The Viscosity-Dependent Fuel Efficiency Index for Engine Oils

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Summary: An algorithm permitting the determination of the viscosity-dependent power loss in an automotive engine was generated. Using Tapered Bearing Simulator Viscometer data at 100° and 150°C from the Institute of Materials Engine Oil Database, the new algorithm was applied to 1300 oils purchased in North America, Europe, and Asia in the years 1999 and 2000. When both the claimed "fuel efficient" oils and the oils not so marked were compared using the new algorithm, the results produced reasonable views of the fuel efficiency which could be expected from the oils of these three databases. The new algorithm has been termed the Fuel Efficiency Index.

An Appendix compares the Fuel Efficiency Indexes of all the averaged individual North American SAE grades.

1. Background

Engine Oil Viscosity and Fuel Efficiency

Lubrication at a Price - Since the earliest application of lubrication to wheeled vehicles, the rheology of the lubricant has absorbed some energy from the propulsion mechanism whether it be a beast of burden or an engine of more refined power.

Absorption of power by the lubricant of the automotive engine has always been a matter of some concern. However, in the last 40 years, increasingly important issues of conservation and environmental health have changed the focus of automotive engineering. Improving the level of fuel efficiency has become a mantra to many of the world's peoples, governments, as well as manufacturers of the automotive conveyances in their myriad forms.

The task of making the motive power of vehicles more and more efficient has the goad of serious penalties embedded within governmental regulations. In the US, literally hundreds of millions of dollars are at stake each year in penalties for noncompliance and more millions are spent to prove that engines and vehicles are as fuel efficient as claimed. Moreover, many of the more apparent, larger gains have already been made and, as a result, the continuing effort to further reduce emissions by improving engine efficiency has become increasingly more difficult.

Viscous Friction - Protector of the Engine and Thief of Energy - The viscosity of a fluid lubricant is a form of friction. At the various sites at which lubrication takes place, this friction converts energy into unavailable heat proportionately to the viscosity but exponentially (to the square of shear rate) with increasing engine speed. However, among other advantages, higher speed engines permit greater fuel economy, consequently reducing the viscous effects of the engine lubricants is even more desirable.

The Viscosity Gate to Improved Fuel Efficiency - For a decade and more, among other efforts, engineering attention has been given to reducing the viscosity of the engine oil without losing hydrodynamic protection of lubricated surfaces. Finer manufacturing tolerances and closer fitting parts have helped by making engines more hydrodynamically stable in operation. As a consequence, the engine has become more and more of a very mechanically complex viscometer with most of the power loss attributed to viscous friction rather than mechanical friction. It has been estimated that 60% to nearly 90% of the modern engine's friction is viscous under normal highway driving speeds. All of these facts and figures clearly establish the need for inexpensively and readily predetermining the potential energy absorption of a lubricant.

Initial Thoughts on an Algorithmic Approximation

Early Studies - Some of the author's earlier work in relating high shear rate viscometry to fuel efficiency with engines of that day **[1, 2, 3, 4]**, led to an interesting discussion several years ago with Marvin Smith (retired, previously of Exxon Chemical). He and the author were discussing the remarkable improvements in engine design which were, as mentioned, creating engines that behaved as energetic viscometers. Both agreed that the level of viscosity dependence of these engines, would make a predictive algorithm valuable in determining the fuel efficiency potential of an engine oil with much more precision and much less expense than engine or vehicle tests.

The Tapered Bearing Simulator Viscometer - Instrument for the Algorithm - In the above conversation, it was noted, that the data for such an algorithm could be generated by using the high shear rate Tapered Bearing Simulator (TBS) Viscometer. Smith, earlier for his company, had commissioned the author's company to develop this viscometer for simulation of the operating viscosity levels of multigrade engine oils in engine bearings (thus the name). The author and his associates developed the device in the late 1970s **[5, 6, 7]** and later patented it **[8]** as the first commercial, high shear rate instrument.

