits set for previously used GF-3 oils.
- Kinematic Viscosity – SAE J300 test method was used to classify the engine oils. Few samples demonstrated viscosities outside the SAE specification and this observation was more pronounced with increase in oil age. Eight of these samples represented an oil age greater than 5000 miles.
- Oxidation Resistance – Oxidation stability properties for the eight fresh engine oil samples were measured using the conventional Pressure Differential Scanning Calorimetry (ASTM E1858) test. The range of oxidation induction times varied from 191 minutes to 632 minutes indicating a wide difference in the oxidative stability of API/ILSAC GF-4 engine oils.
- TAN and TBN – Total Base Number (TBN) is the measurement of the overall alkalinity of a lubricant and the amount of acid that is present in engine oil is referred to as the Total Acid Number (TAN). The point at which TAN exceeds TBN is commonly used as a measure to define useful lubricant life. For the test samples, a broad trend of TAN and TBN crossover was illustrated beginning near the 3000-mile oil drain interval point. 25 of the 82 used engine oil samples tested demonstrated TAN and TBN crossover and 5 of these were below 5000 miles.

The authors conclude that the statistical determination of the data from everyday vehicles was unable to demonstrate a quantifiable correlation between miles driven and engine oil performance as a wide variety of factors like different engine designs, operating conditions, and driving habits influence the degradation of oil in service. But they suggest that the engine oils with new specifications have a considerable improvement over their predecessors in their performance characteristics.

1.2.3 General Motors Research and Development Center [6]

GM studied the effects of trip length and oil type (synthetic vs mineral) on engine and engine oil degradation. The objectives of the driving test were to study the engine oil degradation when using synthetic oil compared to a mineral oil and when operating in short-trip service compared to long-trip freeway service. A 1992 high-performance sport vehicle, equipped with a port-fuel injected 5.7L engine was used for the drive test. To determine the rate of oil degradation as calculated by the vehicle’s on-board engine oil-change indicator (GM oil-life monitoring system [5]), readings were directly taken from computer’s memory. To obtain quantitative measures of the effects of different service conditions, the vehicle was tested as follows:

- During the first oil-change interval the vehicle was driven for 10,000 miles of free service using synthetic oil, followed by four weeks of low temperature short-trip, cold-start service.
- During the second oil-change interval the vehicle was driven for four months in low-temperature short-trip service using the same synthetic oil, followed by 100 miles of long-trip service.
- During the third oil-change interval the vehicle was driven for 10,000 miles of freeway service using the mineral oil, followed by four weeks of short-trip service.

Oil samples were taken at 2000-mile intervals during the long-trip portions and at much shorter intervals for the rest of the test. The samples were analyzed for physical and chemical properties, and elemental composition using standard laboratory test methods. The following changes were observed in the engine oil during the various tests performed as a part of the study:

- Water Contamination – No water was found in the engine oil during the first 10,000-mile long-trip service. During the short-trip service in winter, water contamination levels were high even in case of synthetic oil and there was no water contamination during the short-trip service in summer. During the long trip service at the end of second oil-change interval, water was removed from the engine oil within 20 miles. It was found that an ambient temperature of 25^0C was sufficient during short-trips to avoid accumulation of significant amount of water in the engine oil.
- Fuel Contamination – In contrast to the case with water, some fuel entered the engine oil during the 10,000-mile long-trip service. Once the service was changed to short-trips, fuel concentration increased in the engine oil and the increase was greatest when ambient temperatures were low. Despite high levels of contamination, no apparent loss of vehicle performance was reported.
- Viscosity – When fuel entered the engine oil during short-trip service, a viscosity decrease was observed. When the oil temperature increased due to warmer weather or longer trips, a rise in viscosity was reported as fuel evaporated from the oil.
- Antioxidant Protection – In the short-trip winter testing during second oil-change interval, the oil lost oxidative stability rapidly. With warmer weather or longer trips, the fuel concentration in the oil decreased and the oxidative stability increased. In the case of long-trip service, the antioxidant in both synthetic oil and mineral oil degraded approximately at same rate for more than 8,000 miles of service. The synthetic oil had a significant amount of antioxidant protection remaining till the end of the test. However, the oxidative stability of the mineral oil degraded rapidly for the last 2000 miles of long-trip service and remained at a low level during the short-trip service. This suggests marginal antioxidant protection in mineral oil.
- Iron Content – The rate of iron accumulation was far greater in short-trip service than in long-trip service. The presence of significant amount of water in the engine oil suggested that corrosion is a primary mechanism for entry of iron into the engine oil, especially considering that engine inspections did not reveal significant wear.

- TBN – Engine oil alkalinity or TBN dropped rapidly in short-trip service, although it was partly reversible. Reversibility suggested that once trip lengths become longer, acidic contaminants were removed from the oil and (or) alkaline oil additives were re-dispersed in the oil. The results also indicate that 500 miles of short-trip service cause as much reduction in TBN as 8000 miles of long-trip service.
- TAN – For synthetic oil, there was very little change in oil acidity during the long-trip testing. In case of mineral oil, there was a slow rise in the oil acidity during the long-trip testing and an apparent drop in the acidity during the short-trip portion of the testing. The authors speculate that this drop in acidity of the mineral oil may represent acidic agents dropping out of the oil into the bottom of the oil pan.

GM studied the results and suggested that, when using even a borderline SG-quality mineral oil, a vehicle can be driven under freeway conditions for 10,000 miles between oil changes with only minimal oil degradation and without serious damage to the engine. In case of synthetic oil, the vehicle can be driven above 12,000 miles. During short-trip service, the engine oils used in the study degraded rapidly due to contamination and an oil-change interval of 3000 miles is recommended.

From the results obtained in such laboratory experiments and field tests, one can clearly see that, in reality, there are many unique factors and conditions that influence the decision of oil change interval. For illustration purposes, these conditions and influencing facts can be categorized in two ways as shown in the lists below.

1.3 Factors and Conditions that Shorten the Oil Change Interval [2, 3, 4, 8, 14]

- **Short-trip Driving in Winters** - The problem is most pronounced for frequent trips under five miles in cold wintertime conditions. Water and fuel have a tendency to accumulate in the crankcase and contaminate the engine oil, when the oil temperature doesn’t reach the thermostat setting.
- **Road Dust** - Driving in dusty conditions (dirt/gravel roads/desert environment) with an economy-grade oil filter can turn the engine oil into more of a honing compound than a

lubricating medium. The dirty oil generates more wear metals which increase the risk of sludge formation and corrosion from acids.

- **High-Mileage Engine** - Engines with more than 75,000 miles generate more blow-by gases, unburnt fuel and corrosive agents that enter the crankcase oil.
- **Diesel Engines** - Diesels produce more soot and acidic blow-by products.
- **Flex Fuels** - Alcohol-gasoline blends are prone to accumulate water in the crankcase.
- **Turbo-charged Engines** - High temperatures distress the base oil and additives.
- **High Oil Consumption -** While on one hand high oil consumption replenishes additives, on the other hand the affliction is also associated with high blow-by of combustion gases into the crankcase.
- **Hot Running Conditions** - Hot running conditions, including desert terrain, in general can lead to premature oil oxidation, volatility problems and rapid additive depletion.
- **Heavy Loads** - Generally relates to hot running conditions, thin oil films, higher shearing of viscosity index improvers and more wear metals in the oil. Wear metals catalytically shorten oil life, causing premature oxidation, sludge, acids and deposits.

1.4 Factors and Conditions that Lengthen the Oil Drain Interval [2, 3, 6, 15]

- **Synthetic Lubricants** - Premium synthetic lubricants have very good oxidation stability, thermal stability and shear stability.
- **High Capture Efficiency Oil Filter -** Controls catalytic wear metal production.
- **Predominate Highway Miles** - Lower average engine revolutions and fewer operating hours per distance traveled (miles) compared to slow-speed urban driving.
- **New Engines** - Low levels of engine blow-by after the first 500 to 5,000 miles and less than 50,000 miles (unless oil consumption is high).
- **Frequent Oil Inspections** - Simple and frequent oil inspections can be effective at identifying various motor oil problems.
- **Environmental Concerns (waste oil)** - Emphasis on reducing waste oil generation.

Distilling all this down to an optimum oil change interval is quite complicated - too many variables and too much guesswork. There has long been a need for a practical and effective workaround. Rather than attempting to quantify the collective impact of these many conditions and factors, the best approach might simply be for a monitoring system to tell us when the oil needs to be changed. The transportation industry giants are hence conducting more and more research in the area of oil-life monitoring systems. The following section gives a review of three such implemented oil-life monitoring systems.

1.5 Implemented Oil-Life Monitoring Systems

1.5.1 General Motors Corporation GM Oil-Life System [4, 5]

The General Motors (GM) oil-life system, first introduced in 1988, determines when to change the engine oil and filter based on the operating conditions of the engine. The technology does not actually monitor any single quality or physical property of the oil. Instead, the oil-life system records engine revolutions, calculates engine oil temperature and engine oil contamination content. The rate of degradation of the engine oil is calculated by assessing the severity of engine operation as a function of the calculated engine oil temperature and oil contamination. Based on a similar principle, GM also introduced an oil-life monitoring system specifically for vehicles having a direct or indirect injection diesel engine in 2001.

The invention is based on GM's determination that nearly all driving conditions can be grouped into one of four categories: easy freeway driving; high-temperature, high-load service; city driving; or extreme short-term, cold-start driving. GM discovered that oil degradation in the first three categories was largely a function of the oil temperature. During extreme short-trip driving or cold-start driving (the fourth category), fuel and water (due to condensation) can accumulate in the engine oil. Fuel and fuel reaction products can also enter the engine oil and cause a decrease in the oil viscosity. Also, at high engine oil temperatures, antioxidants in the oil, an additive that provides chemical stability to the engine oil, no longer remain as effective as they were initially. As a consequence, the oil becomes more viscous and acidic due to oxidation and nitration. In addition, insoluble materials may be deposited on the engine surfaces as a varnish or sludge. GM concluded that the engine oil degradation is determined by assessing the following two effects:

- Chemical changes that occur as a consequence of exposure of the engine oil to high or low temperatures, without regard to engine loading or other operating conditions which may be indirectly related to oil temperature.
- Formation of contaminants such as soot and acids due to incomplete combustion (related to the fuel injection rate), which typically are produced at high load and high temperature. Soot and acids reduce the ability of the oil to prevent corrosion and increase wear.

When the engine oil temperature (T_o) value is below a predetermined temperature (approximately 80^0C), the engine oil temperature is calculated using equation 1.1 from the measured initial coolant temperature (T_{ic}) and the number of engine revolutions (R_e) since the beginning of the current engine operation.

$$T_o = T_{ic} + k_1 R_e \qquad (1.1)$$

where, k_1 is a constant determined by statistical techniques to smooth the oil temperature curve. Once the engine oil temperature value reaches the predetermined temperature, the engine oil operating temperature is calculated using equation 1.2 from the measured coolant temperature (T_c), engine rotational speed (S_e), fuel quantity injected per cylinder (F_q), intake air temperature (T_a) and vehicle speed (V_s).

$$T_o = k_2 + k_3 S_e + k_4 T_c + k_5 F_q + k_6 T_a + k_7 V_s \qquad (1.2)$$

where, k_2 to k_7 are constants determined by statistical techniques to smooth the oil temperature curve.

Alternatively, GM suggests that a measured engine oil temperature read from an engine oil temperature sensor can be used rather than the calculated engine oil temperature value.

The engine oil contaminant value is calculated using equation 1.3 from the engine oil temperature (T_o), fuel injection timing (I_t), fuel quantity (F_q), and engine rotational speed (S_e).

$$C = k_8 + k_9 I_t + k_{10} F_q + k_{11} T_o + k_{12} S_e \qquad (1.3)$$

where, k_8 to k_{12} are constants determined as the statistically best fit for the above equation based on actual engine operating and corresponding oil contamination experience for the specific engine design (constants k_1 to k_{12} are looked up from specific tables stored in system memory).

Using the engine oil temperature value and figure 1-1, corresponding oil temperature penalty factor (T_{PF}) is obtained and using the engine oil contaminant value and figure 1-2, corresponding oil contamination penalty factor (C_{PF}) is obtained. The penalty factors increase the measured engine revolutions value to compensate for engine operating conditions that tend to degrade the engine oil. Periodically during each period of vehicle operation, an effective engine revolutions (EER) value is determined in relation to the product of measured engine revolutions (MER), T_{PF} and C_{PF}. The EER value is subtracted from the stored maximum number of engine revolutions resulting in a remaining allowed revolutions (RAR) value. Each time the EER value is calculated and subtracted from the RAR value, a new RAR value is stored in memory, replacing the old value. Equations 1.4 to 1.7 give a list of calculations carried out in order during each period of vehicle operation. After each period of vehicle operation, the stored RAR value is compared with a predetermined threshold number of engine revolutions (TNR) value indicative of the useful life of the engine oil and once RAR value goes below the threshold value, the system actuates an indicator advising the operator to change the engine oil.

$$EER = T_{PF}\ C_{PF}\ MER \tag{1.4}$$

$$RAR_{new} = RAR_{old} - EER \tag{1.5}$$

$$RAR_{old} = RAR_{new} \tag{1.6}$$

$$If\ RAR_{old} < TNR, signal\ oil\ change \tag{1.7}$$

Because the oil-life system does not actually sense oil condition, it is important to reset the timer each time an oil change takes place. Figure 1-3 shows a flowchart illustrating the flow of operations. The system is now available on all light-duty North American GM cars and a few heavy-duty trucks.

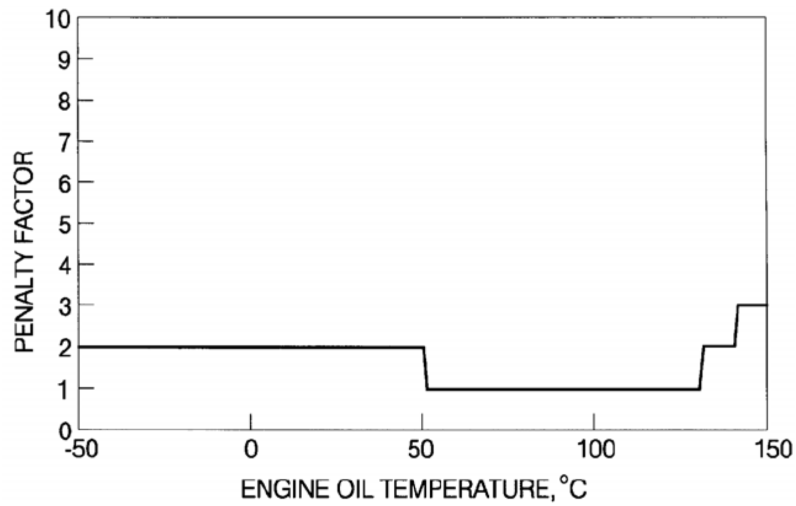

Figure 1-1: Engine oil temperature and the corresponding penalty factor

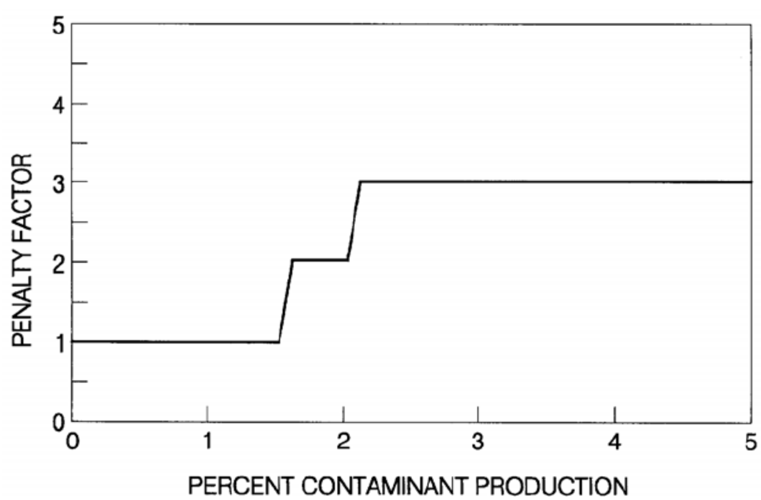

Figure 1-2: Oil contaminant content and the corresponding penalty factor

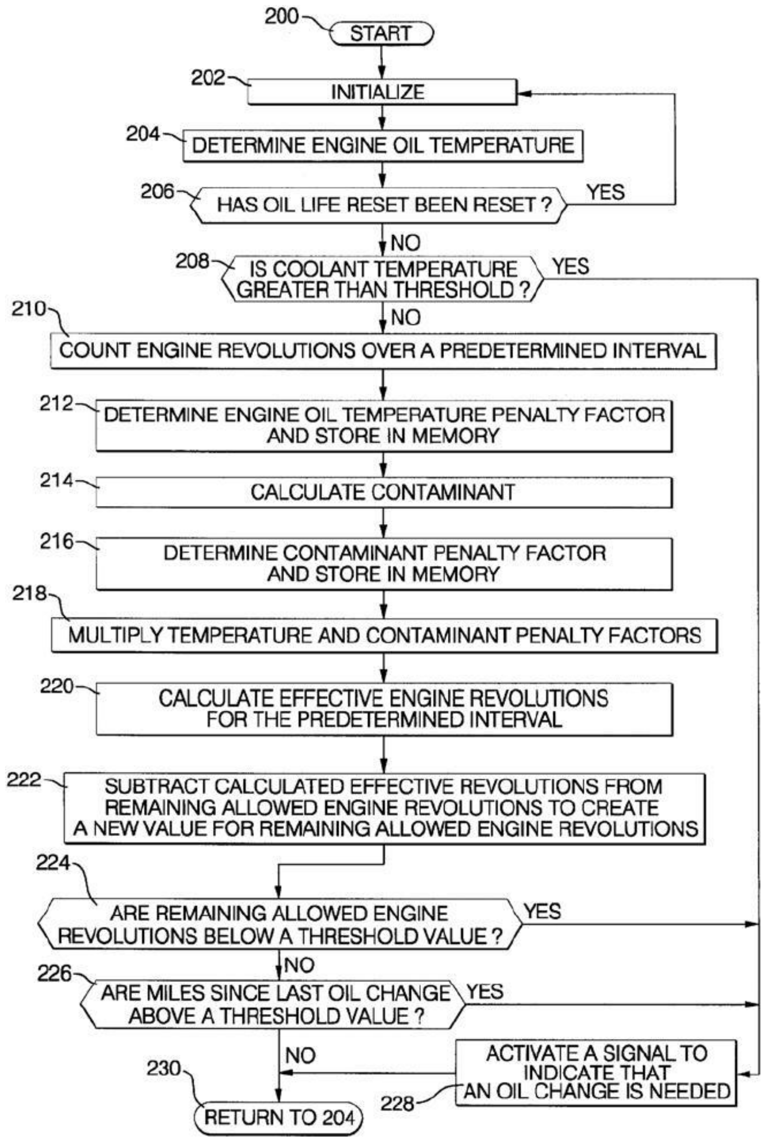

Figure 1-3: Flowchart illustrating the flow of operations

1.5.2 DaimlerChrysler Corporation Flexible Service System [1, 7, 16]

DaimlerChrysler's version of the oil monitor is called ASSYST in Europe and the Flexible Service System (FSS) in the United States. Like GM's monitoring system, the FSS uses a computerized system to track multiple engine operating conditions. From research experiments on oil quality through the span of an engine's life, Daimler discovered that the breakdown in oil-life is determined by factors such as driving habits (rough operating condition, short haul and long haul), driving speed and failure to replenish low oil levels. As the real application of vehicle doesn't fit into the classification of rough operating condition, short haul and long haul, the FSS monitors the engine load required by the vehicle. FSS also monitors time between oil changes (t) and vehicle mileage, records engine speed and vehicle speed, measures engine oil temperature, coolant temperature, and engine oil level, and calculates oil conductivity. Penalty factors which are said to be obtained by laboratory experiments and field testing are assigned specific to each of the engine parameters. There is no data in the literature suggesting the calculation or retrieval of these penalty factors. During each period of vehicle operation (i.e., once in every 10 seconds), the elapsed number of miles (NM) are recorded and penalty factors L_{PF}, S_{PF}, V_{PF}, T_{PF}, and CT_{PF} are calculated corresponding to engine load, engine speed, vehicle speed, engine oil temperature, and engine coolant temperature respectively to calculate the effective number of miles (ENM). The value of ENM is continuously updated with each period of vehicle operation. FSS sets the oil change interval either by time or by mileage limits. Set threshold mileage limits (M_{max}) are 16,000 miles for gasoline engines and 20,000 miles for direct injection diesel engines and the set threshold time limit is 24 months (t_{max}). Once the value of ENM or t goes above M_{max} or t_{max} respectively, an oil change message is displayed. Equations 1.8 to 1.10 show the list of calculations carried out in order during each period of vehicle operation.

$$ENM_{new} = ENM_{old} + (L_{PF} S_{PF} V_{PF} T_{PF} CT_{PF}) * (NM) \quad (1.8)$$

$$ENM_{old} = ENM_{new} \quad (1.9)$$

$$If\ ENM_{old} > M_{max}\ or\ t > t_{max}, signal\ oil\ change \quad (1.10)$$

FSS uses a sensor [17] that measures oil level and oil temperature, and calculates oil conductivity, as Daimler discovered that oil degradation can be correlated to its ability to conduct electric current. To calculate the oil conductivity this sensor measures change in capacitance, which is used as a proxy for the amount and type of contaminants and oil degradation products present in the oil. The oil level is measured to warn the operator about oil leaks and any abnormal oil contamination. The oil conductivity parameter is used to warn the operator when either water is being generated and accumulating in the sump, due to extreme driving, or a coolant leak is occurring in the engine. This digital oil quality sensor is fitted above the oil pan on V-6 and V-8 engines. DaimlerChrysler (Mercedes-Benz) has been incorporating this sensor in conjunction with FSS into its vehicles since 1998.

