A Global Perspective of Engine Oil Properties

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Summary

The absolute dependence of the automobile on its engine is, over time, primarily dependent on the properties of its engine oil. These qualities of the engine oil have become more and more important as engine re-design has increasingly emphasized power, performance, smaller size and greater fuel efficiency. Engine oils must meet increasingly higher standards to serve these engines. Fortunately, these standards are increasingly applied through relatively inexpensive bench tests based on good correlation with engine tests on the dynamometer or in the field.

However, there are many hundreds of engine oils placed on the world's marketplace claiming certain levels of performance. It is reasonable and prudent to question and determine whether they will meet the standards they claim. The Institute of Materials (IOM) has annually collected hundreds of oils from the marketplace for over 30 years and objectively published the responses of these oils to bench tests required for standards and performance as well as other quality-informative bench tests. This paper uses the data from the IOM Engine Oil Database to appraise the present quality and dependability of marketed oils to meet the rapidly growing needs of modern engines.

1. Introduction

1.1 The Automobile and Society

Over the last hundred years, the automobile has become an essential and highly desired mode of human transportation throughout the world. In some areas such as North America and Europe, this dependence has been sharply evident for decades. In other areas, such as portions of Asia and the Pacific, this relationship is more recent. However, no matter where it is used, the automobile is only as dependable as its engine and the engine oil carefully made for its continued operation.

1.2 The Critical Role of the Engine Oil

With today's increasingly demanding needs for the difficult combination of performance, protection and fuel efficiency with smaller, more powerful engines, there is a rapidly growing need to assure that wherever an automobile is used there is an adequate engine oil to protect it in the environment of its use. This requires more and more carefully formulated engine oils based on deeper understanding of the physics and chemistry of engine lubrication. More than this, greater attention is needed to be given to the actual (versus the claimed) quality of the engine oils being put on the world's markets for use.

1.3 Engine Oil Specifications

The need for information and understanding of the relationship between the engine and its lubricant existed since the development of the automobile. However, the automobile has long passed from being an expensive hobby to being a necessity for most owners. As use of the automobile grew, its cost and owner's expectations of reliability similarly grew. With that growth and accompanying warranty responsibility, engine manufacturers began specifying minimum performance levels using engine and bench tests and these specification grew with time and understanding of engine needs.

1.4 Engine Oil Sources and Acceptability

As the automobile became common in various societies around the world, the sources of engine oil also have multiplied rapidly in those regions. As would be expected, these marketed engine oils carried various claims of good performance.

Without objective supporting data, the actual level of knowledge and skill applied in manufacturing an engine oils is not easily imparted to the customer on purchase.

However as this paper will show, objective data on engine oils is available from the Institute of Materials.

2. Source of this Paper's Engine Oil Performance Information – The Institute of Materials

The Institute of Materials (IOM) was formed in 1984 to meet the needs of the automotive, petroleum and lubricant additive companies that became evident in a study presented to the SAE Fuels and Lubricants Sub-Committee by one of these companies in 1983. The data presented indicated the need to effectively evaluate and communicate the properties of engine oils actually reaching the market for use by automobile owners. Although the SAE took a less public path to attempt to meet the need, the Institute for Materials was formed to gather engine oils from the market, analyze them by well=recognized bench tests and publish the resulting data including the location of acquisition and the information on the container. The first geographic area covered was to select engine oils marketed in North America.

Over the ensuing years, the scope of engine oil collections has been extended from North America to the markets of Europe and Asia in the early 1990's and has been expanded even further since that time. Each year during IOM's 30-year history, several hundred engine oils have been purchased on the retail market. Each of these oils are subjected to several dozen bench tests by an accredited few laboratories to determine their properties and how these compare to the expected performance.

To date, over 14,000 engine oils have been tested. It is the world's largest collection of such data. The data has been made available to those interested by both subscription or by individual reports as well as on the Internet.

Since the engine oils collected by IOM actually indicate the quality of manufacture reaching the market, the IOM Engine Oil Database has been used for a number of purposes by Subscribers including those monitoring manufacturing consistency and competitive products. A number of papers have been published using IOM data. However, the IOM data are carefully restricted in published use to avoid adulteration with non-IOM data.

This paper shows how the Database reveals the engine-protective benefits of well-informed engine oil formulation as well as the presence on the market of less knowledgeable or concerned formulation, In some cases, otherwise well formulated engine oil may give surprisingly adverse response because of unexpected stresses such as weather conditions for which the particular engine oil had not been formulated.