The original instrument was capable of being adjusted to any shear rate between 50,000 to 3,000,000 sec^{-1} and shear rates could be set to any desired intermediate shear rate during operation of the TBS. This has given the instrument the unique status of being an absolute viscometer **[7]** capable of determining viscosity from basic physical parameters without first being calibrated (although, for ease, the latter technique is most often used).

In 1995, a TBS Viscometer having a dialable broad range of very high shear rate was introduced to the field **[9]**. The entire range available is from shear rates of 50,000 to 7,500,000 sec^{-1}. The torque capacity was doubled to over 25 cP at 1,000,000 sec^{-1} and this set the stage for accomplishing the algorithmic approach.

On his own, the author again picked up the challenge of developing and applying an algorithm. This paper presents that approach and data.

2. Development of the Algorithm

The Viscosity Loss Trapezoid

Another application of the TBS Viscometer (that indirectly prepared the way to the fuel efficiency algorithm) was the Viscosity Loss Trapezoid (VLT) **[10, 11, 12]** used to determine the vulnerability of an oil to mechanical degradation (as well as to approximate the molecular weight [MW] distribution before and after degradation). The VLT required the measurement and comparison of the viscosities of engine oils and other lubricants at both low and high shear rates of 200 and 1,000,000 sec^{-1}. For more information on the behavior of VI Improvers the VLT is run at both 100° and 150°C.

Fortunately for the author's work on the fuel efficiency algorithm, the Institute of Materials Engine Oil Database has been publishing the VLT at both temperatures for some time.

The Engine and Its Viscosity- and Temperature-Affected Components -- Data for the Algorithm

Critical Information - Two pieces of information are required, to the author's thinking, in order to develop a meaningful algorithm for fuel efficiency. The first is to determine the energy lost at all important lubrication sites in the engine. The second is to denote the temperature at which these sites operate in normal, steady-state engine operation. With this information, and the viscosities of the oils at these temperatures, the author could determine the viscous effect on fuel efficiency.

Shear Rate - Another variable is the shear rate of each of the lubrication sites. Each lubrication site has its own operating shear rate which may vary somewhat from one another. The author elected to use one shear rate value, 1,000,000 sec^{-1} as an approximation of all main engine sites.

The Major Engine Sites and Their Energy Loss - A study of the several engine sites of greatest contribution to viscous energy loss was included in a book written by Richard Stone in 1993 (2nd Ed.) **[13]**. The contribution of each major lubricated area of the engine to friction power loss was obtained by isolating effects of that engine component by progressively physically subtracting them from a motored engine.

Figure 1 shows these five major areas and the viscosity-related power loss associated with them in the operating

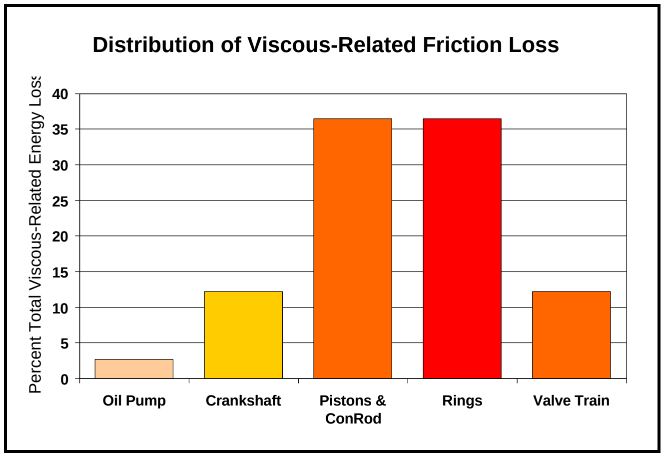


Fig. 1 Viscous-related power loss distribution among five major engine components

engine. (In the development of the algorithm no other forms of major energy loss such as pumping loss was relevant to the algorithm.)

Considering these viscous-related values for the moment as being intrinsic to the "universal" modern engine, it remains to find out how these values vary collectively for a given oil and what responses are exhibited by different oils having different viscosities and viscosity-temperature relationships affecting their viscous-related fuel efficiency.