Daimler conducted cold temperature tests on five cars over two years, limiting the maximum trip length to 10 miles. The used oil data was tested every 1200 miles for fuel dilution, viscosity decrease, oil nitration, wear, and TBN. High temperature tests were also conducted on six cars, consisting of two cars of each model, which used high quality oil. These cars were driven over 15,000 miles without oil changes under hot driving conditions and the used oil analysis results in high temperature oxidation and nitration, oil thickening and rapid TBN decrease. The above mentioned tests were conducted to develop and validate FSS. Daimler later tested FSS on 20 vehicles, FSK 1938S model for long haul application. These trucks amounted for more than 3 million miles in different road conditions for two years. The average oil change was carried out once in more than 18,000 miles (for long haul).

The system is programmed such that the oil change messages, system failure and abnormal operating condition messages are displayed automatically on the instrument cluster. FSS can be applied in all Mercedes Benz utility vehicle models equipped with electronically controlled motors. Some parts of the vehicle should have sensors in order to activate the services.

1.5.3 Ford Motor Company Oil-Life System [18]

Ford Motor Company's oil-life monitoring system uses an apparatus to infer engine oil temperature which is used to determine the oil change interval in an internal combustion engine. According to Ford, engine oil change intervals vary depending primarily on the manner in which the vehicle is driven and the conditions under which it is driven, both of which are related to engine oil temperature. Using this method and apparatus, the engine oil temperature is determined without the need of a temperature sensor.

A steady state difference ($OILT_{SSDEL}$) value is calculated as a function of engine speed (N) which is indicative of rotational speed of the engine and aircharge (AC). A steady state oil temperature ($OILT_{SS}$) value is then determined as a function of $OILT_{SSDEL}$, engine coolant temperature (ECT) and two additional values FNB(ECT) and FNC(T_{amb}, V_s). The value FNB(ECT) is indicative of higher heat transfer into the oil at lower engine coolant temperatures and the value FNC(T_{amb}, V_s) is indicative of loss of heat via the oil pan and exposed engine parts due to ambient temperature (T_{amb}) and vehicle speed (V_s). An oil temperature time constant

(TC_{OILT}), which is indicative of rate of change of oil temperature in the engine, is generated as a function of airmass (AM) value. AM is the mass flow rate of air into the intake manifold as measured by a mass flow sensor. The instantaneous oil temperature (OILT) is then determined by taking the rolling average (ROLAV) of steady state oil temperature ($OILT_{SS}$) and oil temperature time constant (TC_{OILT}). Equations 1.11 to 1.14 give the list of calculations carried out in order during each period of vehicle operation.

$$OILT_{SSDEL} = FNA(N, AC) \quad (1.11)$$

$$OILT_{SS} = (OILT_{SSDEL} + ECT) * FNB(ECT) * FNC(T_{amb}, V_s) \quad (1.12)$$

$$TC_{OILT} = FND(AM) \quad (1.13)$$

$$OILT = ROLAV(OILT_{SS}, TC_{OILT}) \quad (1.14)$$

where, all the functional values are retrieved from specific tables that contain empirically derived values stored in the system memory.

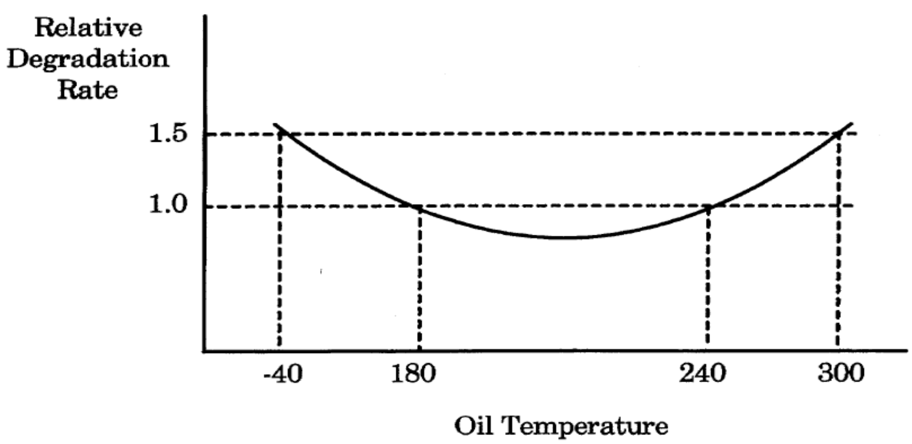

Figure 1-4: Relation between relative oil degradation rate and oil temperature (^{0}F)

An oil stress value (OIL_{MUL}) which is indicative of oil degradation rate is calculated as a function of the instantaneous oil temperature (OILT). OIL_{MUL} is determined periodically by retrieving an oil stress value from an oil stress table which contains a plurality of oil stress values, each of which is indicative of an empirically determined oil degradation rate at a particular oil temperature. Figure 1-4 shows relative rates of oil degradation (OIL_{MUL}) for different oil temperatures in graphical form, where an oil degradation rate of 1.5 indicates a rate of degradation which is 50% greater than a degradation rate of 1.0. The elapsed number of engine revolutions (ENG_{REV}) during each period of vehicle operation is calculated as shown in equation 1.15, where N is the rotational speed of engine in rpm and TMR is a value indicative of the number of seconds elapsed from the start of current period.

$$ENG_{REV} = \frac{N}{60} TMR \qquad (1.15)$$

The effective number of engine revolutions (OIL_{LIFE}) is calculated periodically by modifying the current OIL_{LIFE} value using the elapsed number of revolutions (ENG_{REV}) and the oil stress value (OIL_{MUL}). The effective number of engine revolutions value is then compared with a predetermined threshold value (OIL_{MAX}) indicative of maximum oil-life. Once the OIL_{LIFE} value is greater than OIL_{MAX} value, the system provides a signal to change the engine oil to the operator of the vehicle. It is important to reset the timer once the engine oil is changed. Equations 1.16 to 1.18 show the list of calculations carried out in order during each period of vehicle operation.

$$(OIL_{LIFE})_{new} = (OIL_{LIFE})_{old} + OIL_{MUL} ENG_{REV} \qquad (1.16)$$

$$(OIL_{LIFE})_{old} = (OIL_{LIFE})_{new} \qquad (1.17)$$

$$If\ (OIL_{LIFE})_{old} > OIL_{MAX}, signal\ oil\ change \qquad (1.18)$$

Ford suggests that, by using this apparatus to determine the engine oil temperature, the cost of the system is reduced by eliminating the need for an engine oil temperature sensor. The other advantage of the system is that, numerous modifications may be made to the described method and apparatus to determine the optimum oil change interval. In recent times, Ford has been implementing this system in its vehicles.

Apart from these monitoring systems, Nissan Motors [19] is conducting extensive research on its own oil-life monitoring system which works on the similar principle of predicting the oil temperature to determine the oil deterioration rate. In order to measure engine oil temperature, instead of using a thermostat or a temperature sensor, Nissan uses an engine oil temperature prediction method that was developed by them in 2005.

Although these oil-life monitoring systems have been implemented in vehicles and are currently in use, there still can be reasonable improvements to account for the factors mentioned in section 1.3. Also, these units monitor the oil-life based on the operating conditions of the engine and do not measure oil quality and oil properties, in the same way that an actual oil analysis would. This can be due to the reason that it is highly challenging for oil condition sensors alone to monitor the engine oil life in real time while the vehicle is running. This has led more and more oil analysis laboratories to a flurry of new onboard sensors and related technology which concentrates on measuring the important oil properties while the engine is in operation. Companies with sizeable research budgets are eyeing the huge transportation industry and are trying to develop oil condition sensors that may help in determining the life of the engine oil.

Typically, most of the oil condition sensors determine the life of engine oil by quantitatively sensing an oil condition variable, for example, oil viscosity, oil conductivity, or oil acidity (TAN/TBN). The manufacturers of these sensors claim that when a particular oil condition variable reaches a certain threshold value, a message that the oil has deteriorated beyond the acceptable or usable limit is conveyed. For this group of sensors, the remaining oil life is calculated based on interpolation between fresh oil condition and threshold value obtained from the particular parameter, and translation of the result into time. The following section gives a brief review of few such oil condition sensors.

1.6 Oil Condition Sensors

1.6.1 Delphi Corporation INTELLEK Oil Condition Sensor [20, 21]

Methodology:

The INTELLEK Oil Condition Sensor uses a computer algorithm as well as a sensing element that directly measures various oil properties. The algorithm is said to take into account, the important factors affecting the rate of oil deterioration like temperature, driving severity, oil level, and oil type. A proprietary capacitive sensing element is the core technology. It is claimed to track the oil’s conductivity, detect water and glycol contamination, measure oil temperature, and determine the oil level. According to Delphi, the oil’s conductivity is important because it characterizes additive depletion and changes in viscosity and acid number.

The sensor is supposed to be attached to the oil pan (or wherever there is a continuous flow of oil) and communicate with the oil in the oil pan. It is set to measure the oil temperature once in every 10 seconds and also record the number of times the engine turns on and off. The countdown rate of the remaining oil life (ROL) towards a predetermined threshold value of maximum oil-life (MOL) in time depends on the oil deterioration rate (α). Although, there is no data in the literature suggesting the calculation or estimation of α. Equations 1.19 to 1.21 show the list of calculations carried out in order during each period (once in every 10 seconds) of vehicle operation.

$$ROL_{new} = \alpha \, ROL_{old} \quad (1.19)$$

$$ROL_{old} = ROL_{new} \quad (1.20)$$

$$If \; ROL_{old} > MOL, signal \; oil \; change \quad (1.21)$$

When the oil is nearing the end of its service life, an onboard signal is used to indicate the driver to change the oil. Delphi claims that any countdown rate or the actual ROL value can be adjusted in a positive or negative direction in response to the addition of fresh oil to the system or contamination of the oil.

Infeasibilities:

1. It is not clear how the sensor differentiates between conductivity of various external particles in the oil like soot, polar molecules (water and antifreeze), and other charged particles (ions).
2. The sensitivity of sensors to various compositions of oils and different brands of oil is not clear.
3. As conductivity of various particles present in the oil is highly sensitive to temperature [22], the temperature of the sample fluid, used for conductivity measurement, must be accurately measured. This is highly difficult and requires in-situ statistic analysis.

1.6.2 Voelker Sensors Inc. Oil Insyte [23]

Methodology:

The Oil Insyte sensor operates by utilizing a technology based on the electrical properties of a conductive polymeric bead matrix to track the change in the solvent properties of the oil (see Automotive Sensor Technologies explained in Appendix A for more details). The Oil Insyte employs an in-line method for continuous oil condition monitoring with an LCD readout providing information about oxidation, additive depletion, soot contamination and oil temperature. Voelker Sensors claim that the technology does not require external calibration standards and reports oil condition independent of viscosity, composition (mineral vs synthetic) and additive formulations (commercial oils vs base stock). The sensor is said to use a differential technique where the conductivity of the bead matrix is measured relative to the conductivity of the oil to determine the true polar condition of the oil.

According to Voelker Sensors, Oil Insyte was evaluated by conducting both bench and on-board tests on various engines (4 cylinder turbo engines, V-6 and V-8 equipped minivans) under a mixture of city and highway driving conditions while using different grades of mineral oils. From the obtained results, Voelker Sensors suggest that the Oil Insyte technology measures oxidation and additive depletion in real-time, has the ability to examine the interdependence between the two and the soot detection feature of the sensor determines the amount of undispersed agglomerated soot (vs. dispersed finely divided soot) present in the oil. The sensor was said to be operated over the full temperature range of a vehicle, although the data related to the operating conditions of the vehicle was not found in the literature.

Infeasibilities:

1. It is not clear how the sensor differentiates between conductivity of various external particles in the oil like soot, polar molecules (water and antifreeze), and other charged particles (ions).
2. As conductivity of various particles present in the oil is highly sensitive to temperature [22], the temperature of the sample fluid, used for conductivity measurement, must be accurately measured. This is highly difficult and requires in-situ statistic analysis.

1.6.3 Symyx Technologies Inc. Solid-State Oil Condition Sensor [24]

Methodology:

Symyx Technologies developed a sensor that uses a solid-state micromechanical resonator based on a crystal tuning fork and a special signal-processing algorithm to measure four important and independent physical properties of lubricants: viscosity, density, dielectric permittivity, and AC conductance. This sensor is said to monitor the engine oil in real-time and can be used with various diesel engine oil base stocks and additive packages.

Symyx tested the sensor in various Thermo King diesel engines with fresh and contaminated oil samples of different grades for approximately 5000 hours. According to Symyx, the multi-parametric analysis results for viscosity, density, dielectric constant, and soot concentration compared favorably with those obtained through laboratory analysis. Symyx claim that the miniature sensor allows for innovative packaging and strategic placement in an engine to provide in-situ oil analysis without negatively affecting the design parameters of an overall system.

Infeasibilities:

1. It is not clear how the sensor measures dielectric permittivity accurately as it varies differently with any external particles like soot, polar molecules (water and antifreeze), and charged particles (ions).
2. As viscosity is very sensitive to temperature, the temperature of the sample fluid, used for viscosity measurement, must be accurately measured. This is highly difficult and requires in-situ statistic analysis.
3. It is not clear how the sensor differentiates between various oil grades and compositions.

1.6.4 Diesel Engine Lubricating Oil Contaminant Sensor Method [25]

Methodology:

Lubricating oil used in Diesel engine deteriorates by the depletion of additives and increase in acidity of oil, measured by TAN (Total Acid Number). During usage of Diesel engine, the crankcase oil gradually builds up soot, a combustion product in the combustion chamber of engine and which is transferred in small amounts to the crankcase oil. When soot builds up to an unacceptable level, the quality of lubricating oil is inhibited. For this purpose, measurement of soot content in crankcase oil is important.

Dielectric constant (permittivity) of the oil is used to gauge the soot concentration. It is measured with a sensor built like a capacitor that includes two metal electrodes which take the form of two parallel plates or two concentric cylinders. The lubricating oil acts as the dielectric between the electrodes. Measurement of capacitance between the metal electrodes determines the permittivity of the oil.

Similar sensors that measure loss tangent i.e., ratio of electrical conductivity to dielectric constant are also proposed. These sensors assume dielectric losses can be described by a single relaxation method.

Infeasibilities:

1. The assumption is inapplicable since used oil contains conductive particles (soot), polar molecules (water or antifreeze), and charged particles (ions).
2. These sensors are more sensitive to parasitic signals, such as brand of oil or presence of water or antifreeze.
3. It is not clear how the sensor measures dielectric constant accurately as it varies differently with different external particles.
4. Permittivity of only the sample oil that is between the electrodes is measured, this might lead to disregarding external particles or contaminants.

1.6.5 Micro-Acoustic Wave Sensor for Engine Oil Quality Monitoring [26]

Methodology:

The quality of the engine oil is a measure of the oil's ability to perform its functions that determines the residual useful life of the oil. Viscosity measurement is used to provide general and sometimes critical indication of the oil condition when the oil is close to the end of its useful life.

Micro-acoustic wave sensors which include the bulk acoustic wave (BAW) and surface acoustic wave (SAW) sensors have been widely investigated for fluid property such as viscosity measurement. The BAW sensor based on the thickness shear mode (TSM) in quartz is one of the most commonly used micro-acoustic wave devices for fluid viscosity. Quartz resonators may be used with one or both electrodes in contact with the fluid.

A 2-sided TSM resonator is found to have larger viscosity sensitivity while suffers more liquid damping than the 1-sided device. The influence of the fluid permittivity on the 2-sided device is insignificant. However, the study confirms that the 2-sided TSM resonator is not suitable for measurement in conductive fluids. Sensor prototypes have been developed for both 1- and 2-sided TSM resonators and the test results show that they may be appropriate for providing oil quality information by monitoring the viscosity change in some applications.

Infeasibilities:

1. The 2-sided TSM resonator is not suitable for measurement in conductive fluids.
2. Factors other than the oil viscosity and density may have influences on the sensor response.
3. It is not clear how the sensor differentiates between the changes in viscosity caused by temperature change, oxidation, fuel dilution, and mechanical wear, all of which may lead to oil deterioration but may not be detected by change in viscosity.
4. As viscosity is very sensitive to temperature, the temperature of the sample fluid, used for viscosity measurement, must be accurately measured. This is highly difficult and requires in-situ statistic analysis.

1.6.6 Engine Oil Contamination Sensor [27]

Methodology:

This includes a first sensing electrode and a second sensing electrode. A sensing area is established between the electrodes. The system is kept in an oil pan such that sensing area is immersed in oil. A microprocessor is connected to electrodes and includes a program for determining whether antifreeze is dispersed in oil. Oil contamination sensor is placed and engine is started and oil is heated.

Heating oil to a low temperature range (30 ^{0}C - 40 ^{0}C) and measuring series of output voltages. The present value is compared to an immediately previous voltage value and based on this comparison, it is determined whether antifreeze is being dispersed in the oil.

For medium temperature range (40 ^{0}C - 60 ^{0}C), output voltage is measured and compared to previous values. Differential values are obtained and are compared to threshold voltage value.

Infeasibilities:

1. It is not ensured that the difference in voltage is only because of antifreeze.
2. There is a possibility of presence of conductive particles due to engine wear but the sensor does not account for such cases.
3. Even when the oil shows a voltage difference similar to that of threshold voltage values, it may not ensure that the oil is not contaminated because of neutralizing effects caused by oxidation, temperature changes, nitration, etc.

1.6.7 Combined Oil Quality and Viscosity Sensing System [28]

Methodology:

Combined oil quality and fuel contamination sensing system includes:

1. A capacitive dielectric sensor for measuring dielectric constant of oil.
2. Pressure sensing arrangements for measuring oil pressure indicative of oil viscosity and contamination.
3. May include an additional sensor measuring the temperature of oil within the system to adjust oil dielectric constant and viscosity indications.

Infeasibilities:

1. Oil viscosity and contamination are calculated by measuring just pressure. Clearly, it cannot account for extreme conditions (HTHL etc.) and external contamination.

2. Dielectric constant is affected by various factors that the sensor does not account for.
3. Factors other than the oil viscosity may have influences on the sensor response.
4. It is not clear how the sensor differentiates between the changes in viscosity caused by temperature change, oxidation, fuel dilution, and mechanical wear, all of which may lead to oil deterioration but may not be detected by change in viscosity.
5. Needs local temperature sensing rather than a single average reading.
6. Local readings may be sensitive and scattering is also a possibility. In-situ statistical measurements are required. Bulk average readings are much more reliable.

1.6.8 Viscosity Sensor [29]

Methodology:

Viscosity of engine oil is measured using a viscosity sensor that has piezoelectric diaphragms disposed in a fluid chamber of housing. An elongated amplification channel is formed in the housing and extends away from the chamber. The diaphragm can be excited to induce fluid movement that in turn induces the diaphragm to output a sensor signal representative of the viscosity of the fluid.

Mechanical stress induced in the piezoelectric element is used to determine the viscosity of the oil.

Infeasibilities:

1. Mechanical stress induced in the piezoelectric element may not be only from viscosity.
2. It is not clear how the sensor differentiates between the changes in viscosity caused by temperature change, oxidation, fuel dilution, and mechanical wear, all of which may lead to oil deterioration but may not be detected by change in viscosity.

Bosch multifunction oil condition sensor [30] and Lubrigard oil condition sensor [31] monitor the oil condition based on the similar properties discussed in the aforementioned section.