3. Four Engine Oil Properties to be Analyzed

Of the more than 30 bench tests used to evaluate the marketed engine oils, four were chosen as examples of variation among these marketed products. Other equally important bench tests of engine oil properties and performance could have been chosen but these four were thought particularly illustrative.

For those readers interested in other aspects provided by the IOM Engine Oil Database, several previously published papers by one of the authors (Selby) have shown the depth of understanding and range of information available regarding engine lubricants.

The areas chosen for discussion were

1. Oxidation resistance
   a. in the engine and
   b. in the turbocharger,
2. Engine oil pumpability (a newly resurgent concern from recent winter field failures in Europe), and
3. Fuel efficiency improvement by choice of the high shear rate viscosity of the engine oil.

3.1 Oxidation Resistance in the Turbocharger

Turbochargers have been used for years in various part of the world to improve power and fuel efficiency of the automotive engine on more costly automobiles. Europe, however, has set the pace by incorporating the turbocharger in commonly-used vehicles and, in today's strong push to higher fuel efficiency, use of turbochargers is becoming common everywhere.

With the integration of the turbocharger and engine, engine oil is also used for turbocharger lubrication. However, it has been shown that the turbocharger and engine present two different oxidation environments [1,2]. The engine presents its environment while operating while the turbocharger affects the engine oil after the engine has been shut off. The very hot (often greater than 1000°C) turbocharger rotor forces high temperatures down the turbocharger shaft thus progressively baking the oil and additives into a 'coke' during which turbocharger lubrication is more and more restricted until failure occurs.

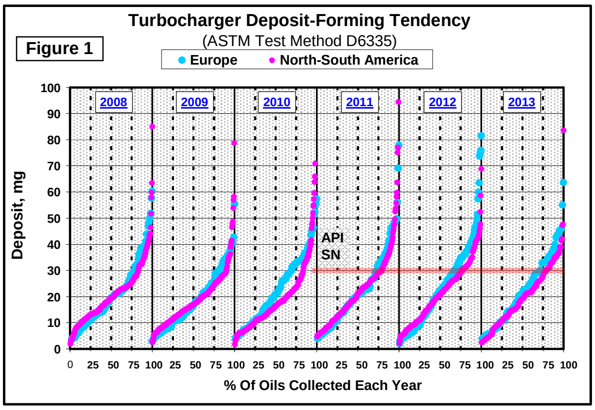
In the late 1980's, the Thermo-oxidation Engine Oil Simulation Test, TEOST 33C was developed [3,4] using as standards of correlation several European engine oils which performed well or poorly in the field in resisting turbocharger deposit formation. Subsequently, the test was incorporated into North American and Japanese engine oil specifications and was formalized into ASTM Test Method D6335 in 1998 [5].

3.1.1 Comparison of Marketed Engine Oils in the TEOST 33C Turbocharger Oxidation Test, D6335

To provide a comparative view of engine oil response to the ASTM D6335 test, it was thought to be most informative to first give an overall view of the distribution of test values over a period of six years from 2008 to 2013.

For this paper a special plotting format was developed which permitted comparing a chosen property or response of oils marketed in different areas of the world in progressive years. This had the advantage of visualizing whether or not marketed oils were progressively improving or not and how their formulary compositions compared from one area of the world to another.

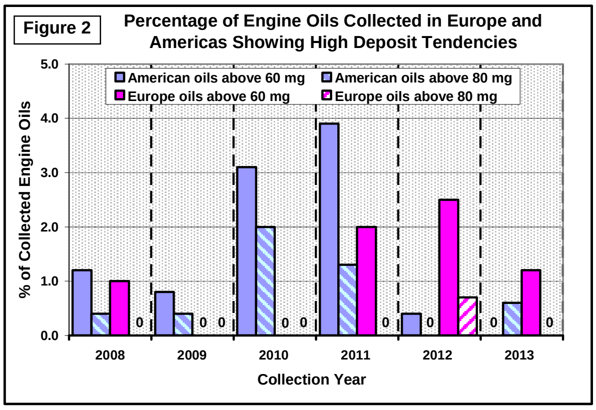
Fig. 1 uses this plotting technique to make a comparison of the oils collected by the Institute of Materials in Europe and in North-South America regarding the tendency to form turbocharger deposits. On the ordinate (Y-axis) is given milligrams of deposit formed while the abscissa (X-axis) showed the percentage of the oils collected each year giving the associated deposit level.