Determination of Temperature - A reasonable choice for temperature may be made for each of the five sites of lubrication shown in Figure 1. Obviously, temperatures will be somewhat different for each engine design. However, any algorithm is an approximation and the author was at this point interested in building a generally applicable algorithm appropriate, if not exact, for a number of modern passenger car engines. Figure 2 shows the temperatures chosen for the five sites. (Since this is a first attempt by the author to develop an algorithm for fuel efficiency and since the temperature of the major area of lubrication are important, he would be grateful for any information adding to or correcting these assumptions.)

Viscosity Determination - Each of these sites of power loss are affected by the viscosity of the lubricant. In view

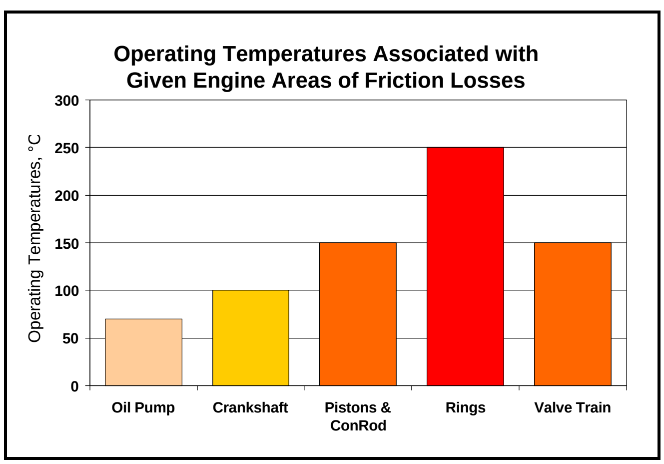


Fig. 2 Temperatures assumed for the five lubrication sites

of the different temperatures affecting the viscosity at each site, the question was "what is that viscosity?".

The technique used by the author was to obtain the TBS Viscometer values on the oils at 100° and 150°C in the Institute of Materials (IOM) Engine Oil Database. He then applied the MacCoull-Walther-Wright equation to both interpolate and extrapolate the viscosity data to the desired temperature values for each oil. (Previous experience by the author indicated that this was, in fact, an acceptable approach for engine oils he tested.)

The Algorithmic Statement

Assuming that the ratios of the viscous-related power losses one to another are constant with any engine oil in the IOM database, the following statement for the Fuel Efficiency Index was used:

Fuel Efficient Index = the sum of the power loss contributions of the major sites, each multiplied by the calculated viscosity of the oil at that site

It should be noted that the Fuel Efficiency Index value decreases with improvement in viscous fuel efficiency.

3. Application of the Algorithm

Institute of Material Database Information

The Institute of Materials (IOM) Engine Oil Database for the years 1999 and 2000 in three areas of the world were used to obtain the desired TBS viscosities at 100° and 150°C. The three areas were North America, Europe, and Asia.

All data reported from the IOM database is with their permission. As mentioned previously, the author's analysis encompassed 1300 engine oils.

Analysis Using the North American IOM Database

Applying the algorithm to the oils from North America for the years 1999 and 2000 gave the results shown in Figure 3.