1.7 Shortcomings of Implemented Systems and Sensors

1.7.1 Insufficiency and Reliability Issues of Oil-Life Systems

General Motors, DaimlerChrysler, Ford Motor Company and other auto industry leaders have been conducting extensive research in predicting the oil change intervals and have implemented systems (discussed earlier) that monitor the oil life. Whether or not these systems consider the important aspects of oil deterioration (with reference to section 1.3), their insufficiency and reliability issues are discussed in this section.

GM Oil-Life System monitors engine revolutions and calculates engine oil temperature and engine oil contamination content to predict the oil condition. Calculating or estimating the oil contamination content is a complex task as it varies with the engine design, engine mileage, oil-type, and oil age. GM's system uses an identical method to calculate the oil contamination content, using mainly the oil temperature, throughout the life of an engine and engine oil. This approach is certainly questionable on how meaningfully the oil change interval is calculated. GM uses statistical techniques to determine as many as twelve constants (k_1 to k_{12}) which are used to calculate engine oil temperature and engine contamination content during each period (one in every 5 or 10 seconds) of vehicle operation. It is highly complicated to find the best fit with so many variables involved. Also, this fit is obtained from a limited data set available in the system memory, raising questions on the general reliability of such approximations in calculating oil change intervals. It is apparent from the system that the oil-life is discounted by calculating the effective number of engine revolutions mainly as a function of only engine oil temperature and engine rotational speed. Also, with reference to section 1.3, the factors like heavy engine loading, short-trip (frequent cranking) driving in winters, driving in dusty conditions, engine mileage and oil aging have not been considered in GM's system. Hence, their system seems to miss few major factors that affect the oil quality while using complicated and fancy calculations to calculate oil contamination content and oil temperature.

In DaimlerChrysler's Flexible Service System (FSS), it is mentioned that many operating conditions like engine oil temperature, engine coolant temperature, engine load, engine speed, and vehicle speed are considered. But there is no data in the literature suggesting how the corresponding penalty factors and remaining engine oil life are calculated or predicted. This makes the system not transparent enough on the methodology used to predict oil change interval which might hinder the buyers from investing in the product. FSS has a sensor that is used to determine the conductivity of the oil. But, it is not clear how the system accounts for the changes in conductivity of contaminants (or external particles) at varying temperatures. Conductivity varies with temperature and since oil temperature has a broad range, the conductivity of the oil does not remain the same under all operating conditions. Thus, it becomes highly difficult for the sensor to account for the external particles having different conductivity values at different temperatures. Also, the data available on conductivity measurement of engine oils shows a lot of noise scattering, which does not give a clear picture of variation in conductivity due to oil quality deterioration. Daimler uses the same sensor to check for the oil level, but it is not clear how the sensor accounts for changes in oil level while driving on mountain slopes, speed breakers etc. Apart from this, the reliability issues of the sensor at extreme temperatures (below -20°C and above 150°C) and its durability over a long period of time under extreme operating conditions have not been addressed. Also, with reference to section 1.3, the factors like short-trip (frequent cranking) driving in winters, driving in dusty or desert conditions, and engine and oil aging have not been considered in the FSS.

Ford Motor Company's oil-life system has an apparatus that predicts the engine oil operating temperature. Ford suggests that the effective engine oil operating temperature can be predicted as a function of engine speed, engine revolutions, aircharge, mass flow rate, coolant temperature and heat transfer by convection. It can be highly complicated to model engine oil heat transfer that depends on many variables like vehicle speed, engine speed, engine design, oil-type, and environmental conditions. The correctness of such quantitative numbers obtained from the designed heat transfer model can be questioned. Also, there is no data in the literature that gives details on the calculations of functional values which are said to be derived empirically. The applicability of performing such empirical calculations using a limited data set over a wide variety of vehicle operating conditions can be questionable. In reality, it can be highly difficult to predict the engine oil operating temperature as it depends on many factors that vary with engine type, engine age and engine operating conditions. Instead, having multiple reliable temperature sensors would be a much simpler approach to measure the oil temperature. Apart from these, the maximum relative rate of oil degradation used is 1.5 at extreme temperatures of -40^{0}F and 300^{0}F, which can certainly be questionable, as it suggests that even while operating at extreme temperatures for extended periods, the engine oil can be used for an amount of time that is comparable to its maximum threshold limit. Also, with reference to section 1.3, the factors like short-trip (frequent cranking) driving in winters, driving in dusty conditions, oil aging and heavy engine loading have not been considered in the proposed system. Similar argument holds for Nissan Motors' oil-life monitoring system which proposes a method to predict engine oil temperature to calculate the remaining oil life.

1.7.2 Feasibility and Reliability Issues of Oil Condition Sensors

Most of the oil condition sensors monitor one or more of the following properties: viscosity, density, conductivity and permittivity of the oil. Although oil viscosity plays an important role in predicting the oil life, a viscosity sensor might not capture the oil deterioration. For example, chemical oil deterioration is associated with an increase in viscosity, whereas mechanical wear (shear) and fuel dilution lead to a decrease in viscosity. In a case where both chemical deterioration and mechanical wear occur, the viscosity sensor might not sense any change in viscosity value resulting in a wrong prediction of oil deterioration. Similar argument holds true for density monitoring. Conductivity and permittivity of external particles that contaminate the engine oil do not vary similarly with temperature [22]. For example, conductivity of ultrapure water changes by 5.5% per ^{0}C and conductivity of normal fresh water changes by 2% per ^{0}C [22]. When two different forms of water have significant change in conductivity per temperature rise, it is difficult to imagine how various external particles that contaminate the engine oil are differentiated. Thus, it is highly difficult for the sensors to capture the changes in conductivity or permittivity accurately over a wide temperature range.

The oil condition sensors have not yet been implemented as reliable oil-life monitoring systems for real time measurement of lubricant properties. For this to happen, signal processing of the sensors should be reliable and the response time needs to be low and extremely accurate. Laboratory based oil condition approaches have significant time lag and other logistical difficulties. Major concerns like sensor reliability to monitor the quality of oil, durability over long periods of operation, operational temperature range, survival at severe mechanical, chemical and thermal conditions, and functionality with different engines, oil grades and additives are yet to be addressed, without which the sensors cannot be used for oil life monitoring. The data available on the measurement of different engine oil condition variables shows a lot of noise scattering, which does not give a clear picture of variation in oil condition parameter due to the oil quality deterioration under various operating conditions. Also, it is not clear from the data available in the literature, whether the sensors are easily mountable on any engine (gasoline or diesel, heavy- or light-duty) and on any vehicle. The manufacturing and maintenance cost of these oil condition monitoring sensors prohibit their everyday use and their size and design constraints might make them impractical to include in all vehicles. Hence, before these sensors are used to monitor the quality of engine oil during vehicle operation, extensive laboratory testing and field test data are required to predict their performance considering the above mentioned criterion.

1.8 Proposal of Present Approach

Automotive oil-life monitoring is far from a mature technology as majority of vehicles do not come standard with oil-life monitoring systems today. It is almost impossible to accurately recommend an oil change interval even with the best possible equipment and hence, instead of trying to find a crystal bowl one must aim at improving the present trend of oil-life monitoring. The common current practice for the vehicles which are not equipped with oil-life monitoring systems is to change the oil once in approximately 5000 miles or 6 months, whichever occurs first. On the other hand, for the vehicles equipped with oil-life monitoring systems which are presented in this chapter, DaimlerChrysler's FSS claims to account for a number of factors mentioned in section 1.3, but it is not clear, from the literature, how reasonably FSS accounts for those factors. To improve this present trend of oil-life monitoring, a system that is transparent and performs better than the current practice for vehicles with or without an oil-life monitoring system, needs to be developed. An intelligent system should have a balance between human interference and automation to improve the reliability of oil-life prediction without affecting the engine components or their performance. As oil-life monitoring progresses and becomes more popular in the automotive industry, there will be many generations of oil condition sensors developed to improve accuracy, reliability and range of capability. But it is highly unlikely that the feasibility and reliability issues of oil condition sensors, mentioned in section 1.7, would be addressed to an extent that can convince the automotive industry and the general public to invest in them. Even if some of these issues are successfully resolved, we may only see oil condition sensors used to warn the operator of the vehicle of any abnormalities like oil leaks and extreme contamination of oil.

Hence, it is highly recommended to develop an oil-life monitoring system using the classical approach (algorithm based method to monitor the operating conditions of the engine) to predict the effective engine oil life. Temperature, pressure, speed, and load measuring sensors, which are highly reliable, can be used to monitor the operating conditions of the engine. In order to convince the automotive industry and the public in general, an efficient oil life algorithm:

- Should factor for major chemical, mechanical and thermal effects, condensation and formation of acids, high temperature oxidation and thermal breakdown, mechanical stresses, short-trip (frequent cranking) winter driving, environmental conditions and oil aging.
- Must be placed on a conservative side and the system should account for abnormal lubrication conditions like oil leaks, coolant leaks, metallic wear debris accumulation etc.
- Should be robust enough to predict the life of any engine oil, be it mineral or synthetic and to be mounted on any engine, be it diesel or gasoline, heavy- or light-duty.
- Must be easily modifiable so that it can account for the latest advancements in engines and engine oils.
- Should be implemented as a cost effective system to encourage the auto manufacturers to invest in the product.

Taking all these factors into account, a meaningful, simple and cost effective oil-life algorithm is proposed in the present work. The algorithm can be easily modified and applied to any type of engine (gasoline or diesel; light-duty or heavy-duty) or engine oil (mineral or synthetic). Also, it can be evaluated and updated through timely field data, from which a statistical trend and pattern may be established. The major oil deterioration effects mentioned in section 1.3 (and detailed in Chapter 2, later) are factored in on a meaningful trend (order of magnitude) based on various literatures including patents, technical papers, laboratory and field tests, operation manuals, and guidelines in conjunction with lubrication science and engine operation knowledge.

The proposed algorithm takes into account, the nominal engine oil life (can be updated based on the oil type) and monitors engine oil temperature, coolant temperature, engine load, engine speed, engine cranking, and oil aging. It maintains a simple balance between automation and human interference. On one hand, the system notifies the operator of the vehicle to check for the oil level and any visible abnormality, periodically, and on the other hand the operator can notify the system when moving through dusty or desert environment, so that a correction factor is used to increase the used oil life accordingly. As the major oil deterioration effects and shortcomings of current oil-life monitoring systems in the market are considered and accounted for in this algorithm, it is believed that this would lead to an improvement in the current practice of oil-life prediction. The effects of changes in operating conditions on engine oil life, the development of correction factors, and the system level implementation of the oil-life algorithm are broadly discussed in Chapter 2.

Chapter 2

Algorithm Development

A number of factors can impair engine oil performance. Oil thickening, loss of wear protection, and deposit control are of concern primarily in high-temperature, high-load service [32]. Oil thinning, loss of corrosion protection, and low-temperature sludge formation are of concern primarily in short-trip, winter service [32]. The changes in engine oil properties affect its performance and these changes can be related to the engine operating conditions. Section 2.1 gives an understanding on how the engine operating conditions affect the oil properties and in turn the oil life.

2.1 Effects of Operating conditions on Oil properties

2.1.1 Viscosity

Viscosity of engine oil plays a dominant role in the formation of a fluid film between moving metal parts. Changes in engine oil viscosity indicate some form of oil degradation during the vehicle operation. Increases in viscosity can be due to oil oxidation, soot contamination, or volatilization of light base stocks in the oil which occur prominently under high-temperature, high-load conditions [32]. Decreases in viscosity can be due to fuel or low-viscosity soluble contaminants in the oil, or to shearing of the viscosity index improver. This phenomenon becomes more prominent as the age of oil in the vehicle increases [32]. The consequences of an excessive viscosity increase include difficulty in starting a vehicle at low temperatures and the possibility of inadequate lubrication if the oil is so viscous that it cannot reach all the critical components that it must lubricate [4, 7]. The consequences of excessively low viscosity include insufficient oil film thickness and wear of parts such as bearings and crankshaft journals, which depend on an adequate oil film for lubrication [32].

It is clear that high-temperature, high-load conditions, low-temperature, short-trip service, environmental conditions, oil aging, and mode of driving (or trip lengths) have a direct effect on viscosity. In addition, during idling (captured by low engine speeds) fuel is only partially combusted which results in contamination of oil and thus, affecting the viscous properties of oil [33]. The changes in viscosity due to these operating conditions have adverse effects on engine oil performance.

2.1.2 Base Number and Acid Number

Total Base Number or TBN can be defined as a measure of the remaining amount of protective alkaline agents placed in the oil by the manufacturers to neutralize acids, and is used to determine the ability of the oil to neutralize acids from combustion.

Engine oil is continuously exposed to acidic combustion products and these need to be neutralized before they can corrode engine parts. Alkaline additives are present to neutralize both the acids derived from combustion (mainly strong sulfuric and nitric acids) and those weaker, organic acids resulting from oxidation of the oil during its aging. Maintaining sufficient alkaline reserve is critical to prevent corrosion of the upper piston, piston rings and top end bearing. Severe depletion of the TBN results in acid corrosion and fouling within the engine, and additionally, low TBN is indicative of reduced oil detergency. Tests [32] have shown that TBN decreases rapidly during high-temperature, high-load conditions and short trip, winter-time conditions.

On the other hand, Total Acid Number or TAN is a measure of the concentration of acidic species in the oil, which may include weakly acidic components of the fresh oil, acids formed during oil oxidation, and weak to moderately strong acids generated during the combustion process.

Oils continually react with atmospheric oxygen to produce organic oxidation products that are acidic in nature. At ambient temperature, this reaction is very slow and has little effect upon oil conditions. At the elevated temperatures that exist within an operating engine, reaction rates are much higher. This is especially true when localized heating occurs on sliding surfaces, as the temperatures can be very much higher than that of the surrounding metal. Combustion and wear products in solution in the oil can additionally catalyze the reaction between the oil and oxygen. The degradation products are organic acids that do not react easily with the alkaline TBN additives and tend to co-exist. They cause increased oil viscosity and can deposit as lacquers on hot surfaces. Tests [32] have shown that TAN increases rapidly during high-temperature, high-load conditions and short trip, winter-time conditions.

High values of TAN and low values of TBN as the oil age increases, compared to values for the fresh oil, indicate that the oil has lost some of its ability to neutralize acids and that corrosion of engine components is more likely to occur [6, 32], thus affecting the engine oil performance.

Hence, changes in TAN and TBN values, as a result of operating conditions such as temperature, engine load, environmental conditions, oil aging, and mode of driving, affect the engine oil performance.

2.1.3 Fuel in Oil

The presence of fuel in oil can cause a sharp decrease in engine oil viscosity. Under certain conditions, excessive unburned fuel in the oil from cold weather operations can reduce oil viscosity to such an extent that it no longer provides adequate oil-film thickness in critical areas within the engine [6]. However, much of the fuel may be eliminated when the engine oil reaches stabilized operating temperatures. Furthermore, the heavier ends of the fuel, which remain after lighter ends are boiled off, have less tendency to reduce the viscosity of the engine oil. High engine loads and engine speeds generate more blow-by gases and unburnt fuel to enter the crankcase oil [4, 14].

Fuel in oil contributes significantly to the loss of oxidative stability of the oil [6, 7]. Partially oxidized fuel components, arising during short-trip service, can also be condensed in the engine oil and can cause an increase in TAN and a decrease in TBN. This effect can sometimes be reversed at higher oil temperatures [32].

The amount of fuel that enters and remains in the engine oil depends on factors such as the ambient temperature, the oil temperature, the engine load, the engine speed and the trip length [6]. Hence, these operating conditions have been considered important in the development of the algorithm.

2.1.4 Water in Oil

Water is a product of the combustion of fuel. During vehicle operation when the engine is cold, water can enter the oil and cause rust. Excessive water contamination in engine oil can cause increased wear in an engine. Water can also cause excessive corrosion and can affect the solubility of the oil's additive package, sometimes causing "additive drop out", that is, precipitation of additives from the oil [6, 32]. However, during long-trip driving, water present in the oil is evaporated to a major extent due to the high operating temperature range.

Field tests [6] have shown that the water contamination levels are high when the oil and ambient temperatures are low, the trip lengths are short and engine loads are high. Thus, these operating conditions are considered important in algorithm development.

2.1.5 Iron in Oil

Iron may enter engine oil as a consequence of wear, corrosion, or engine damage. Tests have revealed that the rate of accumulation of iron is far greater in short-trip service than in long-trip service [6]. Presence of water in engine oil leads to corrosion, which is a primary mechanism for entry of iron into oil. Also, lack of sufficient amount of oil in the engine leads to significant wear that results in deposition of iron in oil.

Although Section 2.1 gives an idea of changes in oil properties due to operating conditions, it is understood that it is highly complicated to isolate the complex inter-relations between each cause and effect. It is not possible to independently quantify the effect of various factors that impair the engine oil performance as most of them go hand in hand. Hence, the best methodology is to express the degradation of oil quality, over the period of engine oil usage in a vehicle, as a measure of vehicle operating conditions such as oil temperature, engine load, engine speed, frequency of cranking, and environmental conditions.

The oil life monitoring systems, currently in the market, do not necessarily address all the above mentioned factors and an attempt has been made here to include the significant factors affecting the oil deterioration meaningfully into one monitoring system. The unique features of the present algorithm that have not been captured in the existing oil life monitoring systems are detailed below.

- **Engine idling:** During idling, fuel is only partially combusted because an engine does not operate at its peak temperature and air-to-fuel ratio is not optimum [33]. This leads to the buildup of fuel residues on cylinder walls that can damage engine components, contaminate engine oil, and increase fuel consumption. This effect is captured by the low engine speeds.
- **Oil aging:** The ability of engine oil to continuously lubricate the engine moving parts and provide oxidation, thermal, and shear stability does not remain as effective as it is for new oil [4, 6]. This effect is captured by monitoring the number of days of engine oil in the oil sump.
- **Oil level check:** Lack of oil in the engine leads to serious breakdown of the engine and hence it is highly important to maintain sufficient amount of engine oil. This feature is captured by displaying a warning message at regular intervals.
- **Hot and cold cranking conditions:** Short-trips and frequent engine cranking have adverse effects on engine oil performance and its properties, as discussed above. Apart from capturing this effect, the present algorithm has a feature to differentiate between hot and cold starting conditions which is significant in predicting the oil deterioration rate when engine is started. This effect is captured by monitoring the engine cranking and engine starting temperature.
- **Dust/desert environment:** Driving in dusty conditions (dirt/gravel roads/desert environment) results in dust/dirt entering the crank case which can significantly hamper the lubricating properties of the engine oil. The dirty oil generates more wear metals which increase the risk of sludge formation and corrosion from acids [8, 9]. This effect has been captured by providing a toggle switch that can be turned on or off based on the environmental conditions.
- **Balance between automation and human intervention:** Using complicated and unreliable oil condition sensors may lead to wrong predictions of oil life as discussed in Chapter 1. Thus, a simple balance between the system automation and human intervention has been used to avoid this complexity. Warning messages to check oil

level and manually operable toggle switch to capture dust/desert environment are two such examples.

The factors mentioned above and in Section 1.4 of Chapter 1, in conjunction with the effects of oil operating temperature, engine load and engine speed have all been included in the current algorithm on a meaningful trend which is on the basis of laboratory experiments, field test data, and understanding of lubrication science and heuristics.

An accurate measure of oil operating conditions, viz. temperature, engine load and speed is guaranteed by using temperature, load and speed measuring sensors which are highly reliable. These measured values are served as inputs to the current algorithm that calculates the oil deterioration rate and gives the percentage of oil life remaining. The following section gives an understanding of algorithm implementation at the system level.

2.2 System Implementation

In order to predict the remaining oil life, the oil life needs to be related to a quantity that is constantly updated based on oil deterioration rate. The oil life monitoring systems currently in the market (presented in Section 1.5 of Chapter 1) use either engine revolutions or vehicle mileage equivalent to the engine oil life. In this algorithm though, time has been used as equivalence to oil life. This is because engine run time gives a realistic reflection of oil usage when compared to engine revolutions or vehicle mileage. The number of engine revolutions is affected by the operating conditions such as trip length, engine load, engine speed, idling etc. It is also difficult to get a sense of nominal number of revolutions equivalent to oil life. On the other hand, vehicle mileage is affected by city driving or highway driving and idling or towing do not generate any mileage, making it difficult to monitor. Whereas, monitoring engine run time gives the measure of the exact time that an engine is running independent of everything else and gives a better sense and is easier to monitor. This value is then discounted appropriately based on the effect of various operating conditions to obtain the used oil life.

The nominal oil life (nominal_oil_life) is set at N hours. This value is stored in the system memory and is dependent on the type of engine and engine oil. After each sampling time interval (Δt), the oil used life (oil_used_life), cumulated oil used life (cumulated_oil_used_life), engine running time (engine_run_time), and cumulated engine running time (cumulated_engine_run_time) are calculated and updated. The updated values of cumulated oil used life and cumulated engine running time are continuously saved (after each sampling time interval) in the system memory.