It should be noted that near the end of 2010 the American Petroleum Institute issued the latest Standard SN for the engine oils. The new standard was an upgrade of the previous Standard SM and included the requirement to have a deposit level of 30 mg or less in the ASTM D6335 test for turbocharger deposit tendency. This new requirement is also shown in Fig. 1 as a horizontal red line.

Several observations can be made from the comparative data. First of all, over the years from 2008 to 2013 considerably more than 50% of the oils collected in either area met the requirement of SN. However, it is also evident that in both Europe and North-South America a number of engine oils have deposit tendencies well over 60 mg and even 80 mg. These are levels of deposit that – on the basis of the field oils used to develop the bench test – are prejudicial to the continued operability of the turbocharger.

Fig. 2 shows this comparison explicitly. It is particularly evident that in 2010 the Americas showed an increase in unacceptable oils for turbocharger use. Moreover this increased somewhat in 2011 in the Americas and even in Europe. However, the inclusion of the TEOST 33C ASTM D6335 bench test in the requirement for API SN at the end of 2010 may be reasonably responsible for



the evident improvement shown in 2012 and 2013 for the oils marketed in the Americas. With some level of contrast, in Europe where the turbocharger bench test is not a required specification for the engine oils produced, the marketed oils sampled show some increase in the presence of deposit-susceptible oils for 2012 and 2013.

Overall, considerably fewer questionable oils were found in Europe from 2008 to 2010 but some increase is evident from then and engine oils in the Americas improved markedly in the last two years.

One aspect of the oxidative mechanism of ASTM Test Method D6335 should be noted. A low level of some additives improves this test's response since some additives may be involved in deposit formation at these temperatures. Thus, oil that would be inadequate for engine lubrication may be acceptable in resisting turbocharger deposit formation. Consequently, passing D6335 does not imply that an engine oil is suitable for other important service for which the oil must be additionally tested. From this observation, it is not surprising that correlation between deposit formation in this test and other test may be limited.

3.2 Oxidation Resistance in the Ring Belt Area of the Engine Piston

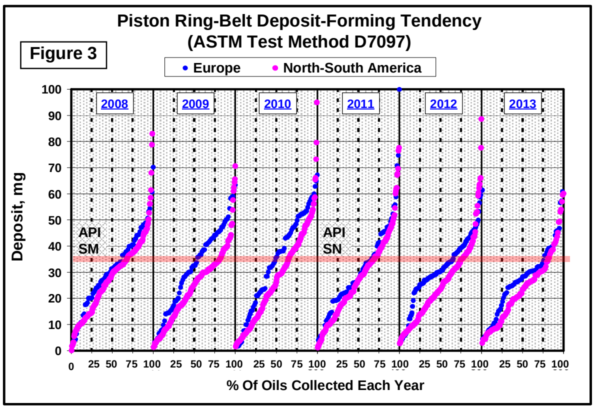
Of the various areas of the engine being lubricated, the piston ring belt is probably the most important and demanding of the oil's resistance to deposit formation. As a consequence, the need for a bench test rather than expensive and variable engine tests was clear.

The general approach of the TEOST 33C was utilized in using a depositor rod. However, the temperature applied (285°C), time of test exposure (24 hours), and amount of sample (approximately 8 grams), were all significantly different [6]. After considering several engine tests, the new bench test was developed to correlate as closely as possible with the well-known Peugeot TU3MH engine test for piston deposit rating.

As a bench test, the technique was termed the Moderately High Temperature Thermo-oxidation Engine Oil Simulation Test or TEOST MHT and became ASTM Test Method D7097 in 2005 [7]. It was incorporated in API Standard SM when that was issued.

3.2.1 Comparison of Marketed Engine Oils in the TEOST MHT Oxidation Test, D7097 -- Concern with piston deposit formation in the automotive engine is world-wide but particularly in the United States and Japan where the development of the TEOST MHT was initiated. The test was required in engine oil specifications issued as GF-4 and GF-5 by the automotive ILSAC (International Lubricants Standardization and Approval Committee) in concert with the API.

Fig. 3 is a comparison of the piston ring-belt deposit tendencies of engine oils collected by the Institute of Materials in Europe and the Americas over the six-year span from 2008 to 2013.