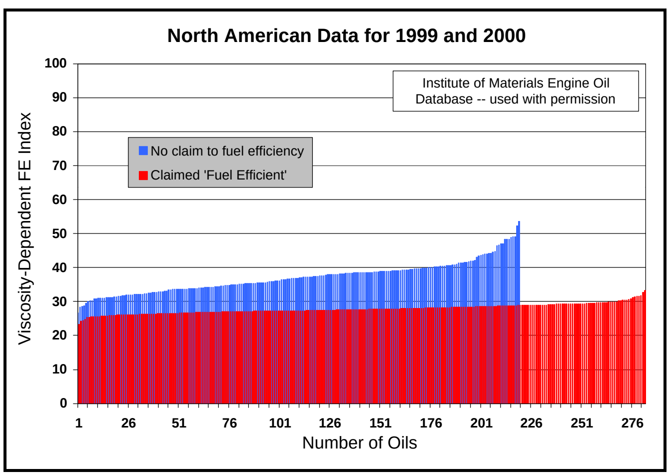


Fig. 3 North American Fuel Efficiency Index values for the years 1999 and 2000

Several observation may be made. Of these, the most important is that when the overall Index data are separated into oils that claim fuel efficiency and those that do not, there is a clear separation in the values -- essentially at about a FE Index of 30. As shown in Figure 3, the separation between the two curves gets less with improving fuel efficiency (decreasing values of the Fuel Efficiency Index). From this, and particularly in North American oils, the Index algorithmic approach looks promising. Appendix 1 further and strongly supports the algorithm.

Analysis Using the European IOM Database

Using the same approach on the oils collected from the market in Europe during 1999 and 2000, Figure 4 is obtained.

The European data differ considerably from the data of North America. First of all there are not as many claimed "Fuel Efficient" oils in Europe. Of these a fair number would probably fail to meet the engine test standards. The values for claimed fuel efficient oils are very near those with no such claim and some of the oils not claimed to be fuel efficient are better than some of the claimed fuel efficient oils. Almost all of the oils have Fuel Efficiency Indexes above 30.

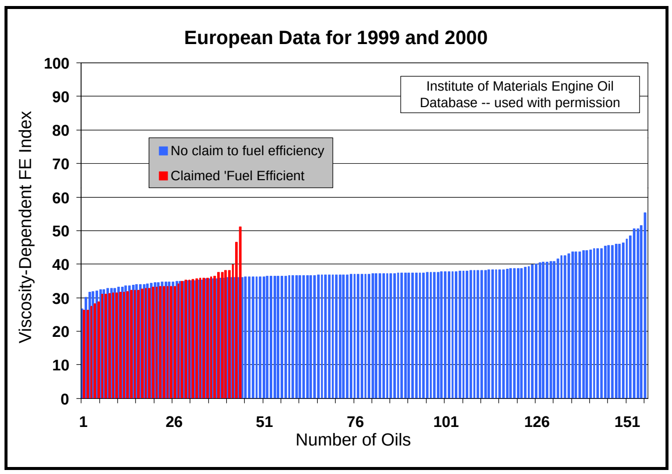


Fig. 4 European Fuel Efficiency Index values for the years 1999 and 2000

In summary, compared to the North American engine oils, the claimed fuel efficient oils are less promising in their algorithmic value of Fuel Efficient Index.

Analysis Using the Asian IOM Database

Considering the forgoing information on the Index, the Asian database information was anticipated to be most interesting. The data are shown in Figure 5.

Essentially, the data are similar to European oils. The oils claiming to meet fuel efficiency standards have Fuel Efficiency Index values very similar to those oils making no claim. Again, a number of those claimed to be "fuel-efficient" are actually poorer in this respect than the oils making no claim.

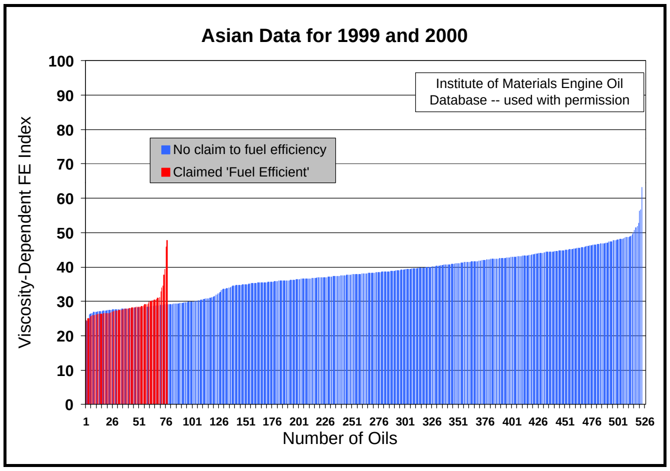


Fig. 5 Asian Fuel Efficiency Index values for the years 1999 and 2000

However, it may be noted that a number of both claimed and non-claimed fuel-efficient oils have FE Indexes less than 30 and there is a relatively sharp rise from an FE Index value of 30 to about 35 for the non-claimed fuel-efficient oils.