Based on the calculated oil used life value, the percentage oil life remaining (percent_oil_life_remaining) is calculated and displayed on the display device provided on the controller. Once the percentage oil life remaining value falls below 50%, a message to check the oil level is displayed on the display device. This is to compensate for any possible oil consumption or leaks in the engine. When the percentage oil life remaining value falls below 1%, a message to change oil is displayed on the display device.

Along with the display device, a reset button is also provided on the controller, which needs to be pressed once the oil is changed. Whenever the reset button is pressed, the values of cumulated_oil_used_life, cumulated_engine_run_time and days_oil_in_sump are all set to 0. The following equations give a mathematical understanding of the system implementation.

$$nominal\_oil\_life = N\ hours \quad (2.1)$$

$$oil\_used\_life = cumulated\_oil\_used\_life + \Delta t * Ct * Cl * Crpm * Cck * Cdust \quad (2.2)$$

$$cumulated\_oil\_used\_life = oil\_used\_life \quad (2.3)$$

where,

Δt = data sampling interval

Ct = temperature correction factor

Cl = engine load correction factor

Crpm = engine speed correction factor

Cck = engine cranking correction factor

Cdust = dust/desert correction factor

All these correction factors, detailed in Section 2.3, make effective Δt longer than physical Δt of the engine run time. Thus, making the used oil life greater than the engine run time.

$$engine\_run\_time = cumulated\_engine\_run\_time + \Delta t \quad (2.4)$$

$$cumulated\_engine\_run\_time = engine\_run\_time \qquad (2.5)$$

$$percent\_oil\_life\_remaining = 100 * \{1 - [oil\_used\_life/(nominal\_oil\_life * Cag)]\} \qquad (2.6)$$

where,

Cag = oil aging correction factor

This correction factor, detailed in Section 2.3, effectively reduces the preset nominal oil life.

When reset button is pressed,

$$cumulated\_engine\_run\_time = 0 \qquad (2.7)$$

$$cumulated\_oil\_used\_life = 0 \qquad (2.8)$$

$$days\_oil\_in\_sump = 0 \qquad (2.9)$$

When percent_oil_life_remaining = 50%,

Display, “Check Oil Level”

This is a simple and effective manual element that makes sure that minimum oil level is maintained by putting a small burden on the operator.

When percent_oil_life_remaining </= 1%,

Display, “Change Oil”

In order to quantify the effect of various operating conditions (on oil deterioration rate) considered in this algorithm, associated correction factors have been calculated and used. The development of these correction factors for a heavy duty diesel engine, as an example, is presented in the following section. A nominal oil life of N = 500 hours is used as a standard value for mineral oils in diesel engines [12] and a value of 5 seconds is used for the data sampling time, Δt.

2.3 Correction Factors

2.3.1 Temperature Correction Factor

Operating temperature plays a very important role in affecting the oil condition, both directly and indirectly, as discussed earlier. It has been showed via laboratory and field test data that the operating temperature range during which the oil has its best lubricating properties is 80^0C to 130^0C and hence a correction factor of 1 has been used for this range. During extreme low temperatures, viz. below 0^0C, fuel and water (due to condensation) can accumulate in the oil. Also, due to incomplete combustion, fuel reaction products are formed that can reduce the viscosity of the oil thereby affecting its performance. Considering these, the correction factor for below 0^0C temperature range is set at 8. It is also in agreement with previous work [4, 7], which suggest a maximum mileage of 18,000 miles under normal operating conditions and a minimum mileage of 2,500 miles under cold driving conditions, resulting in a ratio of approximately 8.

As the temperature rises above 0^0C, the engine oil performance gradually improves and reaches its optimum near 80^0C [2, 8]. Hence, for the temperature range of 0^0C to 80^0C, a linear variation from 8 to 1 in the correction factor is justified. At high engine oil temperatures, viz. above 130^0C, oxidation becomes so prominent that it outweighs the antioxidants in the oil and engine oil starts losing its chemical stability. As a result, the oil becomes more viscous and acidic due to oxidation and nitration. As temperature rises, these effects become more prominent along with the deposition of insoluble materials on the engine surfaces as a varnish or sludge [2, 8]. Also, may lead to viscosity breakdown as viscosity varies exponentially with rise in temperature (equation 2.10). Thus, resulting in engine wear damage. To capture these rapid deterioration effects at high temperatures, an exponential variation with temperature above 130^0C has been used for the correction factor. Figure 2-1 shows the variation of the temperature correction factor with a broad temperature range.

$$\eta = \eta_0 e^{-\beta(T-T_0)} \qquad (2.10)$$

The effective oil operating temperature (T) is calculated as a function of measured oil temperature (eng_oil_temp) and measured coolant temperature (eng_cool_temp). Temperature values are measured at every sampling interval and should be used in ^{0}C units for the purpose of calculations. Equations below give a mathematical understanding of the theory presented above (assuming that temperature is measured in ^{0}F).

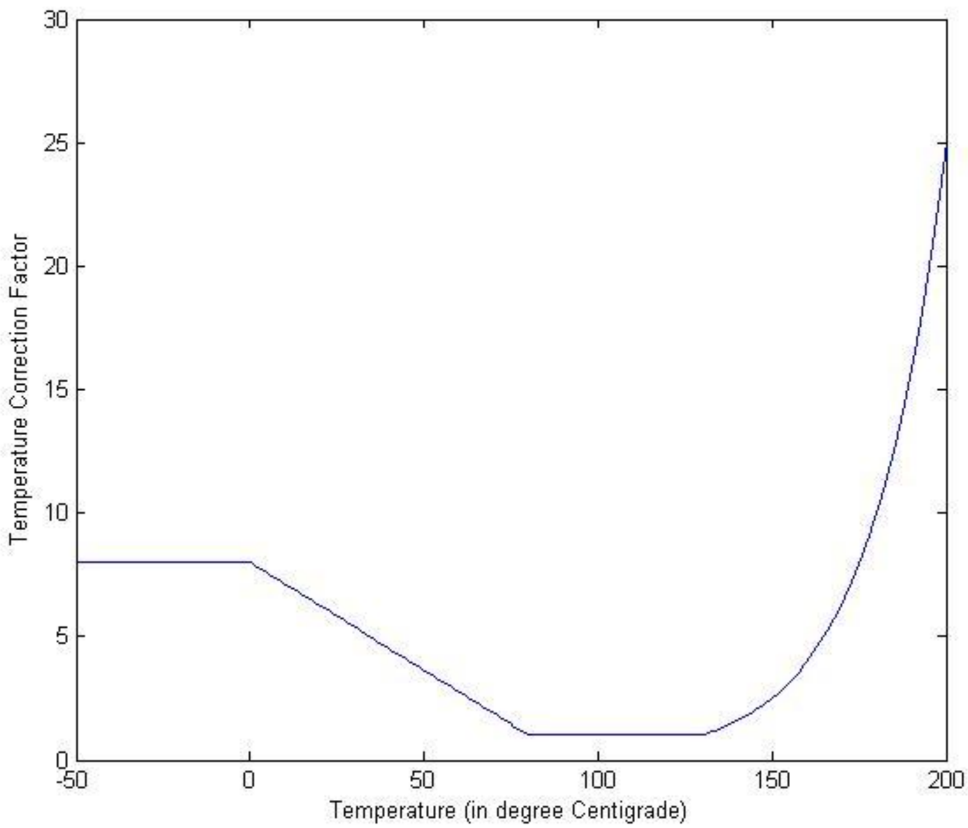

Figure 2-1: Engine Oil Temperature Correction Factor

$$eng\_cool\_temp = (eng\_cool\_temp - 32) * 5/9 \quad (2.11)$$

$$eng\_oil\_temp = (eng\_oil\_temp - 32) * 5/9 \quad (2.12)$$

If eng_cool_temp < 100^{0}C,

$$T = (eng\_cool\_temp + eng\_oil\_temp)/2 \quad (2.13)$$

If eng_cool_temp > 100^{0}C,

$$T = eng\_oil\_temp \quad (2.14)$$

When T < 0^{0}C,

$$Ct = 8.0 \quad (2.15)$$

When 0^{0}C < T < 80^{0}C,

$$Ct = 1.0 + 7.0 * (80 - T)/80 \quad (2.16)$$

When $80^0C < T < 130^0C$,

$$Ct = 1.0 \quad (2.17)$$

When $T > 130^0C$,

$$Ct = 10\text{^}(\frac{T - 130}{130 - 50}) \quad (2.18)$$

2.3.2 Engine Load Correction Factor

Heavy loads on the engine result in thinning of oil films, higher shearing of viscosity index improvers and more wear metals deposition in the oil. Wear metals catalytically shorten oil life causing premature oxidation, sludge, acids, and deposits [3, 8]. Engine mechanical wear, if not controlled, may damage the engine components. High engine loads are generally related to hot running conditions, i.e., high temperature effects and hence the correction factors for engine load are not as high as that for engine temperature (because most of its effects are already captured in temperature correction factor).

When the engine load is below 70%, which is generally the nominal operation load range, a correction factor of 1 is used. As the load value approaches 100%, the correction factor is gradually increased to a value of 2, beyond which a rapid increase is observed. Although on most occasions engine is not loaded beyond 100%, for illustration purposes it is worth mentioning the effects of higher engine loads accounting for the deterioration effects mentioned above. Figure 2-2 shows the variation of the engine load correction factor with a broad temperature range.

Percentage engine load (percent_eng_load) is measured at every sampling interval. Equations below give a mathematical understanding of the theory presented above.

When percent_eng_load < 70,

$$Cl = 1 \quad (2.19)$$

When percent_eng_load > 70,

$$Cl = 2\text{^}(percent\_eng\_load - 70)/(100 - 70) \quad (2.20)$$

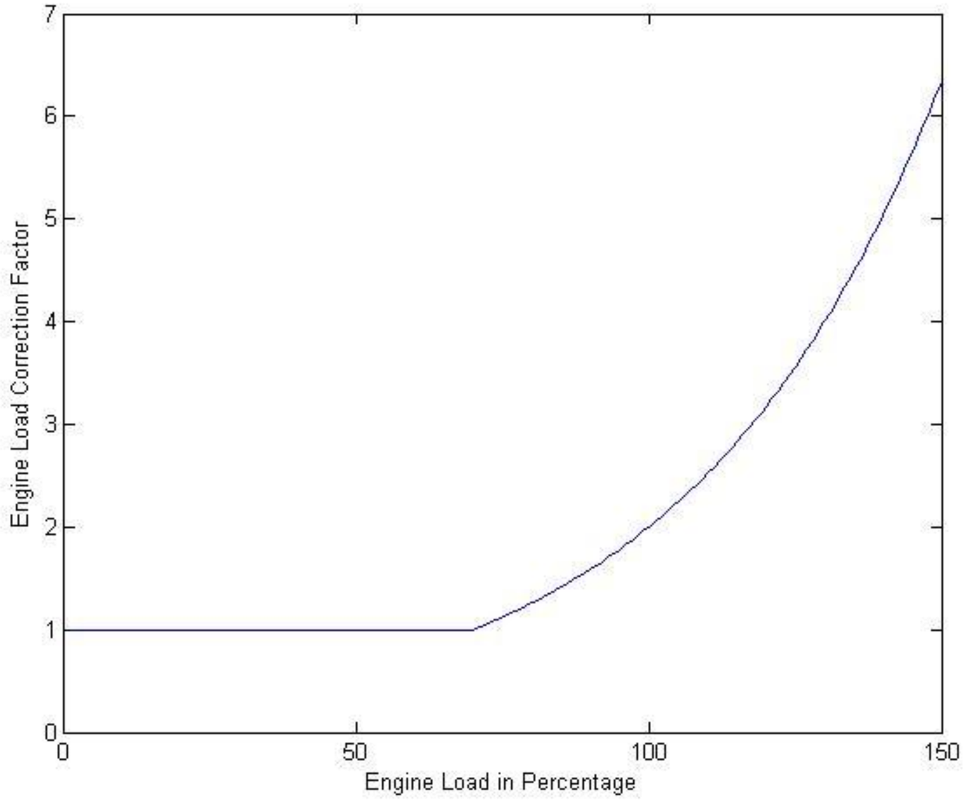

Figure 2-2: Engine Load Correction Factor

2.3.3 Engine Speed Correction Factor

Driving a vehicle at high engine rpm generates unburnt fuel (due to excess fuel-to-air ratio) and corrosive agents (due to mechanical wear) [14]. High engine speeds generate wear particles because of loss of lubricating film, the effects of which are more prominent in boundary film lubrication (piston-cylinder interactions). Boundary film lubrication is a film formation or removal process which may become difficult at very high engine speeds. Also, driving at very high speeds (> 5000 rpm [4]) induces excessive inertial loading which is equivalent to driving under very high load.

Laboratory and field tests have shown that between 900 rpm and 2000 rpm (for heavy diesel engines [4]), engine behaves at its best [7, 12] and engine oil properties are best intact. Thus, a correction factor of 1 is used for engine speed in the range of 900 rpm to 2000 rpm.

During idling (< 500 rpm, typically for heavy diesel engines [4]), the combustion process is not complete and engine produces corrosive agents that enter crankcase oil [4]. To capture this effect, a correction factor of 1.5 is used for engine speed less than 500 rpm. A linear variation of correction factor has been used between 500 rpm and 900 rpm.

For high engine speeds (> 4000 rpm, typically for heavy diesel engines [4]) that are beyond normal operation, due to the ill-effects mentioned above, an increasing quadratic function has been used to model the correction factor variation. The quadratic function is chosen such that the correction factor is doubled at 4000 rpm. Although engine speeds in the range of 7000 rpm are not practical, it is worth mentioning such high speed effects for illustrative purposes. It should be noted that majority of the high engine speed effects are already captured in engine temperature correction factor variation as they go hand in hand in most cases.

Figure 2-3 shows the variation of the engine speed correction factor with a broad temperature range.

Engine speed (eng_rpm) is measured at every sampling interval. Equations below give a mathematical understanding of the theory presented above.

When eng_rpm < 500 rpm,

$$Crpm = 1.5 \tag{2.21}$$

When 500 rpm < eng_rpm < 900 rpm,

$$Crpm = 1.5 - ((eng\_rpm - 500)/2 * (900 - 500)) \tag{2.22}$$

When 900 rpm < eng_rpm < 2000 rpm

$$Crpm = 1 \tag{2.23}$$

When eng_rpm > 2000 rpm

$$Crpm = \{(eng\_rpm/1000)^2 + 8\}/12 \tag{2.24}$$

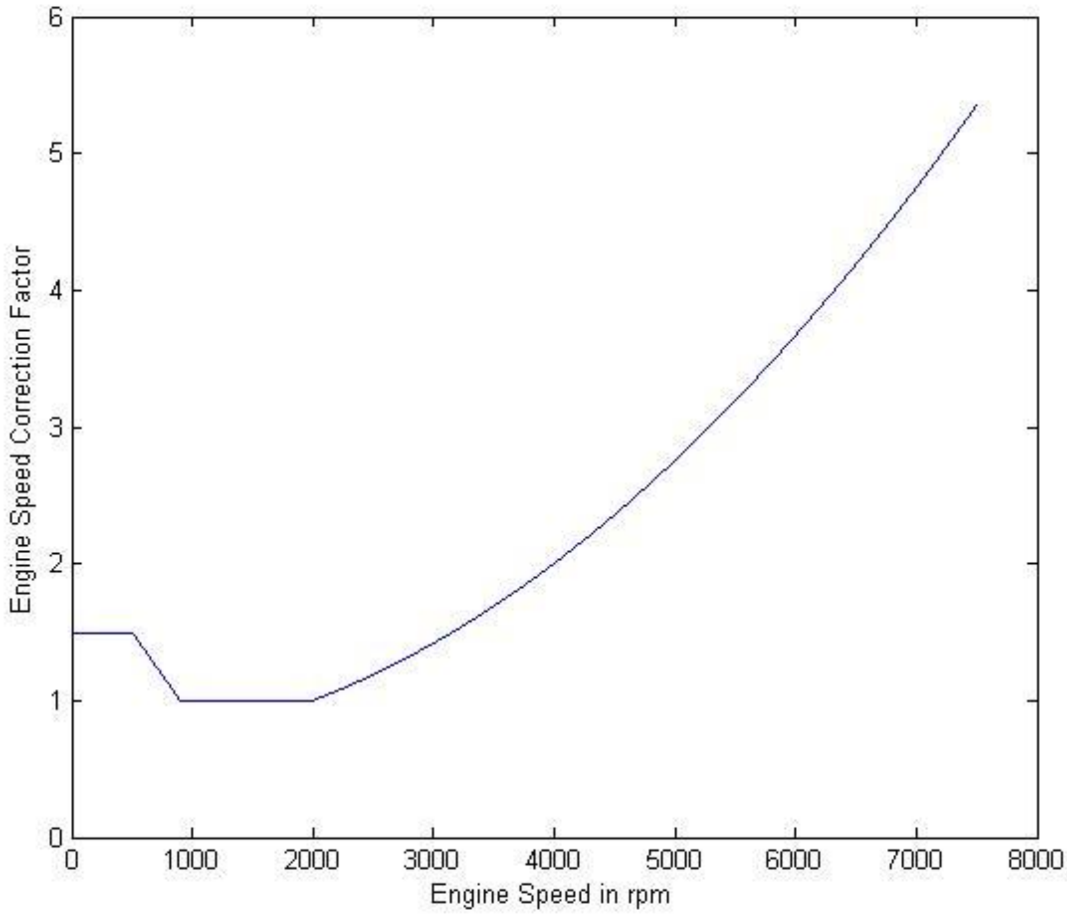

Figure 2-3: Engine Speed Correction Factor

2.3.4 Engine Cranking Correction Factor

Frequent engine cranking, as a result of short trips, leads to shortening of oil change interval. This is because lubricating film is not completely formed when an engine is cranked or started, which might result in mechanical wear. For hot cranking, residual oil in the bearing can help form the lubricating film shortly after cranking, but the problem is most pronounced for cold cranking (frequent trips in cold wintertime conditions). In addition, water and fuel have a tendency to accumulate in the crankcase and contaminate the engine oil, when the oil temperature does not reach the thermostat setting [4, 6]. In general, cold cranking takes longer to complete as it takes longer to develop the lubricating film. To capture this effect, hot cranking and cold cranking have been set differently in the present algorithm. It should be noted that none of the oil life monitoring systems currently in the market have this feature.

A correction factor of 10 is used for cold cranking (T < 0^0C) which linearly decreases to 1 in 40 seconds and a correction factor of 5 is used for hot cranking (T > 80^0C) which linearly decreases to 1 in 20 seconds. For all starting temperatures lying between 0^0C and 80^0C, the cranking time is linearly shortened from 40 to 20 seconds and starting correction factor is also accordingly linearly shortened from 10 to 5. Hot and cold starting conditions are captured based on the initial engine coolant temperature value (eng_cool_temp).

Figure 2-4 shows the variation of the engine cranking correction factor with time. Equations below give a mathematical understanding of the theory presented above.