In comparison with Fig. 1, there is considerably greater difference between the oils of these two areas in response to this bench test. After introduction of the API SN category in late 2010, the percentage of oils meeting the maximum deposit criteria of 35 mg in both Europe and the Americas are reaching higher and more similar levels. This is shown more explicitly in Figs. 4 and 5.

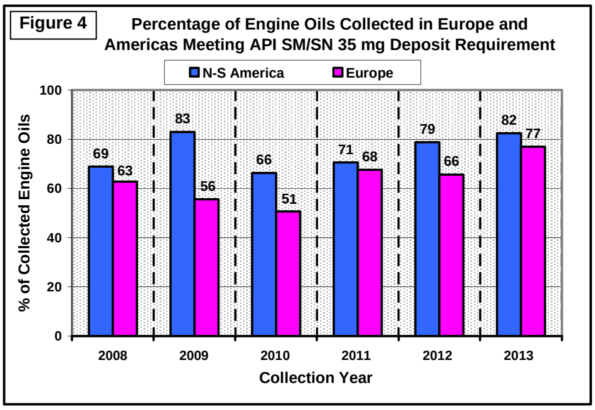
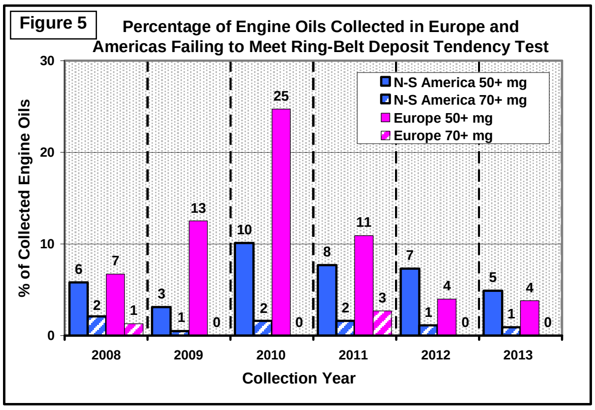


Fig. 4 shows the percentage of the oils collected each year from both Europe and the Americas that meet the criteria of a maximum of 35 mg. Since the ILSAC/API specification of SN in late 2010 both Europe and the Americas have shown increase in the number of engine oils meeting the 35 mg maximum deposit level for the TEOST MHT ring-belt deposit test. Europe improved from 51% to 77% and the Americas from 66% to 82%.

Improvement in the percentage of good engine oils reaching the market is encouraging. However, it does not answer the question of whether the quality levels of those engine oils failing the criterion applied are marginal or serious lapses.

A passing level of 35 mg is associated with continued good operational performance regarding ring-belt deposits. In comparison, a level of 50 mg is associated with poor resistance to deposit formation and 70 mg or poorer results in the TEOST MHT bench test presages serious combustion chamber deposit formation and pre-ignition.

Fig. 5 shows this other side of the market quality picture: The frequency with which failing engine oil actually reach or exceed either a deposit level of 50 mg or a second criterion of 70 mg. The data are plotted for each year of collection for both Europe and the Americas.



The data shown in Fig. 5 give both concern and hope – concern up to 2010 regarding both the Americas and Europe (particularly the latter) – and hope from 2010 on as the level of serious failure drops rapidly. Forthcoming IOM collections from both areas should be very interesting to evaluate and compare.

3.3 Low-Temperature Lubricant Supply to the Engine – Pumpability and Gelation

A half-century ago the primary difficulty in operating the vehicle at low ambient temperatures was in starting the engine. With considerably improved starting systems, a quarter-century ago the low-temperature problem changed relatively quickly to one of having adequate pumpability.

Unfortunately, easier engine starting had uncovered a more serious problem which revealed that at low-temperatures, some engine oils have gelation (gel-forming) tendencies under certain cooling conditions.

3.3.1 Crucial Problem of Engine Oil Gelation – The occurrence of the gelation problem was not simply a matter of the slower flow of thickened oil at lower starting temperatures (although that, too, can be a different problem). Rather, the condition occurs when, exposed to a particular cooling pattern, components of the engine oil are induced to form a matrix or structure.

Thus, what can be termed a 'gel' develops in the engine crankcase which enmeshes the remaining oil so that the gelated mass cannot be readily pumped – if it can be pumped at all (a condition called "air-binding" the oil pump).