4. Discussion

The Validity of the Fuel Efficient Index and Its Algorithm

Results of Application **-** In general, the Fuel Efficient Index seemed to separate engine oils cleanly in the North American Database analysis. This would be expected in a portion of the world where the emphasis is so high on mandated government fuel efficiency standards.

Just as evidently, in Europe and Asia where such emphasis is not yet as severely placed on oils, there are proportionately fewer oils carrying the "Fuel Efficient" mark. Similarly, there is also little difference found in the Fuel Efficient Index values between those oils that carry the mark and those which do not.

Assumptions Used in the Algorithm - A number of assumptions were used in formulating the algorithm producing the Fuel Efficient Index. Among these are:

1. that viscous friction is the major component of power loss in modern engines outside of pumping losses.

2. that relatively recent studies of such power losses also apply to modern engines.

3. that using a single high shear rate for all viscous power loss sites is acceptable.

4. that the temperatures assumed for the power loss sites are reasonably correct.

5. that the viscous friction of the engine can be determined from very high shear viscometry at various temperatures appropriate to the given engine component.

6. that high shear rate viscometry values are subject to the MacCoull, Walther, Wright equation.

The author believes that these assumption and results when applied to three large engine oil databases. However, it must be considered that this is a first approach to the concept and refinement is certainly anticipated with better friction data and, particularly, engine test data and oils with which to compare results.

Plans are being made to apply the Fuel Efficiency Index to a number of selected oils from the databases to further test the concept. In anticipation of some of that work, Appendix 1 shows application of the Fuel Efficiency Index to the North American SAE grades.

5. Conclusions

An algorithm for determining the viscosity-related fuel-efficiency contribution of an engine oil has been developed. Although the algorithm required assumptions, when applied to a large engine oil database published by the Institute of Materials, the results seemed reasonably consistent.

More studies are being planned.

6. Bibliography

[1] Heritage, J.; Johnson, S.I.; Selby, T.W., **Dynamometer studies of the fuel efficiency effects of engine lubricants - Part 1 - Apparatus and approach,** *SAE Fuels and Lubricants Meeting*, Paper #810800 Dearborn, MI, USA (1981).

[2] Black, T.H.; Heritage, J.; Johnson, S.I.; Selby, T.W., **Dynamometer studies of the fuel efficiency effects of engine lubricants - Part 2 - Influences of engine variables,** *SAE Fuels and Lubricants Meeting*, Paper #811189 Tulsa, OK, USA (1981).

[3] Selby, T.W. and Piasecki, D.A., **High shear viscometry and fuel efficiency**, *SAE International Congress and Exposition*, Paper #820510 Detroit, MI, USA (1982).

[4] Piasecki, D.A., and Selby, T.W.., **High shear viscometry and fuel efficiency**, *SAE International Congress and Exposition*, Paper #821224 Toronto, Ontario, Canada (1982).

[5] Piasecki, D.A.; Selby, T.W; Smith, M.F., **Development and performance of the Tapered Bearing Simulator for high-shear, high-temperature viscometry**, *SAE Fuels and Lubricants Meeting*, Paper #811225 Tulsa, OK, USA (1981).

[6] Selby, T.W. and Piasecki, D.A., **Development and performance of the Tapered Bearing Simulator Viscometer**, *SAE/ASTM Symposium*, Toronto, Ontario, Canada (1982).

[7] Selby, T.W. and Piasecki, D.A., **The Tapered Bearing Simulator - an absolute viscometer**, *SAE International Congress and Exposition*, Paper #830031 Detroit, MI, USA (1983).

[8] Tapered Bearing Simulator, *U.S. Patent #4,445,365*, T. W. Selby (1982).

[9] Selby, T.W. and Miiller, G., **Very high shear rate viscometry**, *International Tribology Conference*, Yokohama, Japan (1995).