When t < t0,

$$Cck = 1.0 + (Cck0 - 1.0) * (\frac{t0 - t}{t0}) \qquad (2.25)$$

When t >/= t0,

$$Cck = 1 \qquad (2.26)$$

where Cck0 and t0 are defined as:

When eng_cool_temp </= 0^0C,

$$Cck0 = 10.0 \qquad (2.27)$$

$$t0 = 40 \qquad (2.28)$$

When 0^0C < eng_cool_temp < 80^0C,

$$Cck0 = 10 - 5 * (eng\_cool\_temp/80) \qquad (2.29)$$

$$t0 = 40 - 20 * (eng\_cool\_temp/80) \qquad (2.30)$$

When eng_cool_temp >/= 80^0C

$$Cck0 = 5.0 \qquad (2.31)$$

$$t0 = 20 \qquad (2.32)$$

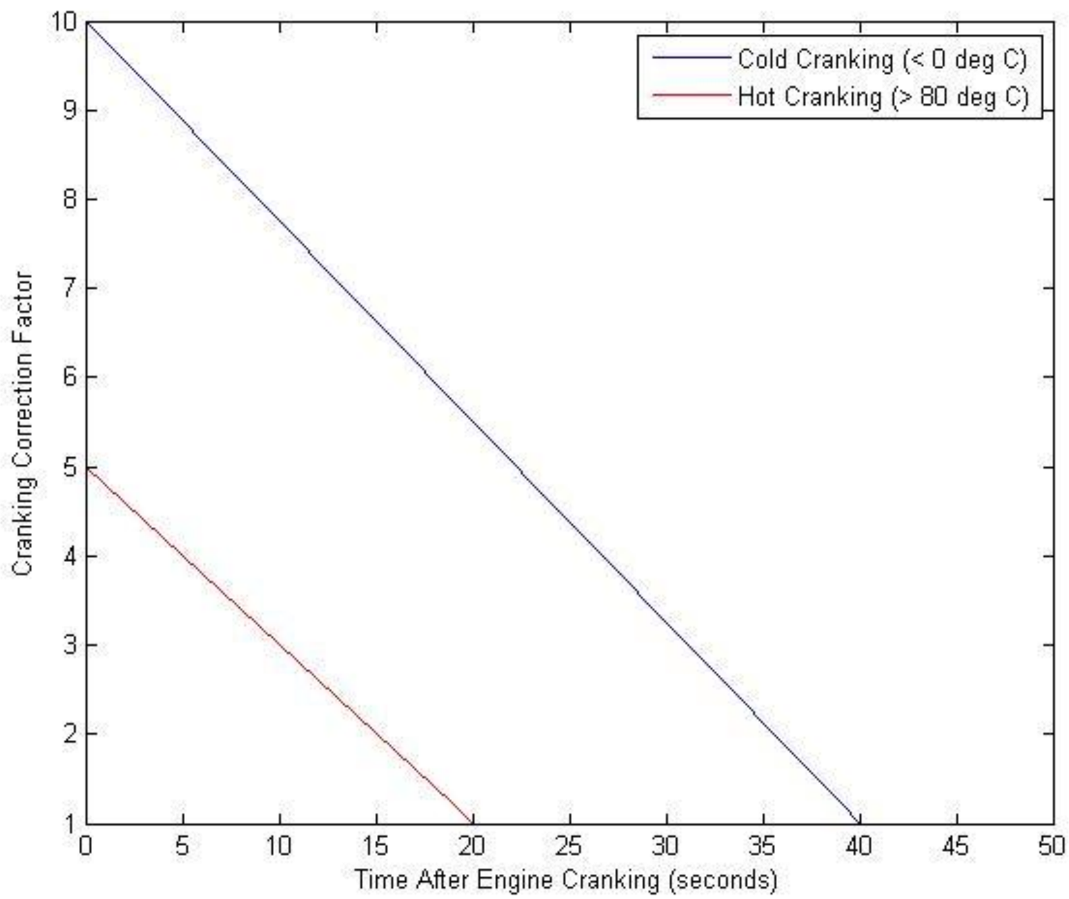

Figure 2-4: Engine Cranking Correction Factor

2.3.5 Oil Aging Correction Factor

Engine oil starts getting depleted of its properties as the age of oil in the vehicle increases. The ability of the engine oil to continuously lubricate the engine moving parts and provide oxidation, thermal and shear stability does not remain as effective as it is when the oil is new [4, 6]. This effect has not been captured in any of the existing oil life monitoring systems. To account for this effect, a period of six months has been used as a nominal value beyond which the oil is assumed to gradually lose its properties. A nominal life of roughly two years (or twenty four months) after the oil has been placed in the oil sump, has been assumed for the oil [13], this ensures that the same engine oil is not used for long periods. The number of days of the oil in sump (days_oil_in_sump) is periodically saved in the system and is used to calculate the oil aging correction factor. Figure 2-5 shows the variation of the engine oil aging correction factor with number of months.

Equations below give a mathematical understanding of its implementation in the algorithm. The equations are set such that beyond twenty four months, the oil life is almost zero.

When days_oil_in_sump </= 183,

$$Cag = 1.0 \quad (2.33)$$

When days_oil_in_sump > 183,

$$Cag = \exp((183 - days\_oil\_in\_sump)/183) \quad (2.34)$$

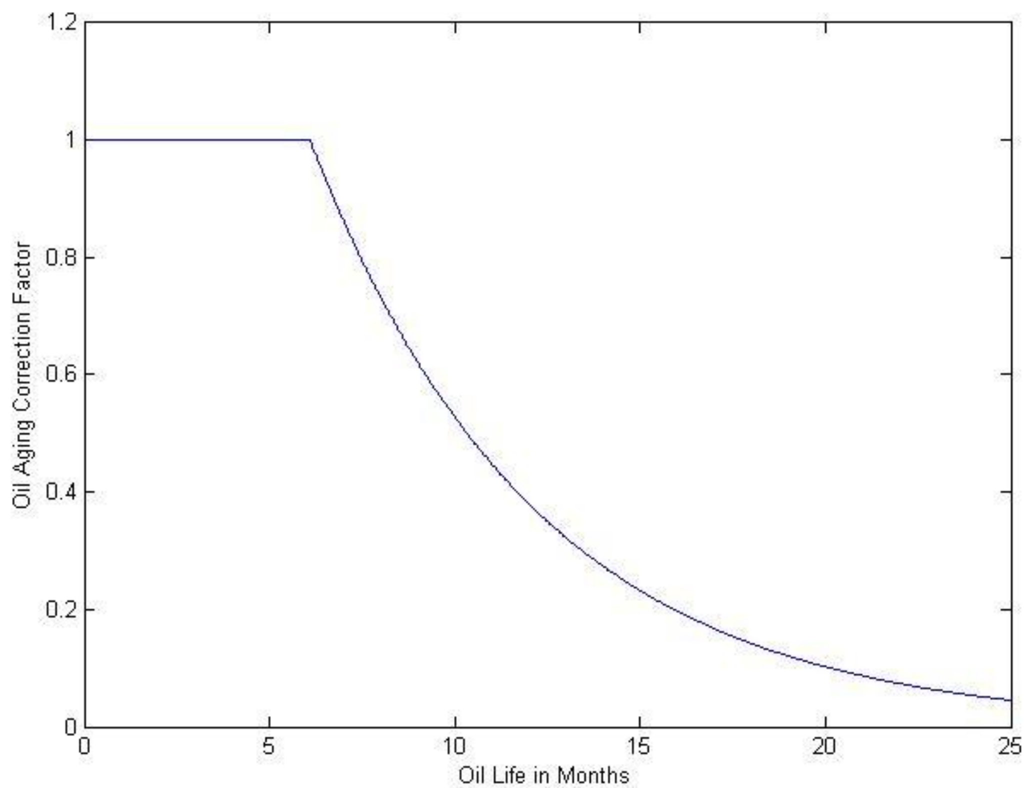

Figure 2-5: Engine Oil Aging Correction Factor

2.3.6 Dust/Desert Environment Correction Factor

Driving in dusty conditions (dirt/gravel roads/desert environment) can turn the engine oil into more of a honing compound than a lubricating medium. The dirty oil generates more wear metals which increase the risk of sludge formation and corrosion from acids [8, 9]. This also results in engine mechanical wear which contaminates the engine oil. In order to prevent severe damage to engine components due to extended driving in deserts or dusty conditions, engine oil might have to be changed at a more frequent rate than normal.

From Section 1.5 of Chapter 1, it can be said that this effect has also not been captured in any of the oil life monitoring systems currently in the market. To capture this effect, a “Desert/Dust” button has been included in the current algorithm, which when switched on or activated, uses a correction factor of 1.5. Thus, during dust or desert environmental conditions, a simple action of pressing the “Desert/Dust” button will capture the oil deterioration effect and once the environmental conditions are back normal, the button can be pressed again to change the correction factor to 1. Accordingly, the Dust/Desert indicator is turned on or off on the display device. This methodology not only removes the complications involved with sensors but also provides a simple balance between human interference and automation. The following equations give a mathematical understanding of this correction factor.

When “Dust/Desert” button is pressed odd number of times,

$$Cdust = 1.5 \tag{2.35}$$

When “Dust/Desert” button is pressed zero or even number of times,

$$Cdust = 1.0 \tag{2.36}$$

2.4 Summary

The effects of changes in various operating conditions on engine oil are explained in this chapter. Uniqueness and merits of the current algorithm, methodology for its implementation, and the development of correction factors associated with each correction factor are also detailed with simple and scientific justifications. The next chapter presents the implementation of this algorithm as a system, its user interface, and its evaluations (using MATLAB [34] simulations) under various vehicle operating scenarios.

Chapter 3

Implementation of Algorithm

Any development needs to be implemented and tested to prove that it is worthy of its cause, without which it can neither get the buyer's interest nor the reviewer's agreement. In order to justify that the algorithm developed in Chapter 2 has all the requirements of being an intelligent and worthy system, numerous simulations under various operating conditions have been performed and key results are presented in this Chapter. To evaluate the oil-life algorithm, an oil-life simulator is developed whose user interface and features are presented in Section 3.1.

3.1 Oil-Life Simulator

The algorithm is implemented using MATLAB [34] and the graphical user interface (GUI) of MATLAB is used for the development of a user friendly oil-life simulator. MATLAB code for the development of the oil-life simulator is included separately as Appendix B. The oil-life simulator assists the user to simulate an actual driving process and monitor the engine oil life under various operating conditions. Figure 3-1 shows a snapshot of the graphical user interface of the oil-life simulator.

Sample test data for a heavy duty diesel engine is used as a starting part for the simulations. Formatted test data is stored in Microsoft Office Excel [35] spreadsheet and is read into the MATLAB program which processes this data to calculate the used oil life and display percentage of oil life remaining. After each data sampling time interval (in this case, five seconds), the program saves certain cumulated values: oil used life, engine run time, and days of oil in sump in a different excel spreadsheet. In the case when the simulation is stopped, these values which are saved in the system memory form a part of the input data whenever the simulation is restarted. MATLAB and Microsoft Excel are used as tools for the simulations and calculations in the current work.

The oil-life simulator, as shown in figure 3-1, is divided into two sections: Panel and Display. The buttons on the panel are used to control the simulations. The "Start" and "Stop" buttons are equivalent to starting and stopping of an engine, respectively. "Reset" button is used when a new run is started and all the cumulated values are reset resembling change of the engine oil. The “Warm Up” button is used to read the test data saved in the excel spreadsheet. The buttons to increase and decrease temperature, load, and speed provide the control to the user to change these operating conditions. These buttons are set such that pressing them once results in a five percent increase or decrease of the corresponding values. For example, if the “Increase Temp” button is pressed once, a five percent increment is applied to all temperatures values processed from then on. Also provided is “Desert/Dust” button which when pressed simulates a desert or dusty environmental condition and uses a correction factor of 1.5 to effectively increase oil used life, as discussed in Section 2.3.6. The display area right next to the “Desert/Dust” button shows whether it is activated (On) or not (Off). Panel buttons provide the control to simulate various driving conditions.

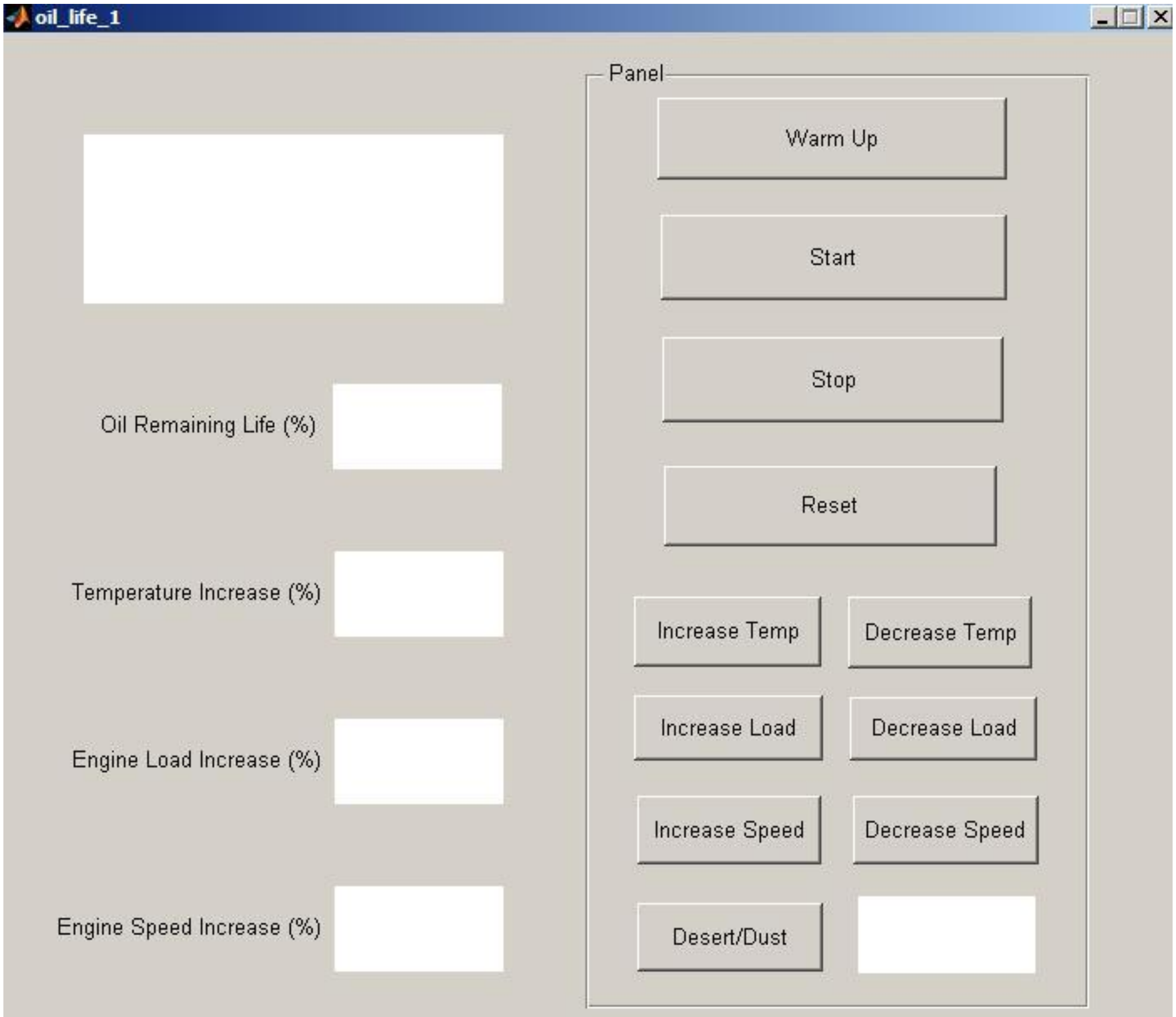

Figure 3-1: Graphical User Interface (GUI) of the Oil-Life Simulator

The left section of the simulator is the display section through which the user can keep a check on the operating conditions and percentage of oil life remaining. Starting from top, the first (biggest) display area shows the status of the engine, whether it is running or stopped, and when the engine oil is changed (i.e., when the "Reset" button is pressed), it displays the message: "All cumulated values have been reset". The second display area shows the percentage of oil life remaining whose value is updated in real time. The next three display areas show percentage increase in the values of temperature, engine load, and engine speed, respectively (percentage decrease is shown as a negative value).

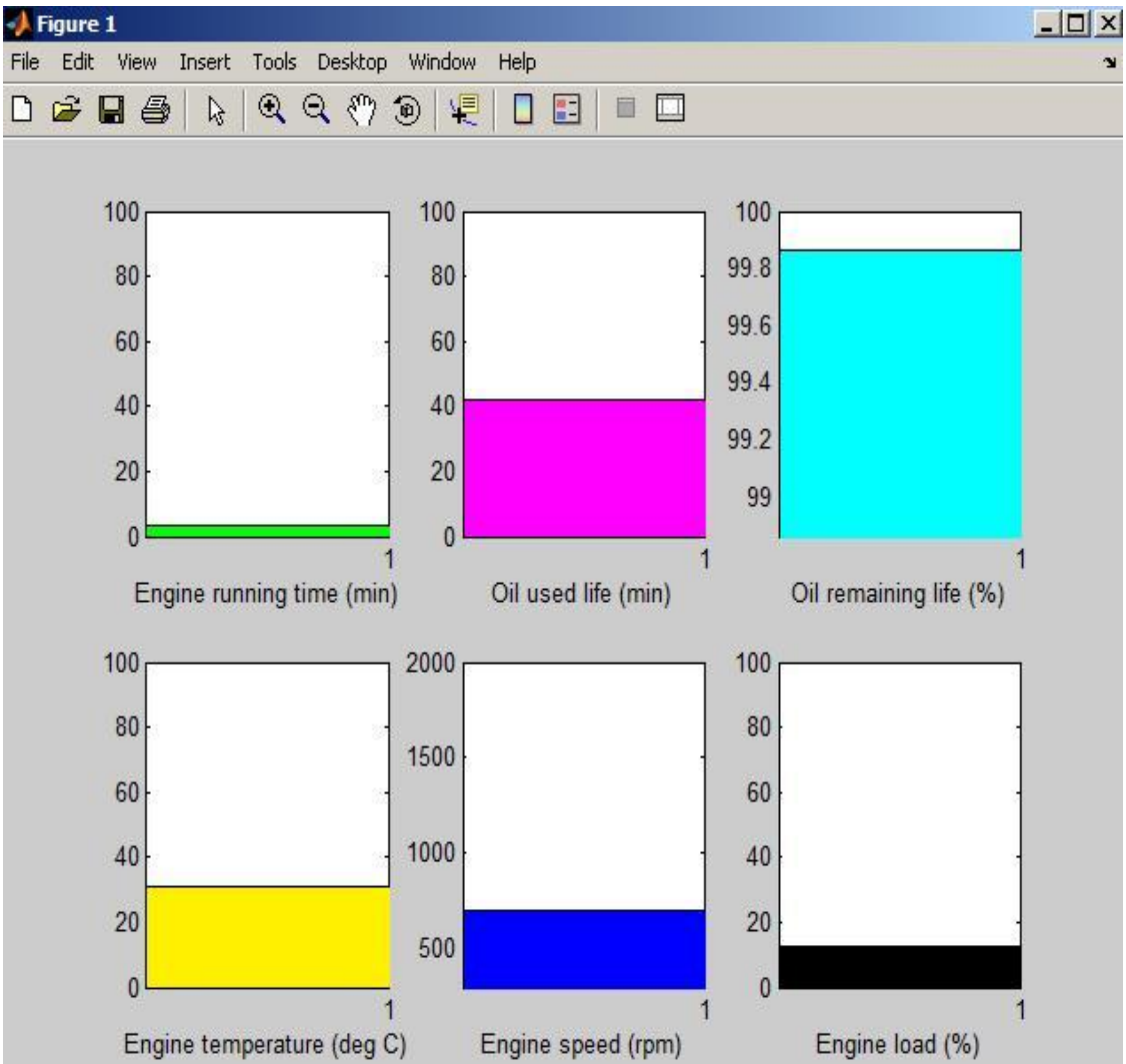

Figure 3-2: Real Time Monitoring of Engine and Oil Parameters

Figure 3-2 shows a snapshot of real time parameters monitor. This acts as a monitor for the user that shows the important engine parameters like engine temperature, load, and speed, and oil parameters like oil used life, percentage of oil life remaining, and engine running time from when the engine oil was changed. The display color for engine temperature, an important factor on which the oil life is dependent, is programmed as a function of its value, i.e., the color of engine temperature is varied from yellow to orange to red as its value increases. For high temperatures around 200 ^{0}C, the color is closer to or equal to red and for low temperatures around 20 ^{0}C, the color is closer to or equal to yellow. “Engine running time” and “Oil used life” parameters displayed in the monitor give a clear indication of the correction factors associated with operating conditions. Oil used life is obtained by multiplying the associated correction factors with engine running time and a major difference between them indicates that the engine is being driven at extreme operating conditions.

As a test case, the data for a heavy duty diesel engine is processed and analyzed in Section 3.2.

3.2 Test Run

For the test run, data from a heavy duty diesel engine continuously run for 5 hours under normal conditions is used. This data is considered as the master data set, a sample segment of which is shown in Table 3-1. The 5 hour (18,000 rows) engine run data includes engine oil temperature (^{0}F), coolant temperature (^{0}F), engine speed (rpm), and engine load (%) as shown in columns 3 to 6 of Table 3-1. Columns 1 and 2 in Table 3-1 give the date and time at which the corresponding data was recorded. The time step for recording the engine data is 1 second as shown in Table 3-1.