The consequence is an engine that can be readily started but will quickly and catastrophically fail during operation. Such incidents usually involve a number of vehicles in the same weather zone. This occurred in Sioux Falls, South Dakota [8,9] and colder climes of Europe in 1980 and very recently again in Europe.

3.3.2 The Scanning Brookfield Technique (SBT) – The Sioux Falls incident led to the development of the Scanning Brookfield Technique (SBT) in 1985 [9,10] which became ASTM D5133 [11]. This rotational viscometric technique measures viscosity continuously over a broad range of continuously and slowly decreasing temperatures (normally from -5° to -40°C at -1°C/hour).

Continuous measurement of viscosity by the SBT reveals the onset and degree of gelation by gelation's viscous contribution to oil's normal exponential increase in viscosity with decreasing temperature. When the additional viscosity increase of gelation is analyzed, the data produce a peak value of gelation influence called the Gelation Index and the temperature at which this peak occurs called the Gelation Index Temperature.

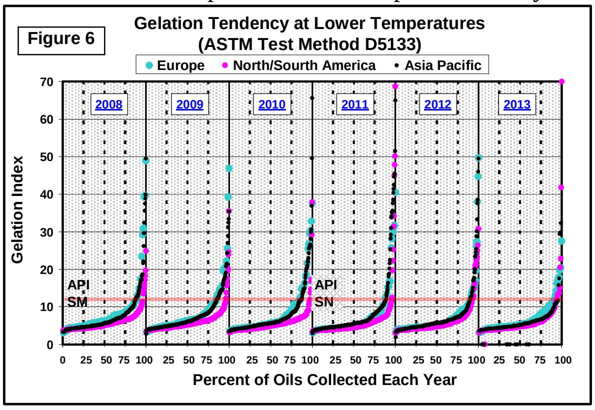
Both the Gelation Index and its temperature are the important variables determined by ASTM D5133.

3.3.3 Use of the MiniRotary Viscometer as TP-1 – Development of the SBT was followed by an effort to regain use of the MiniRotary Viscometer (MRV, ASTM D3829 [12]), a pumpability test that had been developed earlier on the basis of cold-room engine tests [13] but found inadequate in the face of Nature's more complex pattern in the Sioux Falls incident [14]. A recast MRV test technique was called TP-1 [15] and later became ASTM D4684 [16] which replaced use of D3829 in test specifications.

The new TP-1 approach cools the sample relatively slowly from -8° to -20°C (at -1/3°C/hour) after which the cooling rate is increased to -2.5°C/hour to the desired test temperature. The test consists of first gradually increasing the force applied to turn the rotor in the stator in a series of 10 gram increments to determine if the oil has gelated during the 36-hour cooling interval from -8° to -20°C. If so, the level of weight needed to overcome the resistance of the gelated structure is recorded. This load is called the 'Yield Stress'.

Whether or not a Yield Stress is encountered, following the Yield Stress portion of the test, a 150 gram weight is then applied to turn the rotor for three revolutions and, if the rotor will turn, this information is used to calculate the viscosity of the sample at that temperature.

3.3.4 Comparison of Low-Temperature Pumpability Susceptibility Using the SBT – Fig. 6 compares the pumpability of SAE W-grade engine oils using the temperature-scanning technique of ASTM D5133. Included in this portion of the present study are



Institute of Materials data from the Asia-Pacific markets. This area of the world is often not considered to be very vulnerable to pumpability-inducing weather and it was of particular interest to find if this affected the formulation of oils on that market.

As is evident in Fig. 6, from the beginning of the use of ASTM D5133 in specifications in the late 1980s, a level of Gelation Index (GI) of 12 or more was considered undesirable (the Sioux Falls oils gave GIs of 16).

Fig. 6 clearly shows that, as would be expected, engine oils marketed in the Americas from 2008 to 2010 are superior in pumpability to the engine oils marketed in Europe and Asia-Pacific during this period and that pumpability failures were experienced in Europe [18].

However, perhaps partially as the aftermath of the reported pumpability failures in Europe, considerable improvement in low-temperature pumpability is shown in the ensuing years of 2011, 2012 and 2013.

Viewed from the perspective of how many of the oils failing the D5133 SBT pumpability test were possible, marginal failures showing GI values from 12 to less than 20 GI, the bar-graph of Figure 7 is more explicit.