[10] Selby, T.W., **The Viscosity Loss Trapezoid**, *Eighth International Conference on Viscometry of Automotive Lubricants*, Sponsored by Savant, Inc., Dearborn, MI, USA (1991).

[11] Selby, T.W., **A method of generating and appraising the five viscosity loss parameters of lubricating oil - the Viscosity Loss Trapezoid**, *Eighth International Colloquium Tribology*, Proceedings Supplement (1992) Section 4-4, p.1-14.

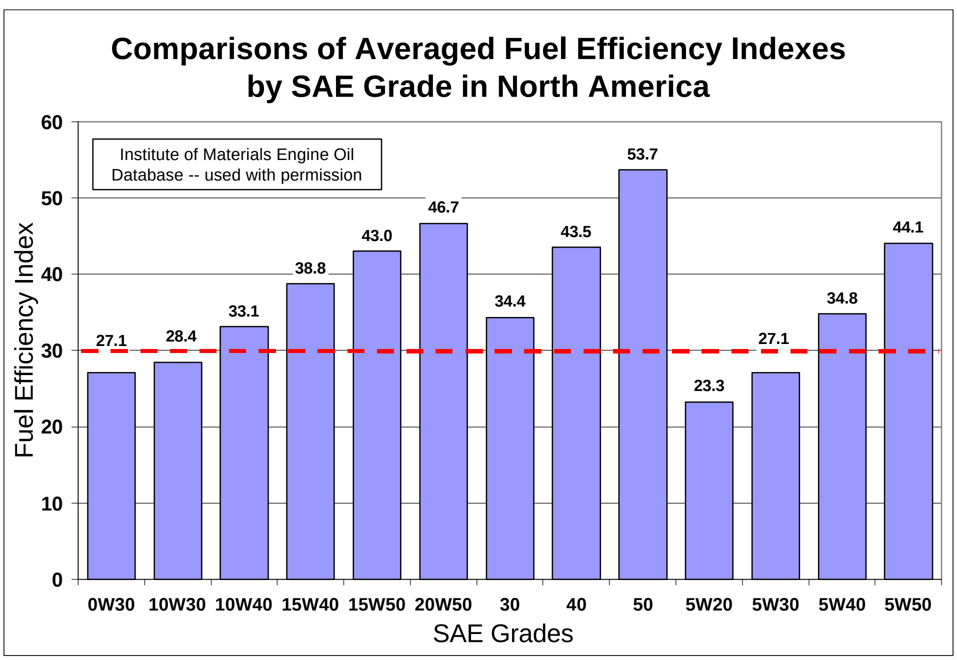
[12] Selby, T.W., **The Viscosity Loss Trapezoid - Part 2: Determining general features of VI Improver molecular weight distribution using parameter of the Viscosity Loss Trapezoid**, *SAE International Fuels and Lubricants Meeting and Exposition*, Paper #932836, Philadelphia, PA, USA (1993).

[13] Introduction to Internal Combustion Engines, 2nd Edition, Author: Richard Stone (1993).

Appendix 1

The degree of validity of the Fuel Efficiency Index is best shown when applied to oils classified by the SAE Engine Oil Classification System. All oils from the North American Engine Oil Database for the years 1999 and 2000 were divided according to their viscosity classification and these were then averaged. The following graph compares their collective Fuel Efficiency Index with a dashed line at a value of the FE Index of 30 which seems to be a level of separation in North America.

It is evident from Appendix Figure 1 that the various grades fall in reasonable order in relation to one another. It is also evident that at fully warmed-up, steady-state conditions assumed for the calculation of the Fuel Efficiency Index, there is not much difference between an SAE 0W30 and a 5W30. However, in discussion of the foregoing paper, the author was encouraged to apply the concept and a somewhat different algorithm to account for temperature conditions of short-trip driving which is the predominant mode of North American automotive use. This aspect will be considered in another paper.



Appendix Fig. 1 Comparison of the Fuel Efficiency Index of all SAE Grades in North American Engine Oil Database.