Since data for one complete engine oil life cycle is not present, the data for the test run of an engine oil life cycle is generated using the master data set. Using the 5 hour master data set, engine data up to 500 hours (nominal oil life) may be generated. The values used in the test run for the operating conditions: engine oil temperature (oil_{temp}), engine coolant temperature ($cool_{temp}$), engine speed (eng_{rpm}), and engine load (eng_{load}) are generated using random numbers, but it is made sure that they fall within 20% deviation from the corresponding values in the master data set ($moil_{temp}$, $mcool_{temp}$, $meng_{rpm}$, $meng_{load}$). To illustrate this better, the equations below give the sequence of operations for generating the test run data.

$$oil_{temp}\,(i) = moil_{temp}\,(i) + [-0.2 + \{0.2 - (-0.2)\} * rand(1)] * moil_{temp}\,(i) \quad (3.1)$$

$$cool_{temp}\,(i) = mcool_{temp}\,(i) + [-0.2 + \{0.2 - (-0.2)\} * rand(1)] * mcool_{temp}\,(i) \quad (3.2)$$

$$eng_{rpm}\,(i) = meng_{rpm}\,(i) + [-0.2 + \{0.2 - (-0.2)\} * rand(1)] * meng_{rpm}\,(i) \quad (3.3)$$

$$eng_{load}\,(i) = meng_{load}\,(i) + [-0.2 + \{0.2 - (-0.2)\} * rand(1)] * meng_{load}\,(i) \quad (3.4)$$

where, rand(1) is a MATLAB command that generates a random number between 0 and 1.

Once data for the first 5 hour period is generated, similar procedure is followed to generate data for the subsequent 5 hour periods. The test run is continued till the percentage of oil life remaining falls below 1%.

The simulation is stopped once after every 1 hour (3,600 seconds) to account for engine cranking. This is done by turning "flag" to either 1 or 0 once in every 3,600 seconds. Also, to account for driving in dusty conditions, "Desert/Dust" button is activated for the first 12 minutes (720 seconds) of each hour (3,600 seconds). This makes sure that the desert driving condition is activated for 20% of the whole period.

Table 3-1: Sample segment of master data set

Date	Time	Eng Oil Temp (F)	Coolant Temp (F)	Engine Speed (rpm)	Engine Load (%)
1/9/2007	7:00:01	176.75	178.00	700.32	10.04
1/9/2007	7:00:02	176.75	178.00	700.18	10.14
1/9/2007	7:00:03	176.75	178.00	700.27	10.18
1/9/2007	7:00:04	176.75	178.00	700.20	10.11
1/9/2007	7:00:05	176.75	178.00	700.24	10.16
1/9/2007	7:00:06	176.75	178.00	700.19	10.18
1/9/2007	7:00:07	176.75	178.00	700.13	10.05
1/9/2007	7:00:08	176.75	178.00	700.09	9.97
1/9/2007	7:00:09	176.75	178.00	699.93	10.16
1/9/2007	7:00:10	176.75	178.00	700.19	10.09

Figure 3-3 shows the snapshot of GUI interface and figure 3-4 shows the snapshot of monitor for engine and oil parameters, at the end of the test run. Based on an average driving speed of 45 mph for the vehicle and 14,992 minutes (or 249.87 hours) of engine run time (from figure 3-4), the mileage (number of miles driven) before an oil change is predicted as below.

$$Engine\ running\ time\ for\ the\ whole\ run\ (ERT) = 249.87\ hours \tag{3.5}$$

$$Assumed\ average\ speed\ of\ the\ vehicle\ (AVS) = 45\ mph \tag{3.6}$$

Therefore,

$$Number\ of\ miles\ driven\ before\ an\ oil\ change = ERT * AVS = 11244\ miles \tag{3.7}$$

The mileage value of 11,244 miles agrees reasonably with the 7,500 – 12,000 mileage range claimed in earlier work [7]. Taking this as the basis, various driving conditions are simulated by controlling the operating conditions. Numerous runs are performed to evaluate the algorithm, whose description and results thus obtained are presented in Sections 3.3 and 3.4.

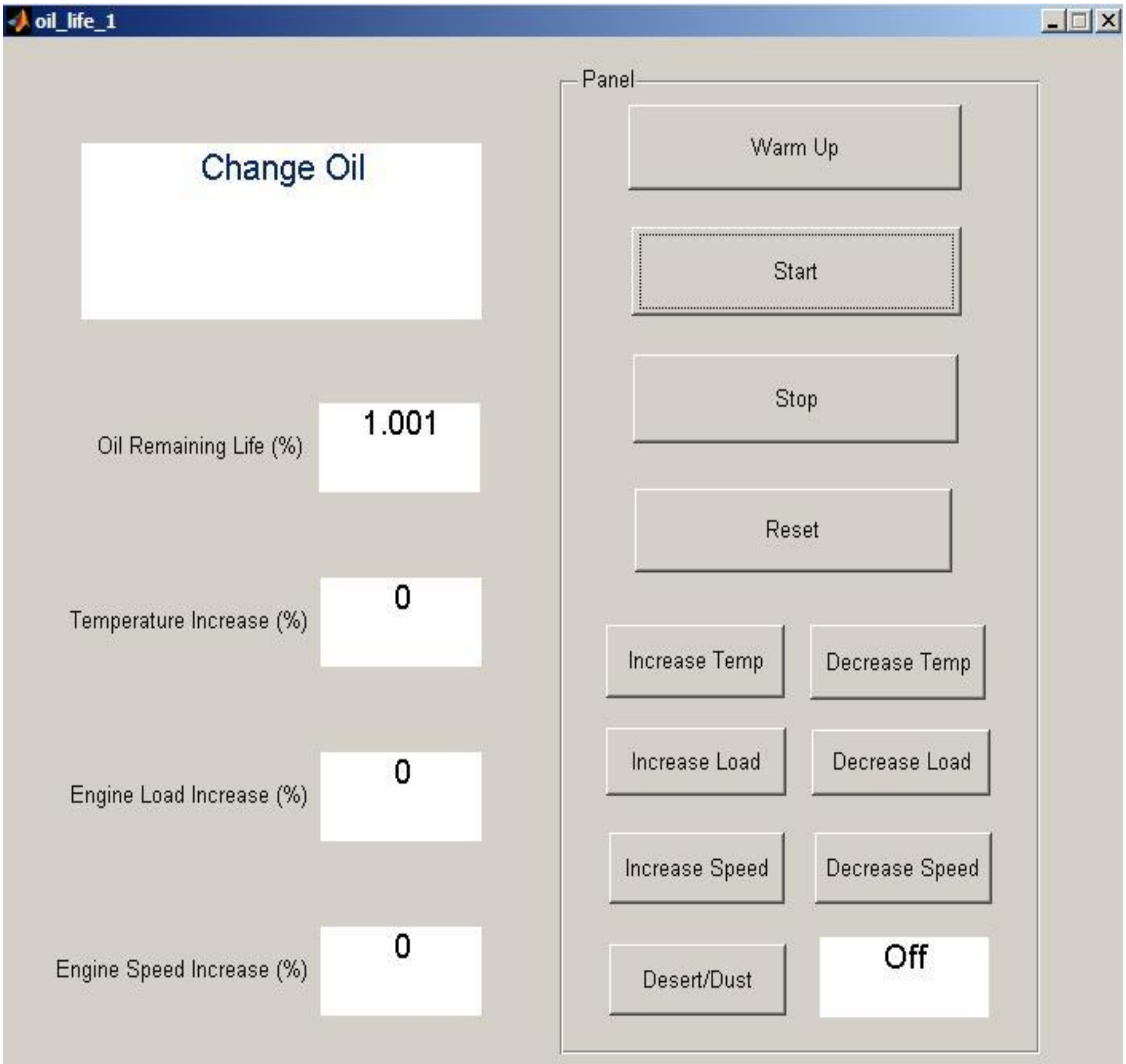

Figure 3-3: GUI Interface at the end of the Test Run

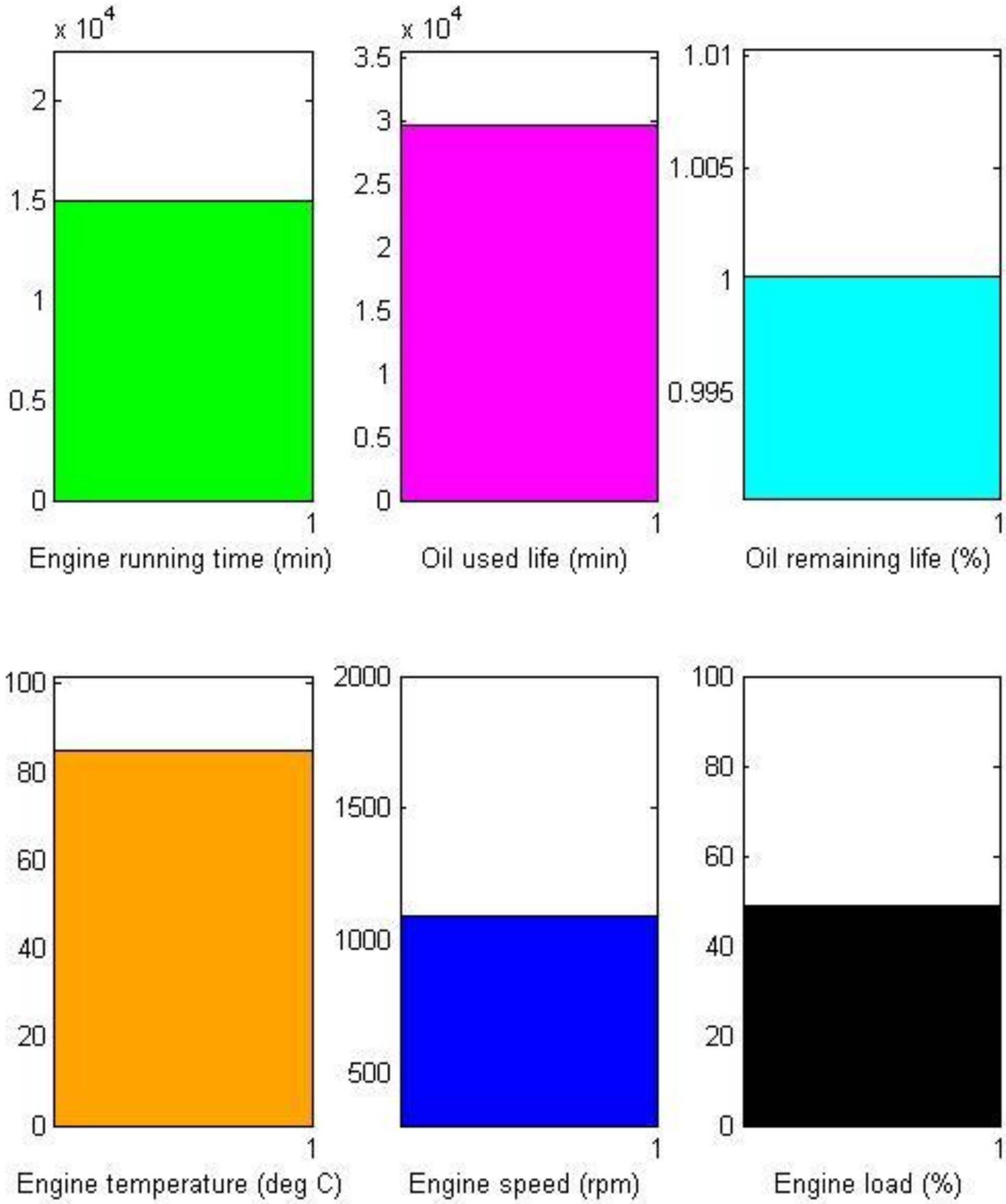

Figure 3-4: Parameters Monitor at the end of the Test Run

3.3 Simulation Results

Various driving conditions can be simulated by changing the operating conditions using the master data set. The evaluations of oil-life algorithm are performed using the oil-life simulator that can control the operating conditions and in the current work the following ten different driving conditions are simulated. The test data for these simulations is generated in a similar way as described in Section 3.2 for the test run. The results for all simulations are presented in Table 3-2.

1. Predominantly long-trip driving:

   The trip length is an important factor that affects the oil life as discussed in detail in Chapters 1 and 2. In order to simulate long-trip driving conditions the operating conditions are controlled by making use of master data set. The simulation is stopped once after every 4 hours (14,400 seconds) to account for predominantly long trip driving. Since long trips predominantly occur while highway driving where speed limits are higher, an average driving speed of 60 mph is assumed for the calculation of vehicle mileage before an oil change. Also, to account for driving in dusty conditions, “Desert/Dust” button is activated for the first 12 minutes (720 seconds) of each hour (3,600 seconds). This makes sure that the desert driving condition is activated for 20% of the whole run. A series of ten such random runs are performed, and an average mileage value of 14,392 miles is obtained and is presented in Table 3-2. The data for all ten runs is generated using random numbers between 0 and 1, but it is made sure that the values fall within 20% deviation from the master data set, as shown in equations 3.1 to 3.4 earlier. Taking the average of ten random runs minimizes any errors from statistical point of view and thus strengthens the results obtained. Results for individual runs are presented in Table 3-2 and details about the operating conditions are discussed in note 2 of the table.

2. High temperature driving:

   The operating temperature of engine oil plays an important role in determining its life, as discussed in Section 2.3.1. High temperature conditions may occur due to hot environmental conditions or due to long runs and high engine load conditions. In order to simulate such driving conditions the operating conditions of the vehicle are controlled by making use of the master test data. The engine oil temperature and coolant temperature are increased by 25% to 75% of the corresponding values in the master data set, as shown in equations 3.8 and 3.9. This makes sure that higher temperature ranges are enveloped in the runs. The values for engine speed and engine load fall within 20% deviation of the corresponding values in the master data set, as shown in equations 3.3 and 3.4 earlier. Simulation stopping and activation of desert driving conditions are similar to that of the test run in Section 3.2. Also, to estimate the number of miles a vehicle can be driven before an oil change, an average speed of 45 mph has been assumed. A series of ten such random runs are performed, and an average value of 4,115 miles is obtained and is presented in Table 3-2. Taking the average of ten random runs minimizes any errors from statistical point of view and thus strengthens the results obtained. Results for individual runs are presented in Table 3-2 and details about the operating conditions are discussed in note 3 of the table.

$$oil_{temp}\,(i) = moil_{temp}\,(i) + [0.25 + (0.75 - 0.25) * rand(1)] * moil_{temp}\,(i) \qquad (3.8)$$

$$cool_{temp}\,(i) = mcool_{temp}\,(i) + [0.25 + (0.75 - 0.25) * rand(1)] * mcool_{temp}\,(i) \qquad (3.9)$$

3. High engine load driving:

High engine loads can have severe effects on engine oil life as discussed in Section 2.3.2. In order to simulate high engine load driving conditions the operating conditions are controlled by making use of the master test data. The engine load is increased by 50% to 100% of the corresponding values in master data set, as shown in equation 3.10. The engine oil temperature and coolant temperature are increased by 0% to 40% of the corresponding values in the master data set, as shown in equations 3.11 and 3.12. This is done to account for the fact that higher engine loads result in higher operating temperatures. The values for engine speed fall within 20% deviation of the corresponding values in the master data set, as shown in equation 3.3 earlier. Simulation stopping and activation of desert driving conditions are similar to that of the test run in Section 3.2. Also, to estimate the number of miles a vehicle can be driven before an oil change, an average speed of 45 mph has been assumed. A series of ten such random runs are performed and an average value of 6,652 miles is obtained. The results for individual runs are presented in Table 3-2 and details about the operating conditions are discussed in note 4 of the table.

$$eng_{load}\,(i) = meng_{load}\,(i) + [0.5 + (1 - 0.5) * rand(1)] * meng_{load}\,(i) \qquad (3.10)$$

$$oil_{temp}\,(i) = moil_{temp}\,(i) + [0.4 * rand(1)] * moil_{temp}\,(i) \qquad (3.11)$$

$$cool_{temp}\,(i) = mcool_{temp}\,(i) + [0.4 * rand(1)] * mcool_{temp}\,(i) \qquad (3.12)$$

4. <u>High temperature and high load (HTHL) driving:</u>

   High temperatures and high engine loads may have abnormal effects on engine oil performance as discussed in Chapters 1 and 2. In order to simulate HTHL driving conditions the operating conditions are controlled by making use of the master test data. The engine oil temperature and coolant temperature are increased by 25% to 75% of the corresponding values in the master data set, as shown in equations 3.8 and 3.9. The engine load is increased by 50% to 100% of the corresponding values in master data set, as shown in equation 3.10. This makes sure that high temperature and high engine load ranges are enveloped in the runs. The values for engine speed fall within 20% deviation of the corresponding values in the master data set, as shown in equation 3.3 earlier. Simulation stopping and activation of desert driving conditions are similar to that of the test run in Section 3.2. Also, to estimate the number of miles a vehicle can be driven before an oil change, an average speed of 45 mph has been assumed. A series of ten such random runs are performed and an average value of 3,148 miles is obtained. The results for individual runs are presented in Table 3-2 and details about the operating conditions are discussed in note 5 of the table.

5. <u>Winter driving:</u>

   Winter driving or driving at low temperatures affects the oil performance and in turn its life as discussed in Chapters 1 and 2. Low temperature conditions may occur due to cold environmental conditions in winters. Such driving conditions are simulated using the master test data. The engine oil temperature and coolant temperature are decreased by 25% to 75% of the corresponding values in the master data set, as shown in equations

3.13 and 3.14. This makes sure that low temperature range is enveloped in the runs. The values for engine speed and engine load fall within 20% deviation of the corresponding values in the master data set, as shown in equations 3.3 and 3.4 earlier. Simulation stopping and activation of desert driving conditions are similar to that of the test run in Section 3.2. Also, to estimate the number of miles a vehicle can be driven before an oil change, an average speed of 45 mph has been assumed. A series of ten such random runs are performed and an average value of 5,217 miles is obtained. The results for individual runs are presented in Table 3-2 and details about the operating conditions are discussed in note 6 of the table.

$$oil_{temp}\,(i) = moil_{temp}\,(i) - [0.25 + (0.75 - 0.25) * rand(1)] * moil_{temp}\,(i) \tag{3.13}$$

$$cool_{temp}\,(i) = mcool_{temp}\,(i) - [0.25 + (0.75 - 0.25) * rand(1)] * mcool_{temp}\,(i) \tag{3.14}$$

6. Predominantly short-trip driving:

   Short trip driving may not let the engine oil to operate at its optimum temperature range which affects the oil performance and in turn its life as discussed in detail in Chapters 1 and 2. Short-trip driving occurs predominantly during city driving and daily commute. In order to simulate such driving conditions the operating conditions are controlled using the master test data. The simulation is stopped once after every 20 minutes (1,200 seconds) to account for predominantly short trips. Also, since short-trip driving predominantly occurs during driving in cities where the speed limits are lower, an average speed of 30 mph has been assumed. The values for engine oil temperature, coolant temperature, engine speed, and engine load fall within 20% deviation of the corresponding values in the master data set, as shown in equations 3.1 to 3.4 earlier. Activation of desert driving conditions is similar to that of the test run in Section 3.2. A series of ten such random runs are performed and an average value of 5,048 miles is obtained. The results for individual runs are presented in Table 3-2 and details about the operating conditions are discussed in note 7 of the table.

7. Short-trip winter driving:

   Short trips during winters or low temperature conditions may result in the worst operating conditions for engine oil and have severe affects on its life as discussed in Chapters 1 and 2. Short-trip driving occurs predominantly during city driving and daily commute and low temperature conditions may occur due to cold environmental conditions in winters. In order to simulate such short-trip and low temperature driving, the operating conditions are controlled using the master test data. The engine oil temperature and coolant temperature are decreased by 25% to 75% of the corresponding values in the master data set, as shown in equations 3.13 and 3.14 above. This makes sure that low temperature range is enveloped in the runs. The simulation is stopped once after every 20 minutes (1,200 seconds) to account for short trips. Also, since short-trip driving predominantly occurs during driving in cities where the speed limits are lower, an average speed of 30 mph has been assumed. The values for engine speed and engine load fall within 20% deviation of the corresponding values in the master data set, as shown in equations 3.3 and 3.4 earlier. Activation of desert driving conditions is similar to that of the test run in Section 3.2. A series of ten such random runs are performed and an average value of 2,997 miles is obtained. The results for individual runs are presented in Table 3-2 and details about the operating conditions are discussed in note 8 of the table.