The three bars of each year show

[1] The percent of oils collected from the markets of each area that are above a value of 12 GI, and have a potential susceptibility to low-temperatures.

[2] The percent of the oils from each region that have GIs of 20 or higher and are likely to fail under low-temperature conditions.

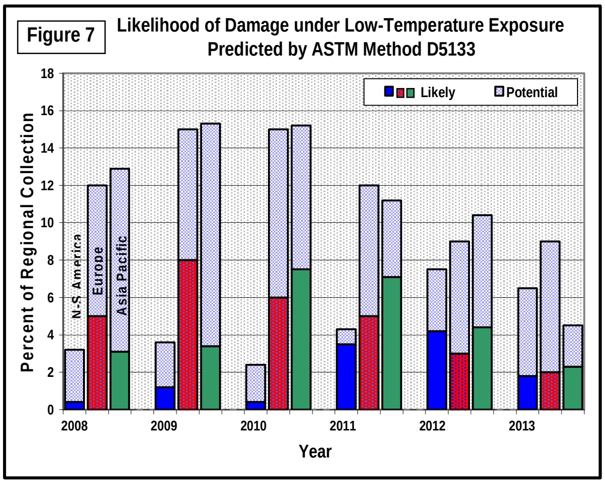


Figure 7 Likelihood of Damage under Low-Temperature Exposure Predicted by ASTM Method D5133

Interestingly, the data seem to explain the recent pumpability failures in Europe in 2008-2009 in which the marketed oils showing Gelation Indices of 20 and above account for as much as eight percent of the oils collected. The adverse weather conditions reported during that time would be likely to cause the damage from pumpability failure that was reported.

Encouragingly, the data also show that since that European experience, the susceptibility to pumpability failure has decreased significantly until in 2013 the level is commensurate to that in the Americas in which the property has always had attention since the Sioux Falls incident.

3.3.5 Comparison of Low-Temperature Pumpability Susceptibility Using the MRV TP-1 – As in the previous analysis of measuring the susceptibility of engine oils to pumpability, Fig. 8 shows the overall pattern of response to measurement by TP-1, using ASTM Test Method D4684.

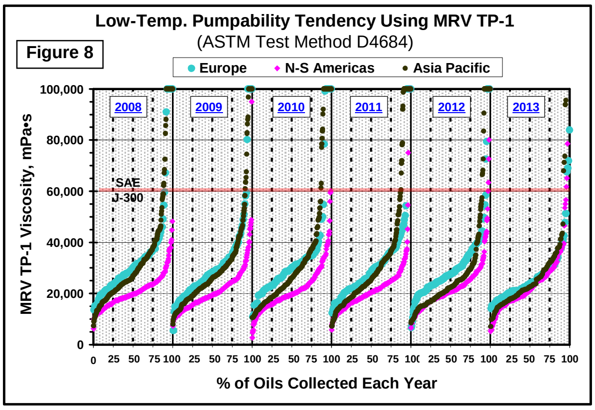


Figure 8 Low-Temp. Pumpability Tendency Using MRV TP-1 (ASTM Test Method D4684)

The SAE J-300 Engine Oil Viscosity Classification requirement of a viscosity level no greater than 60,000 mPa•s (cP) is also shown. Using this criterion of acceptability, the Americas show considerably better response to the test with the exception of 2013. It is likely that this pattern reflects the long North American concern with pumpability since Sioux Falls and the recent adverse European experience of 2008-2009.

It is also of interest to appraise the second criterion of TP-1, that of the Yield Stress. Fig. 9 is a comparative analysis of Europe, the Americas and the Asia Pacific, showing the form and frequency of the failing oils.

The data are quite revealing in showing that essentially all failure by the TP-1 bench test is by gelation indicated by the Yield Stress. Moreover, the data also show the high frequency of gelated oils marketed in Europe and Asia Pacific in comparison to those marketed in the Americas. However, it is also noteworthy that the test indicates an increase in Yield Stress prone oils in the Americas over the six-year period of this data from IOM. This may indicate that the growing use of more carefully refined base stocks may have another aspect needing study.

It will be of interest to see if this trend continues.