8. High temperature driving in desert or dusty conditions:

   Driving in desert or dusty conditions may have severe effects on oil life as discussed in Section 2.3.6. In addition to driving in desert environment, high temperature conditions are also included in simulations. The engine oil temperature and coolant temperature are increased by 25% to 50% of the corresponding values in the master data set, as shown in equations 3.15 and 3.16 above. This makes sure that moderately high temperature range is enveloped in the runs. To account for desert or dusty environment, the desert/dust condition is activated for 75% of the whole run, i.e., “Desert/Dust” button is activated for 45 minutes (2,700 seconds) every 1 hour (3,600 seconds). The values for engine speed and engine load fall within 20% deviation of the corresponding values in the master data set, as shown in equations 3.3 and 3.4 earlier. Simulation stopping is similar to that of the test run in Section 3.2. Also, to estimate the number of miles a vehicle can be driven before an oil change, an average speed of 45 mph has been assumed. A series of ten such random runs are performed and an average value of 3,908 miles is obtained. The results for individual runs are presented in Table 3-2 and details about the operating conditions are discussed in note 9 of the table.

$$oil_{temp}\,(i) = moil_{temp}\,(i) + [0.25 + (0.5 - 0.25) * rand(1)] * moil_{temp}\,(i) \qquad (3.15)$$

$$cool_{temp}\,(i) = mcool_{temp}\,(i) + [0.25 + (0.5 - 0.25) * rand(1)] * mcool_{temp}\,(i) \qquad (3.16)$$

9. <u>High engine speed driving:</u>

   The effects of high engine speeds on oil life are discussed in Section 2.3.3. In order to simulate high engine rpm driving, the operating conditions are controlled using the master test data. The engine speed values are increased by 75% to 125% of the corresponding values in the master data set, as shown in equation 3.17. This makes sure that high engine speed range is enveloped in the runs. The engine oil temperature and coolant temperature are increased by 0% to 40% of the corresponding values in the master data set, as shown in equations 3.11 and 3.12 above. This is done to account for the fact that higher engine speeds have consequential effects on the operating temperature. The values for engine load fall within 20% deviation of the corresponding values in the master data set, as shown in equation 3.4 earlier. Simulation stopping and activation of desert driving conditions are similar to that of the test run in Section 3.2. Also, to estimate the number of miles a vehicle can be driven before an oil change, an average speed of 45 mph has been assumed. A series of ten such random runs are performed and an average value of 7,145 miles is obtained. The results for individual runs are presented in Table 3-2 and details about the operating conditions are discussed in note 10 of the table.

$$eng_{rpm}\,(i) = meng_{rpm}\,(i) + [0.75 + (1.25 - 0.75) * rand(1)] * meng_{rpm}\,(i) \qquad (3.17)$$

10. <u>Random driving:</u>

    Most of the vehicle driving conditions are enveloped in the aforementioned cases and to represent a mixture of all these driving conditions, an additional ten runs are performed. These runs average out all the driving conditions and present a driving scenario where a vehicle is driven in all seasons and in various environmental conditions. Sometimes a vehicle is driven in cities and sometimes on highways. A vehicle is sometimes driven under high engine loads and sometimes under high engine speeds. In order to account for such varying driving conditions, ten random runs over a broad operating range are simulated. The engine oil temperature and coolant temperature are varied between -75% and 75% of the corresponding values in the master data set, as shown in equations 3.18 and 3.19. Engine speed values are increased by 0% to 125% of the corresponding values in the master date set, as shown in equation 3.20. Engine load values are increased by 0% to 100% of the corresponding values in the master data set, as shown in equation 3.21. This makes sure that wide ranges of operating conditions are enveloped in the runs. Simulation stopping and activation of desert driving conditions are similar to that of the test run in Section 3.2. Also, to estimate the number of miles a vehicle can be driven before an oil change, an average speed of 45 mph has been assumed. A series of ten such runs are performed and an average value of 7,861 miles is obtained. The results for individual runs are presented in Table 3-2 and details about the operating conditions are discussed in note 11 of the table.

$$oil_{temp}\,(i) = moil_{temp}\,(i) + [-0.75 + \{0.75 + 0.75\} * rand(1)] * moil_{temp}\,(i) \qquad (3.18)$$

$$cool_{temp}\,(i) = mcool_{temp}\,(i) + [-0.75 + \{0.75 + 0.75\} * rand(1)] * mcool_{temp}\,(i) \qquad (3.19)$$

$$eng_{rpm}\,(i) = meng_{rpm}\,(i) + [-0.75 + \{0.75 + 0.75\} * rand(1)] * meng_{rpm}\,(i) \qquad (3.20)$$

$$eng_{load}\,(i) = meng_{load}\,(i) + [-0.75 + \{0.75 + 0.75\} * rand(1)] * meng_{load}\,(i) \qquad (3.21)$$

The results for all the simulations are presented in Table 3-2 and are discussed in Section 3.4.

Table 3-2: Simulation results for various driving conditions

Driving Mode	Long Trips	High Temp (HT)	High Load (HL)	HTHL	Winter Driving (WD)	Short Trips (ST)	STWD	HT and Desert	High RPM	Random
Run 1 Mileage	15136	3759	6822	3119	5374	5163	2866	3807	7349	8213
Run 2 Mileage	14061	4746	6406	2896	5118	5543	2994	4166	7116	6971
Run 3 Mileage	14129	4963	7017	2981	5029	5220	3422	3665	6994	7436
Run 4 Mileage	15398	3833	6659	3424	5615	4904	2629	3909	7018	8208
Run 5 Mileage	13894	4420	6923	3028	5131	5038	2767	4193	7462	7812
Run 6 Mileage	14007	3119	6535	3229	5398	4812	3099	3617	7043	7307
Run 7 Mileage	14779	3639	6483	3185	5510	4993	3145	3983	7113	8004
Run 8 Mileage	13932	4045	6332	3532	4873	4692	2916	4055	7298	7854
Run 9 Mileage	14375	4402	6701	2904	5207	4818	3317	3766	6845	8665
Run 10 Mileage	14209	4229	6643	3177	4912	5299	2811	3918	7209	8139
Average Mileage	14392	4115.5	6652.1	3147.5	5216.7	5048.2	2996.6	3907.9	7144.7	7860.9

Notes:

1. Units for all numeric values reported in the table: Miles. Values highlighted in yellow give the average over 10 runs for a particular driving condition. Value highlighted in red shows the lowest of all averages for short trip, winter driving and value highlighted in green shows the highest of all averages for long trip driving.
2. For long trip simulations, the average vehicle speed is assumed as 60 mph. Simulation is stopped once in 4 hours to account for predominantly long trips. Temperature, engine load, and engine speed values are varied between -20% and 20% of the master data set. Desert or dusty environment activated for 20% of the whole run.
3. For high temperature simulations, the average vehicle speed is assumed as 45 mph. Temperature values are increased by 25% to 75% of the master data set. Simulation is stopped once after every hour. Engine load and engine speed values are varied between -20% and 20% of the master data set. Desert or dusty environment activated for 20% of the whole run.
4. For high load simulations, the average vehicle speed is assumed as 45 mph. Engine load values are increased by 50% to 100% of the master data set. Temperature values are increased by 0% to 40% of the master data set. Simulation is stopped once after every hour. Engine speed values are varied between -20% and 20% of the master data set. Desert or dusty environment activated for 20% of the whole run.

5. For high temperature, high load (HTHL) simulations, the average vehicle speed is assumed as 45 mph. Temperature values are increased by 25% to 75% of the master data set and engine load values are increased by 50% to 100% of the master data set. Simulation is stopped once after every hour. Engine speed values are varied between -20% and 20% of the master data set. Desert or dusty environment activated for 20% of the whole run.
6. For winter driving simulations, the average vehicle speed is assumed as 45 mph. Temperature values are decreased by 25% to 75% of the master data set. Simulation is stopped once after every hour. Engine load and engine speed values are varied between -20% and 20% of the master data set. Desert or dusty environment activated for 20% of the whole run.
7. For short trip simulations, the average vehicle speed is assumed as 30 mph. Simulation is stopped once after every twenty minutes to account for predominantly short trips. Temperature, engine load, and engine speed values are varied between -20% and 20% of the master data set. Desert or dusty environment activated for 20% of the whole run.
8. For short trip, winter driving (STWD) simulations, the average vehicle speed is assumed as 30 mph. Temperature values are decreased by 25% to 75% of the master data set. Simulation is stopped once after every twenty minutes. Engine load and engine speed values are varied between -20% and 20% of the master data set. Desert or dusty environment activated for less than 20% of the whole run.
9. For high temperature and desert or dusty driving simulations, the average vehicle speed is assumed as 45 mph. Temperature values are increased by 25% to 50% of the master data set. Desert or dusty environment activated for 75% of the whole run. Simulation is stopped once after every hour. Engine load and engine speed values are varied between -20% and 20% of the master data set.
10. For high engine speed (High RPM) driving conditions, the average vehicle speed is assumed as 45 mph. Engine speed values are increased by 75% to 125% of the master data set. Temperature values are increased by 0% to 40% of the master data set. Simulation is stopped once after every hour. Engine load values are varied between -20% and 20% of the master data set. Desert or dusty environment activated for 20% of the whole run.
11. For random driving conditions, the average vehicle speed is assumed as 45 mph. Temperature values are varied between a decrease of 75% and an increase of 75% with respect to the master data set. Engine load values are increased by 0% to 100% of the master data set. Engine speed values are increased by 0% to 125% of the master data set. Simulation is stopped once after every hour. Desert or dusty environment activated for 20% of the whole run.
12. All the values presented in the table are based on the assumption that the maximum engine oil life in the oil sump is 6 months, i.e., oil aging correction factor is 1 throughout the simulations.
13. Care is taken to make sure that engine load percentage never falls below 0 and engine speed never falls below 250 rpm.

3.4 Discussion of Results

Multiple evaluations of the oil-life algorithm under various vehicle driving conditions are performed using the oil-life simulator and the results presented in Table 3-2 show an expected trend. In this section, a comparison between the trend of results obtained here and those presented in earlier work [1, 4, 5, 6, 7, 13] is presented. In most of the earlier work, the driving conditions are divided into three major categories: long-trip driving; high temperature, high load driving; short trip, winter driving. Thus, a comparison of results obtained under these three categories are presented first, followed by a general discussion of trend of results obtained for other driving conditions presented in Table 3-2.

1. <u>Long-trip Driving:</u>

   For long-trip driving, the number of miles that a vehicle can be driven, before an oil change, is calculated as 14,392 miles based on the average of ten different runs presented in Table 3-2. This value falls well within the range (12,000 – 18,000 miles) claimed in earlier work [1, 6, 7]. Such a comparison acts as a good check for the current algorithm and shows that it agrees well with theory and field tests.

2. <u>High temperature high load driving:</u>

   For high temperature and high load driving conditions, the number of miles that a vehicle can be driven, before an oil change, is calculated as 3,148 miles based on the average of ten different runs presented in Table 3-2. This value agrees well with the manufacturer's suggested oil change interval of 3,000 miles while driving in extreme conditions. Also, this value falls within the range (2,500 – 5,000 miles) claimed in earlier work [1, 6, 7]. This comparison acts as a good check for the current algorithm and shows that it agrees well with theory, field tests and claims made in manufacturer's manual.

3. <u>Short-trip winter driving:</u>

   For short-trip driving in cold conditions, the number of miles that a vehicle can be driven, before an oil change, is calculated as 2,997 miles based on the average of ten different runs presented in Table 3-2. This value agrees well with the manufacturer's suggested oil change interval of 3,000 miles while driving in extreme conditions. Also, this value falls within the range (2,500 – 5,000 miles) claimed in earlier work [1, 6, 7]. This comparison shows that there is good agreement with theory, field tests and claims made in manufacturer's manual.

The results obtained for three major categories of vehicle driving are discussed above and for illustrative purposes various other driving conditions are simulated and the results are presented in Table 3-2. This helps in studying the performance of oil-life algorithm under various driving conditions. Two other driving conditions: short-trip driving and driving in desert or dusty environment can be termed as important and are studied separately as they have adverse effects on engine oil performance. The reasons and effects are discussed below.

4. Short-trip driving:

   The effect of short-trip driving is not explicitly presented in the previous work [1, 6, 7], rather it is always tied up with winter driving and results for a combination of two conditions are presented. In reality, studying the effects of short-trip driving is highly important as a major portion of driving may be done for day-to-day regular commute. It is an advantage of the current algorithm in this regard as it accounts for engine cranking effects, presented in Section 2.3.4. An average value of 5048 miles is calculated based on ten different simulations for short-trip driving conditions, the results of which are presented in Table 3-2. This value is much lesser than the 14,392 miles for long-trip driving and considerably higher than the 2997 miles for short-trip winter driving. Thus, it is advantageous to include this evaluation to provide the buyer or reviewer with the additional capabilities of the current algorithm.

5. High temperature driving in desert conditions:

   Driving in desert or dusty conditions is very harmful for the engine oil as discussed in Section 2.3.6. Even though the ill effects of driving in such conditions are presented in previous literatures [8, 9], such effects are not studied by any of the existing oil-life monitoring systems. There may be situations where a vehicle is predominantly driven in conditions where the temperatures are high and environment is dusty. In is an advantage of the current algorithm to account for driving under such conditions. An average value of 3908 miles is calculated based on ten different simulations for high temperature, desert or dusty driving conditions, the results of which are presented in Table 3-2. This value is much lesser than the 14,392 miles for long-trip driving and considerably higher than the 2997 miles for short-trip winter driving. Thus, it is advantageous to include this evaluation to provide the buyer or reviewer with the additional capabilities of the current algorithm.

The other important set of simulations is for random driving which represents a mixture of various driving conditions. This set of simulations can be considered as an average for all the driving conditions and a discussion of results obtained for these simulations are presented below.

6. Random driving:

   This set of simulations presents a broad driving scenario where a vehicle is driven in all seasons and under various operating conditions. Over a period of engine oil life, a vehicle is sometimes driven in cities and sometimes on highways. A vehicle is sometimes driven under high engine loads and sometimes under high engine speeds. Such wide ranges of driving conditions are simulated and the results obtained are presented in Table 3-2. An average value of 7861 miles is calculated based on ten different simulations with a minimum of 6971 miles and a maximum of 7861 miles. The average value agrees very well with the 7500 miles claimed in previous work [1, 7]. This comparison acts as a good check for the current algorithm.

In addition to these, four more sets of simulations are performed. These account for high temperature driving, high engine load driving, high engine speed driving, and driving in cold conditions (winter driving). Such evaluations have not been done for the previous oil-life monitoring systems and inclusion of these evaluations provides the buyer or reviewer with the additional capabilities of the current algorithm.

3.5 Summary

Multiple evaluations of oil-life algorithm using the oil-life simulator developed in MATLAB are presented in this chapter. A test run is performed using the test data for a heavy duty diesel engine and the results are presented. Numerous simulations are performed to account for various driving conditions, the results of which are presented and discussed. Advantages over previous studies and extensive evaluations to win the reader's confidence in the oil-life algorithm are also presented. The next chapter presents the summary of the present work, the advantages of current oil-life algorithm over the existing ones, and the scope for future developments.

Chapter 4

Conclusion and Scope for Future Work

4.1 Summary and Conclusion

In the current work, an engine oil-life algorithm is developed and presented. Its development is based on extensive literature study, understanding of lubrication science, and study of oil-life monitoring systems currently in the market. The oil-life algorithm uses a nominal oil life based on the type of engine oil used and monitors engine oil temperature, coolant temperature, engine load, engine speed, engine cranking, and oil aging. The algorithm also accounts for driving in desert environment. The significant features of the oil-life algorithm are presented below. Many of these features are not explicitly addressed in the oil-life monitoring systems currently in the market.

1. The oil-life algorithm accounts for engine oil operating temperature including the effects of very high and very low temperatures.
2. The algorithm includes the effects of high engine loads and all ranges of engine speeds (more importantly, idling and very high speeds).
3. The algorithm monitors engine cranking to differentiate between short-trip and long-trip driving.
4. The algorithm accounts for driving in dust and desert environments.
5. The algorithm accounts for oil aging. This is an important feature since the ability of the engine oil to continuously lubricate the engine moving parts and provide oxidation, thermal and shear stability does not remain as effective as it is when the oil is new.
6. The algorithm is extensively evaluated and numerous simulations are performed to show the trend of results and capability to address various driving conditions.
7. The oil-life algorithm can be implemented as a simple and cost effective system. It does not include any complicated, fancy, and unreliable oil condition sensors, and accounts for all the major factors, which affect the engine oil performance, on a meaningful trend.
8. The algorithm is robust enough to be modified and applied to any type of engine (heavy duty or light duty and gasoline or diesel) and can be used with any type of engine oil (mineral or synthetic).

9. The algorithm includes a simple and effective manual element that makes sure that minimum oil level is maintained by putting a small burden on the operator. Through this, the operator will also come to know if there is any unwanted contamination or heavy discoloration of the engine oil. This establishes a simple balance between automation and human interference.
10. Finally, the oil-life algorithm can be evaluated and updated through timely field data from which a statistical trend and pattern can be established.

The developed oil-life algorithm is evaluated by implementing it using a software tool (MATLAB, in this case). Various driving conditions are simulated by generating data from the heavy duty diesel engine test data and by controlling the operating conditions. The following conclusions are drawn based on the study and multiple evaluations performed.

1. Engine oil life is affected by trip lengths. Long trips on highways result in better oil performance and thus, higher oil used life. On the other hand, short trips or city driving has adverse effects on oil performance and results in much lower oil used life. In terms of mileage, predominant long trip driving accounts to an average of around 14,000 miles and short trip or city driving accounts to an average of around 5,000 miles. Short trips during winters result in an even lower average of around 3,000 miles.
2. Engine oil operating temperature plays a very important role in affecting the oil life. Studies have shown that 80 ^{0}C – 130 ^{0}C is the optimum temperature range for engine oil during operation. Driving at very high temperatures (>> 130 ^{0}C) and at very low temperatures (<< 80 ^{0}C), both have adverse effects on lubricating properties of oil and hence, for such driving conditions oil changes are performed at significantly lower mileage. Driving in high temperature or low temperature conditions leads to an average mileage of less than 5,000 miles and becomes even lower for short-trips and heavy engine load conditions.
3. Driving in desert or dusty conditions increase mechanical wear in the engine and thus, affects the engine oil performance. Driving in such conditions is simulated and an average mileage of around 4,000 miles is obtained when desert conditions and high temperature conditions are applied in conjunction.

4. High engine load conditions result in thinning of oil films which results in affecting its performance and life. Driving in such conditions is simulated and an average mileage of around 6,600 miles is obtained. When simulated in conjunction with high temperature, an average mileage of around 3,000 miles is obtained.
5. High engine speeds generate mechanical wear because of loss of lubricating film thus, driving at high engine speeds results in affecting oil performance and oil life. Such driving conditions are simulated and an average mileage of around 7,000 miles is obtained.
6. Driving in a wide range of operating conditions (viz. temperature, engine load, and engine speed) leads to an average mileage of around 7,800 miles.

4.2 Scope for Future Work

Testing the oil-life algorithm with extensive field test data is required. Testing different engines in varying environmental and operating conditions will provide a wide range of field data and evaluating the oil-life algorithm using such data will increase its credibility.

To understand the effect of oil aging better, test data over a long period of oil life (> six months, after an oil change) may be used in the evaluations.

Meaningful estimates of nominal oil life for different oil grades (mineral vs. synthetic) need to be found so that an optimum value is used based on the oil grade used.

Better and accurate results can be obtained if vehicle driving speed is also monitored and an exact average speed value is used rather than a rough estimate.

To monitor the oil level, an oil pressure sensor can be used. Pressure sensors have been tried and tested extensively and are widely accepted. This will ensure that the operator is notified of any oil leaks in the vehicle.

Finally, it would be very interesting to implement the system in a vehicle and study its performance in real time.

References

1. Karl, Kollmann., Klaus, Land., Wolfgang, Warnecke., et al., "Extended Oil Drain Intervals – Conservation of Resources of Engine Life (Part II)", SAE Technical Paper 981443, 1998.
2. Fitch, James C., "How to Select a Motor Oil or Filter for your Car or Truck", Noria Corporation, 2003.
3. Hochstein, Peter A., "Method and apparatus for monitoring oil degradation", US Patent 4007629, 1977.
4. John, Mc Donald E., Shirley, Schwartz E., et al., "Oil Life Monitor for Diesel Engines", U.S. Patent 6327900, 2001.
5. Shirley, Schwartz E., Donald, Smolenski J., et al., "Automatic Engine Oil Change Indicator System", U.S. Patent 4742476, 1988.
6. Pamela, Younggren J., Shirley, Schwartz E., "The Effects of Trip Length and Oil Type (Synthetic Versus Mineral Oil) on Engine Damage and Engine-Oil Degradation in a Driving Test of a Vehicle with a 5.7L V-8 Engine", SAE Technical Paper 932838, 1993.
7. Albertino, Pereira dos Santos Junior., Helcio, Onusic., "The Flexible Service System (FSS) launched by DaimlerChrysler for Commercial Vehicles", SAE Technical Paper 2002-01-3419, 2002.
8. Eric, Schneider W., "Development of an Engine Dynamometer Test for Rapid Evaluation of Engine Oil Degradation under High-Temperature, High-Load Conditions", SAE Technical Paper 2005-01-3821, 2005.
9. Ruonan, Sun., David, Kittelson B., Perry, Blackshear Junior L., "Size Distribution of Diesel Soot in the Lubricating Oil", SAE Technical Paper 912344, 1991.
10. "Exhaust Gas Recirculation", Retrieved from Wikipedia web site: http://en.wikipedia.org/wiki/Exhaust_gas_recirculation, November 14, 2008.
11. Snider, Matthew J., Quigley, David P., Barkman, Richard A., et al., "Oil Life Monitoring System for a Diesel Engine", US Patent 20080163678, 2008.
12. Scott, Rappaport T., Mark, Ferner D., Lawrence, Hecker S., et al., "Evaluation of API/ILSAC GF-4 Oil Life in Today's US Fleet", SAE Technical Paper 2008-01-1740, 2008.

13. Kent, Froelund., Michael, Ross G., “Laboratory Benchmarking of Seven Model Year 2003-2004 Heavy-Duty Diesel Engines Using a CI-4 Lubricant”, SAE Technical Paper 2005-01-3715, 2005.
14. Sem, Thomas R., Hanson, Jay L., Herrig, Doyle G., “Method of Dynamically Determining Oil Change Intervals for Internal Combustion Engines”, U.S. Patent 5530647, 1996.
15. Axel, Berndorfer H., “Method for Continuously Predicting Remaining Engine Oil Life”, U.S. Patent 6741938, 2004.
16. “How does FSS, the Mercedes-Benz M-Class Flexible Service System, Work?”, Retrieved from http://www.4x4abc.com/ML320/ML_FSS.html, September 15, 2008.
17. Irion, E., Land, K., Klein, M., et al., “Oil-Quality Prediction and Oil-Level Detection with the TEMIC QLT-Sensor leads to Variable Maintenance Intervals”, SAE Technical Paper 970847, 1997.
18. Michael, Cullen J., Stephen, Zulczyk B., “Method and Apparatus for inferring engine oil temperature for use with an engine oil change indicator”, U.S. Patent 5633796, 1997.
19. Yasushi, Noda., Naohisa, Mamiya., Masashi, Hosoya., et al., “Development of an Engine Oil Temperature Prediction Method Using 3D Model Simulation”, SAE Technical Paper 2005-01-1881, 2005.
20. Berndorfer, Axel H., “Method for continuously predicting remaining engine oil life”, U.S. Patent 6741938, 2001.
21. “Intellek Oil Condition Sensor”, Retrieved from Delphi Corporation web site: http://www.delphi.com, September 25, 2008.
22. Barron, John J., Ashton, Colin., “The effect of temperature on Conductivity Measurement”, Technical Services Department, Reagecon Diagnostics Ltd, Ireland.
23. Paul, Voelkar J., Joe, Hedges D., “An On-Board Method of Measuring Motor Oil Degradation”, SAE Technical Paper 962112, 1996.
24. James, Bennett W., Leonid, Matsiev., Robert, Lattin., et al., “New Solid State Oil Condition Sensor for Real Time Engine Oil Condition Monitoring”, SAE Technical Paper 2006-01-1324, 2006.
25. Heremans, Joseph P., Wang, Su-Chee S., et al., “Diesel Engine Lubricating Oil Contaminant Sensor Method”, U.S. Patent 6911830, 2005.

26. Zhang, Chao., "A Micro-acoustic Wave Sensor for Engine Oil Quality Monitoring", Proceedings of 2003 IEEE International Frequency Control Symposium and PDA Exhibition", 2003.
27. Wang, Su-Chee S., Lin, Yingjie., "Engine Oil Contamination Sensor", U.S. Patent 20030062910, 2003.
28. Park, Kyong M., Nassar, Marcos A., "Combined Oil Quality and viscosity Sensing System", U.S. Patent 200200110095, 2002.
29. Carmona, Jesus., Lin, Yingjie., "Viscosity Sensor", U.S. Patent 20080314128, 2008.
30. "Oil Level Sensor and Oil State Sensor", Retrieved from Bosch web site: http://www.bosch.us/content/language1/html/index.htm#, October 3, 2008.
31. Joel, Schmitigal., Steve, Moyer., "Evaluation of Sensors for On-Board Diesel Oil Condition Monitoring of U.S. Army Ground Equipment", SAE Technical Paper 2005-01-1810, 2005.
32. Smolenski, Donald J., Schwartz, Shirley E., "Automotive Engine-Oil Condition Monitoring", CRC Handbook of Lubrication and Tribology, 1994.
33. "Truck Engine Idling", Retrieved from Environmental Protection Agency (EPA) web site: http://www.epa.gov/ne/eco/diesel/idling.html, October, 2008.
34. MATLAB, A numerical and technical computing environment, MathWorks, 2007.
35. Microsoft Office Excel, A spreadsheet application, Microsoft, 2007.

Appendix A

Automotive Sensor Technologies

1. Capacitance Method

A capacitor consists of two conducting plates separated by an insulating material called a dielectric. In the case of oil condition sensors, the oil is the insulating fluid. Capacitance is dependent on the surface area of the plates, the gap between the two plates and the insulating material. As the oil degrades, the capacitance measures this change. Capacitors store charge over time. Similar to filling a bucket with a hole at the bottom, it provides pressure on the hole when it is full. A capacitor takes time to fully charge and it also takes time for it to discharge. When it is fully charged, voltage is provided across the capacitor.

2. Dielectric Constant Method

A dielectric is an insulator. Dielectric constant is the rate of electric flux density produced in a material to the value in free space provided by the same electric field. This technique detects a change, when occurred, in the oil that alters the oil's dielectric properties. These include oxidation, water, acids, mixed fluids and wear debris. There are only subtle differences between the capacitance and dielectric constant methods.

3. Electrochemical Bead Matrix Method

This is a proprietary technique that employs a polymeric bead matrix (held between two conducting permeable surfaces) containing charged groups that serve as a conductive medium for measuring the solvent properties of oil. This method also works similar to the way a battery works. Milligram-sized charged resin beads are contained between two conducting surfaces separated by a nonconductive medium. The charged groups of beads (composed of both anions and cations) adjust to form an electrochemical bridge of varying strength depending on a relative change in the polarity of the oil. Because engine oils are relatively non-polar and the beads are ionic, the beads do not form a conductive bridge. As the oil starts to degrade or become soot contaminated, the fluid becomes more polar (conducive to ionic interactions) and a bridge begins forming. This relative change in conductivity or capacitance is then measured between the two conducting surfaces.

4. Algorithm Method

This method uses mathematical models based on research to determine the optimum oil change intervals. Conditions like engine temperature, engine speed, time and other critical factors are monitored and incorporated into the algorithm. Because the method does not actually test the condition of the oil, it cannot test for engine damage, coolant leaks, etc.

5. Dual Approach

This method is a combination of monitoring driving conditions and using sensors. Conditions like engine temperature, engine speed, time and other critical factors are monitored. Sensors are used to continuously monitor the oil properties like oil level, temperature, dielectric constant, viscosity etc.

Appendix B

MATLAB Code for Oil-Life Simulator

```
function varargout = oil_life(varargin)
% OIL_LIFE M-file for oil_life.fig
%      OIL_LIFE, by itself, creates a new OIL_LIFE or raises the existing
%      singleton*.
%
%      H = OIL_LIFE returns the handle to a new OIL_LIFE or the handle to
%      the existing singleton*.
%
%      OIL_LIFE('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in OIL_LIFE.M with the given input arguments.
%
%      OIL_LIFE('Property','Value',...) creates a new OIL_LIFE or raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before oil_life_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to oil_life_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help oil_life

% Last Modified by GUIDE v2.5 30-Aug-2009 11:32:50

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @oil_life_OpeningFcn, ...
                   'gui_OutputFcn',  @oil_life_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
```

```
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before oil_life is made visible.
function oil_life_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to oil_life (see VARARGIN)

% Choose default command line output for oil_life
handles.output = hObject;

global flag;
global T_inc;
global load_inc;
global rpm_inc;
global des;
global num;
flag=1;
T_inc=0;
load_inc=0;
rpm_inc=0;
des=1;
num=0;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes oil_life wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = oil_life_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;
```

```
% --- Executes on button press in displayText_pushbutton1.
function displayText_pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to displayText_pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

set(handles.display_staticText2,'String','Warming up');
figure(1)
        subplot(2,3,1)
        xlabel('Engine running time (min)')
        subplot(2,3,2)
        xlabel('Oil used life (min)')
        subplot(2,3,3)
        xlabel('Oil remaining life (%)')
        subplot(2,3,4)
        xlabel('Engine temperature (deg C)')
        subplot(2,3,5)
        xlabel('Engine speed (rpm)')
        subplot(2,3,6)
        xlabel('Engine load (%)')

        pause(2)

[s,txt,raw]=xlsread('engine_data.xls','A1:F18000'); % read in the first 18000 rows of excel data

for i=2:length(raw)
   raw{i,2}=datestr(raw{i,2},'HH:MM:SS PM');
end

j=length(raw)-1; % Number of sample readings

nominal_oil_life=1.8e6; % Nominal Running Life of Oil = 500 hrs

handles.s=s;
handles.raw=raw;
handles.j=j;
handles.nominal_oil_life=nominal_oil_life;

guidata(hObject,handles);
set(handles.display_staticText2,'String','System Ready');



% --- Executes on button press in displayText_pushbutton2.
function displayText_pushbutton2_Callback(hObject, eventdata, handles)
```

```
% hObject    handle to displayText_pushbutton2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

s=handles.s;
raw=handles.raw;
j=handles.j;
nominal_oil_life=handles.nominal_oil_life;

% Loading and Retrieving the Cumulated values
load data.csv;

global flag;
global T_inc;
global load_inc;
global rpm_inc;
global des;
flag=1;
T_inc=0;
load_inc=0;
rpm_inc=0;
des=1;

k=data(5);

set(handles.display_staticText2,'String','Engine Running');
set(handles.display_staticText3,'String',0);
set(handles.display_staticText4,'String',0);
set(handles.display_staticText5,'String',0);
set(handles.display_staticText6,'String','Off');

%Oil_life calculations
for i=k:j
   date(i,:)=datevec(raw(i+1,1));
   time(i,:)=datevec(raw(i+1,2));
   engine_oil_temperature(i)=(s(i,2)-32)*5/9; % In Deg C
   engine_coolant_temperature(i)=(s(i,3)-32)*5/9; % In Deg C
   engine_speed(i)=s(i,4); % In RPM
   percent_engine_load(i)=s(i,5);

   engine_oil_temperature(i)=engine_oil_temperature(i)+T_inc*engine_oil_temperature(i);

engine_coolant_temperature(i)=engine_coolant_temperature(i)+T_inc*engine_coolant_temperat
ure(i);
   percent_engine_load(i)=percent_engine_load(i)+load_inc*percent_engine_load(i);
   engine_speed(i)=engine_speed(i)+rpm_inc*engine_speed(i);
```

```
if i==k
    cranking=1; %engine cranking
    delta_t=10;
else
    previous_time=(((date(i-1,2)*30+date(i-1,3))*24+time(i-1,4))*60+time(i-1,5))*60+time(i-
1,6);
    current_time =(((date(i,2)*30+date(i,3))*24+time(i,4))*60+time(i,5))*60+time(i,6);
    delta_t=abs(current_time-previous_time); % Sampling interval should be shorter than or
equal to 5 sec for continuous running
    if delta_t > 5
        cranking=1; % delta_t greater than 5 seconds implies engine cranking
    end
end

% Calculation of Working Temperature
T=engine_oil_temperature(i);
if engine_coolant_temperature(i) < 100
    T=(engine_oil_temperature(i)+engine_coolant_temperature(i))/2;
end

% Calculation of Ct (Temperature Discount Factor)
if T < 0
    Ct(i)=8;
elseif T >= 0 && T <= 80
    Ct(i)=1+7*(80-T)/80;
elseif T > 80 && T < 130
    Ct(i)=1;
else
    Ct(i)=10^((T-130)/50);
end

% Calculation of Cen (Engine Load Discount Factor)
Cen(i)=1;
if percent_engine_load(i) > 70
    Cen(i)=2^((percent_engine_load(i)-70)/30);
end

% Calculation of Ces (Engine Speed Discount Factor)
if engine_speed(i) < 500
    Ces(i)=1.5;
elseif engine_speed(i) >= 500 && engine_speed(i) <= 900
    Ces(i)=-0.00125*engine_speed(i)+2.125;
elseif engine_speed(i) > 900 && engine_speed(i) < 2000
    Ces(i)=1;
else
```

```
    Ces(i)=(engine_speed(i)^2+8e6)/12e6;
end

%Calculation of Cck (Cranking Doscount Factor)
Cck(i)=1;
if cranking == 1 % cranking
    if delta_t > 5
        time_after_crank=0;
        T0=engine_coolant_temperature(i);
    else
        time_after_crank=time_after_crank+delta_t;
    end
    Cck0=5;
    t0=20;
    if T0 < 0
        Cck0=10;
        t0=40;
    elseif T0 >= 0 && T0 <=80
        Cck0=10-5*(T0/80);
        t0=40-20*(T0/80);
    end
    Cck(i)=1+(Cck0-1)*(t0-time_after_crank)/t0;
    if time_after_crank > t0
        Cck(i)=1;
        cranking=0;
    end
end

%Calculation of Cag (Oil Aging Discount Factor)
Cag=1;
if i==k % reading in cumulated oil_in_sump data
    previous_day = data(4); % Date stamp on engine used earlier
    current_day = datenum(raw(i+1,1));
    days_oil_in_sump = data(3)+(current_day-previous_day);
else
    previous_day = datenum(raw(i,1));
    current_day = datenum(raw(i+1,1));
    delta_day = abs(current_day-previous_day);
    days_oil_in_sump = days_oil_in_sump+delta_day;
end
if days_oil_in_sump > 180
    Cag=exp((180-days_oil_in_sump)/180);
end

% Calculation of oil used life, percentage oil remaining life and engine running time
if i==k
```

```
   oil_used_life(i)=data(1);
   engine_running_time(i)=data(2);
elseif delta_t <= 5
   oil_used_life(i)=oil_used_life(i-1)+delta_t*Ct(i)*Cen(i)*Ces(i)*Cck(i)*des;
   percentage_oil_remaining_life(i)=100*(1-(oil_used_life(i)/(nominal_oil_life*Cag)));
   engine_running_time(i)=engine_running_time(i-1)+delta_t;
else
   oil_used_life(i)=oil_used_life(i-1);
   percentage_oil_remaining_life(i)=percentage_oil_remaining_life(i-1);
   engine_running_time(i)=engine_running_time(i-1);
end

if i>k
   if percentage_oil_remaining_life(i)>= 49.5 && percentage_oil_remaining_life(i) <= 50.5
      set(handles.display_staticText2,'String','Check Oil Level');
   end
   if percentage_oil_remaining_life(i)<1
      set(handles.display_staticText2,'String','Change Oil');
      break
   end
end

% Saving the cumulated values
fid = fopen('data.csv','wt');
fprintf(fid,'%f\n',oil_used_life(i));
fprintf(fid,'%f\n',engine_running_time(i));
fprintf(fid,'%f\n',days_oil_in_sump);
fprintf(fid,'%f\n',current_day);
if i==j
   fprintf(fid,'%f\n',1);
else
   fprintf(fid,'%f\n',i);
end
fclose(fid);

miles=45*engine_running_time(i)/3600

% Graphical Display
if (i>k)
   n=num2str(percentage_oil_remaining_life(i));
   handles.n=n;
   guidata(hObject,handles);
   set(handles.display_staticText,'String',n);

   if(count==5)
      figure(1)
```

```
            subplot(2,3,1), bar(engine_running_time(i)/60, 'g')
            yhigh1=max(100,1.5*engine_running_time(i)/60);
            axis([.6 1 0 yhigh1])
            xlabel('Engine running time (min)')
            subplot(2,3,2), bar(oil_used_life(i)/60, 'm')
            yhigh=max(100,1.2*oil_used_life(i)/60);
            axis([.6 1 0 yhigh])
            xlabel('Oil used life (min)')
            subplot(2,3,3), bar(percentage_oil_remaining_life(i), 'c')
            ylow=0.99*percentage_oil_remaining_life(i);
            ymax=min(100, 1.01*percentage_oil_remaining_life(i));
            axis([.6 1 ylow ymax])
            xlabel('Oil remaining life (%)')
            if T<20
               subplot(2,3,4), bar(T, 'y')
            elseif T>=20 && T<=200
               col=(200-T)/(200-20);
               subplot(2,3,4), bar(T, 'FaceColor', [1 col 0])
            else
               subplot(2,3,4), bar(T, 'r')
            end
            axis([.6 1 0 max(100,1.2*T)])
            xlabel('Engine temperature (deg C)')
            subplot(2,3,5), bar(engine_speed(i), 'b')
            axis([.6 1 300 max(2000,1.2*engine_speed(i))])
            xlabel('Engine speed (rpm)')
            subplot(2,3,6), bar(percent_engine_load(i), 'k')
            axis([.6 1 0 max(100,1.2*percent_engine_load(i))])
            xlabel('Engine load (%)')
            count=0;
%             pause(0.01)
        else
            count=count+1;
        end
    else
        count=5;
    end

    if flag == 0
        break
    end
end

if i==j
    set(handles.display_staticText2,'String','Engine Stopped');
end
```

```
% --- Executes on button press in displayText_pushbutton3.
function displayText_pushbutton3_Callback(hObject, eventdata, handles)
% hObject    handle to displayText_pushbutton3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global flag;
flag=0;

n=handles.n;
set(handles.display_staticText2,'String','Engine Stopped');
set(handles.display_staticText,'String',n);
set(handles.display_staticText3,'String',0);
set(handles.display_staticText4,'String',0);
set(handles.display_staticText5,'String',0);
set(handles.display_staticText6,'String','Off');


% --- Executes on button press in displayText_pushbutton4.
function displayText_pushbutton4_Callback(hObject, eventdata, handles)
% hObject    handle to displayText_pushbutton4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global flag;
flag=0;
raw=handles.raw;
current_day = datenum(raw(2,1));
m=0; d=1;
fid = fopen('data.csv','wt');
fprintf(fid,'%f\n',m); % Setting Cumulated Oil Used Life to 0
fprintf(fid,'%f\n',m); % Setting Cumulated Engine Running Time to 0
fprintf(fid,'%f\n',d); % Setting Number of Days of Oil in Sump to 1
fprintf(fid,'%f\n',current_day); % Setting the Date stamp
fprintf(fid,'%f\n',d); % Setting the Index to initial step, i.e., 1
fclose(fid);

set(handles.display_staticText2,'String','The cumulated values have been reset');

set(handles.display_staticText,'String',100);
set(handles.display_staticText3,'String',0);
set(handles.display_staticText4,'String',0);
set(handles.display_staticText5,'String',0);
```

```
% --- Executes on button press in displayText_pushbutton5.
function displayText_pushbutton5_Callback(hObject, eventdata, handles)
% hObject    handle to displayText_pushbutton5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global T_inc;
T_inc=T_inc+0.05;

inc=num2str(T_inc*100);
set(handles.display_staticText3,'String',inc);


% --- Executes on button press in displayText_pushbutton6.
function displayText_pushbutton6_Callback(hObject, eventdata, handles)
% hObject    handle to displayText_pushbutton6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global T_inc;
T_inc=T_inc-0.05;

inc=num2str(T_inc*100);
set(handles.display_staticText3,'String',inc);


% --- Executes on button press in displayText_pushbutton7.
function displayText_pushbutton7_Callback(hObject, eventdata, handles)
% hObject    handle to displayText_pushbutton7 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global load_inc;
load_inc=load_inc+0.05;

inc=num2str(load_inc*100);
set(handles.display_staticText4,'String',inc);


% --- Executes on button press in displayText_pushbutton8.
function displayText_pushbutton8_Callback(hObject, eventdata, handles)
% hObject    handle to displayText_pushbutton8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global load_inc;
```

```
load_inc=load_inc-0.05;

inc=num2str(load_inc*100);
set(handles.display_staticText4,'String',inc);


% --- Executes on button press in displayText_pushbutton9.
function displayText_pushbutton9_Callback(hObject, eventdata, handles)
% hObject    handle to displayText_pushbutton9 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global rpm_inc;
rpm_inc=rpm_inc+0.05;

inc=num2str(rpm_inc*100);
set(handles.display_staticText5,'String',inc);


% --- Executes on button press in displayText_pushbutton10.
function displayText_pushbutton10_Callback(hObject, eventdata, handles)
% hObject    handle to displayText_pushbutton10 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global rpm_inc;
rpm_inc=rpm_inc-0.05;

inc=num2str(rpm_inc*100);
set(handles.display_staticText5,'String',inc);


% --- Executes on button press in displayText_pushbutton11.
function displayText_pushbutton11_Callback(hObject, eventdata, handles)
% hObject    handle to displayText_pushbutton11 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global num;
global des;

num=num+1;

if mod(num,2) == 1
    des=1.5;
    set(handles.display_staticText6,'String','On');
```

```
else
   des=1;
   set(handles.display_staticText6,'String','Off');

end
```