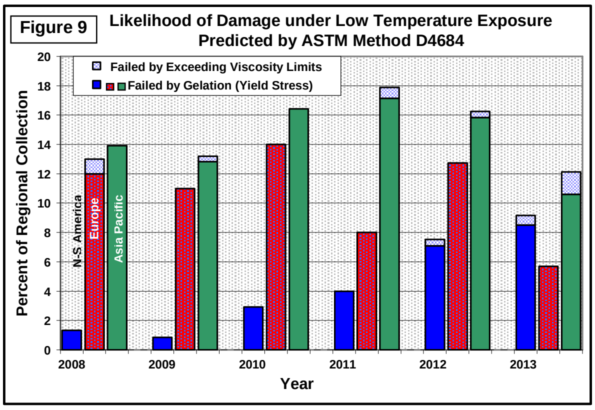


Figure 9 Likelihood of Damage under Low Temperature Exposure Predicted by ASTM Method D4684

3.3.6 Comparison of the Fuel Efficiency Effects of Marketed Engine Oils – As was briefly noted early in this paper, the difficult combination of performance, protection and fuel efficiency of smaller, more stressed engines is a rapidly growing challenge.

From this viewpoint, perhaps the most important aspect of the viscosity of engine oil – beyond that of protecting the engine through hydrodynamic lubrication – is the energy the engine oil viscosity requires from the engine in order to provide its wear protection. The fact is that the engine oil has a strong influence on the engine's fuel efficiency. These considerations lead to another concerning the level of viscosity needed at an engine's operating temperatures to provide wear protection in concert with the various anti-wear additives which also should be present.

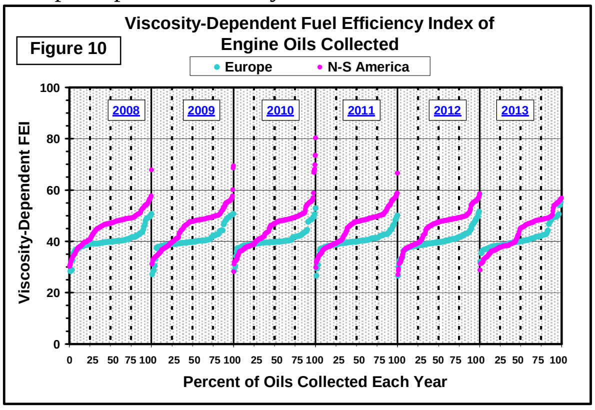
Very recent requests to the SAE Engine Oil Viscosity Classification Task Force have, in fact, emphasized the need for new, lower viscosity grades. As a consequence one new grade (i.e.: SAE 16) specified by SAE.

From these perspectives, it was thought to be of interest to the reader to evaluate the Viscosity-Dependent Fuel Efficiency Index (FEI-V) – a method developed [17] to permit comparison of the energy required by various engine oils. Increasing numerical value of the FEI-V indicates increasing fuel efficiency of the oil. A value of 100 FEI-V is not possible but would indicate an engine oil absorbing no energy from the operating engine.

Fig. 10 shows the distribution of FEI-V of engine oils collected from the markets of Europe and the Americas by the Institute of Materials over the selected years of 2008 to 2013.

The comparison shows surprising and unexpected differences between the two regions. It is evident that, on average, each year the oils selected arbitrarily from those readily available on the two marketing areas are considerably less fuel efficient in Europe than the Americas.

This may reflect a more conservative view that it is more important to preserve the engine condition than to save operating costs through fuel efficiency. Another and perhaps more likely scenario is that the lower



viscosity Multigrade oils of SAE 5W and 0W classification may be more acceptable in the harsher winters of the North American continent. It will be of interest to watch the values of FEI-V of the new lower viscosity engine oils being brought to the market.

4. Discussion and Conclusion

The Institute of Materials information presented has compared and contrasted data of marketed engine oils from various regions of the world. Four of the many IOM bench tests were chosen for this comparison of the quality of marketed engine oils.

Of these four it was evident that in each test most of the oils tested were of acceptable quality or pressing the limit. However, it was also evident that some products were very lacking in the particular property even to the level of causing engine malfunction or failure.

For example, the determination of Gelation Index for the European engine oils seemed to predict the likelihood of pumpability failure in 5 to 8 percent of the engine oils collected in 2008-2009 under certain weather conditions. These failures did occur.

These data from the Institute of Materials suggest that such data trends as given in its Engine Oil Database can be critically important if marketed engine oils will be collectively able to maintain an acceptable level of engine lubrication. As a guide, the data from IOM will be of increasing interest and importance as the use of the automobile grows around the world.

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