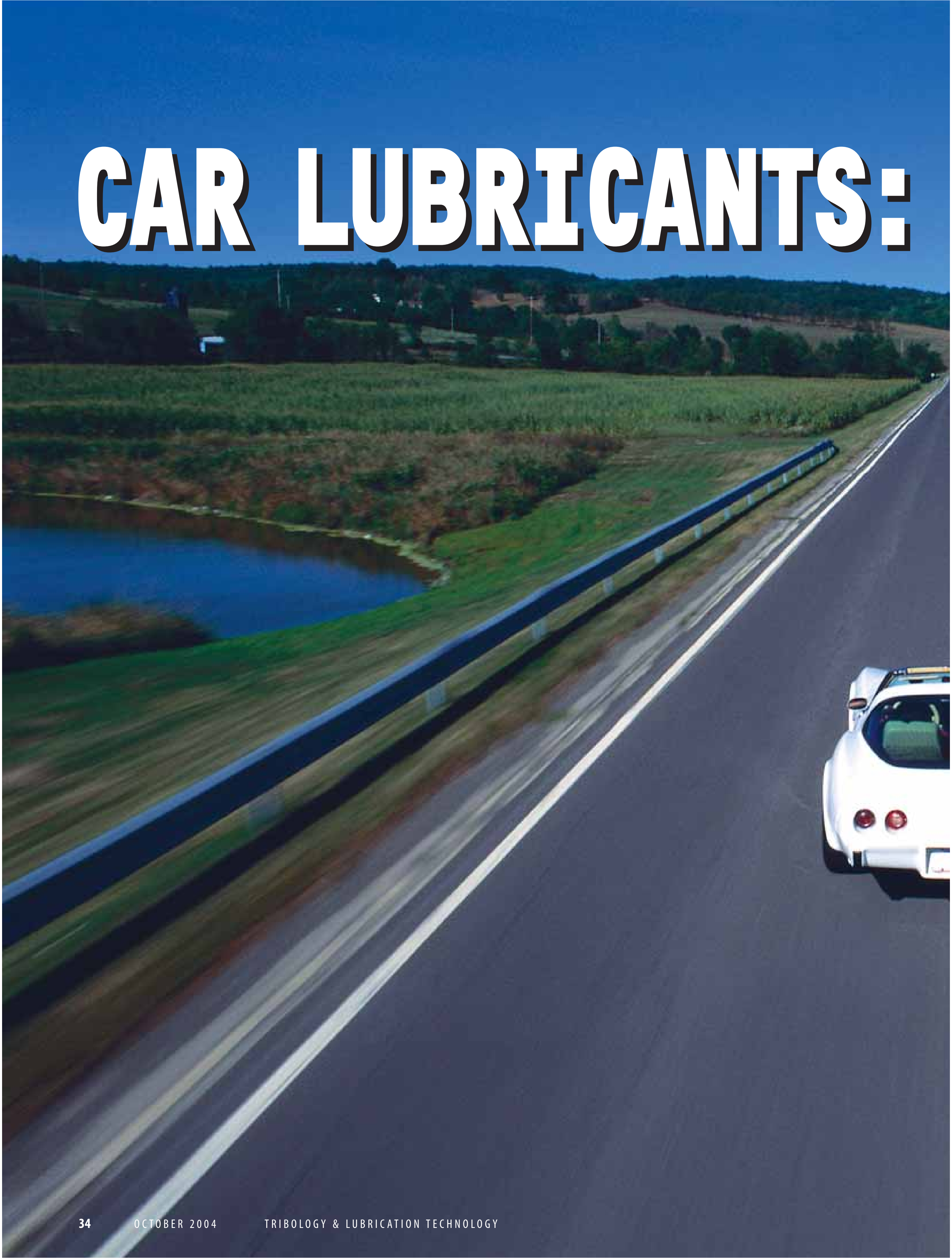
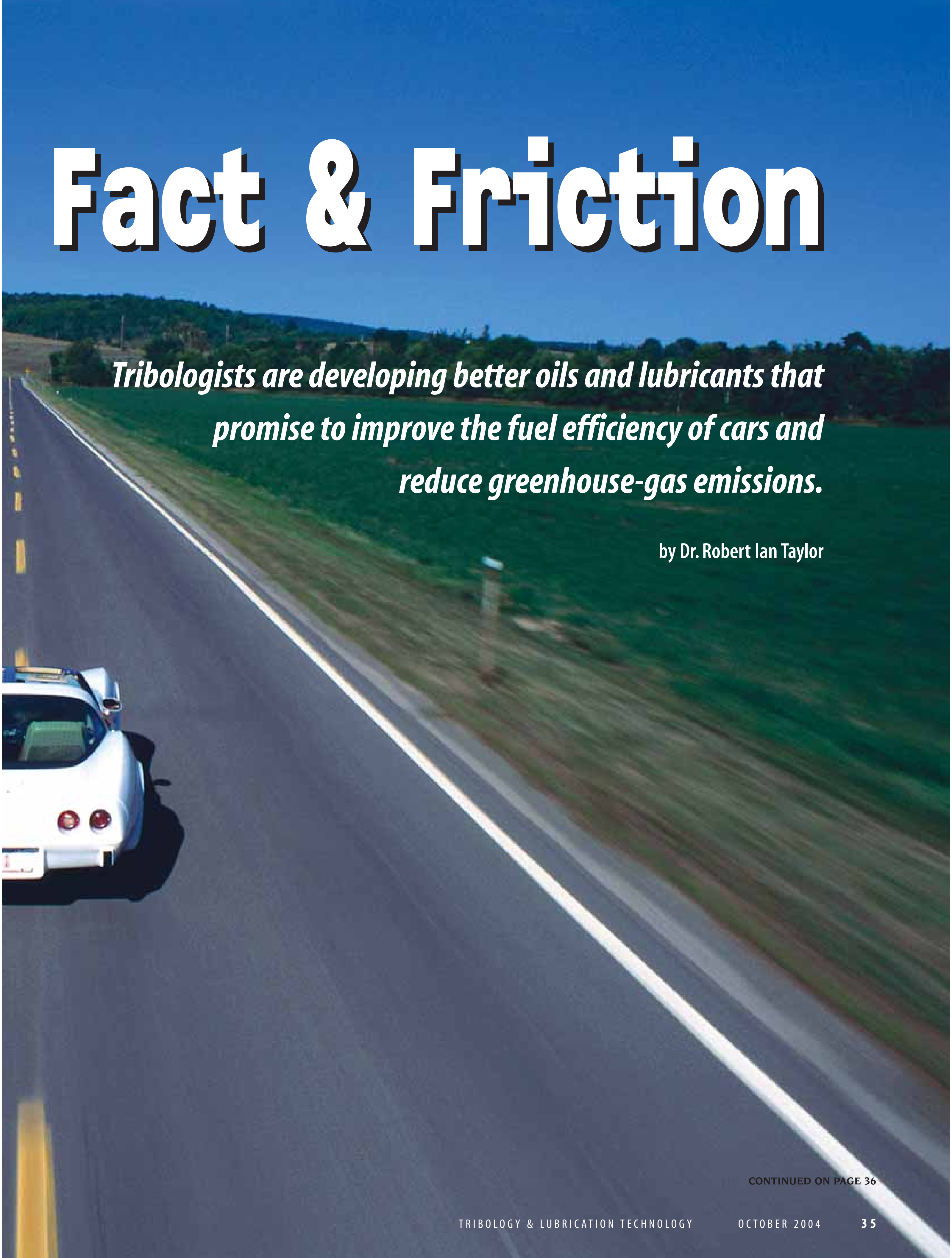
CAR LUBRICANTS:





Fact & Friction

Tribologists are developing better oils and lubricants that promise to improve the fuel efficiency of cars and reduce greenhouse-gas emissions.

by Dr. Robert Ian Taylor

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Lubricants are essential in modern life. Car engines and gearboxes run smoothly thanks to sophisticated oils and greases, while computer hard disks rely on thin organic films to ensure the read/write head can move reliably at high speeds across the recording medium.

According to some analysts, however, the direct cost of friction and wear can account for nearly 10% of GNP in many industrial nations. Moreover, they estimate that cost savings of up to 1% of the GNP could be achieved simply by using the right lubricant for the job.

Lubricants are remarkable fluids. During winter in Detroit, for example, the same engine oil has to operate reliably over temperatures ranging from -40 C to above 250 C, the temperature near the top piston ring. It also has to cope with pressures between 10^5 and 10^9 pascals, as well as contaminants including metal particles and soot. The final straw is that this fluid must deal reliably with these conditions everyday for up to two years, which is the recommended time between oil changes, according to some vehicle manufacturers.

Surprisingly, one of the major driving forces behind the development of lubricants is the environment. Modern vehicles are required to emit much less pollutants than older cars and trucks. Indeed, the emissions from a typical modern vehicle are some 50 times lower than those manufactured in the 1960s.

Carbon dioxide is a natural by-product arising from the combustion of fuel and is among the most significant pollutants being targeted for reduction. Indeed, vehicles that have a high fuel consumption emit large amounts of carbon dioxide. However, the European Union is taking a strong lead in tackling this problem and has indicated that the fleet average carbon dioxide emission (for cars) should be reduced from today's average figure of around 200 grams per km to less than 140 grams per km in 2008. This is roughly equivalent to improving the average fuel consumption from 33 to 47 miles per gallon. Such an increase would lead to big cuts in carbon dioxide. In the UK alone, where there are roughly 20 million passenger cars, each covering an average of 16,000 km per year, the total annual drop in CO_2 would be around 19 million tons.

Clearly manufacturers are making a number of engineering changes to their vehicles to improve fuel economy. Less well known, however, is the fact that fuel consumption can be significantly improved just by changing the lubricants. For example, it is possible to decrease the amount of fuel consumed by modern cars by up to 5% simply by switching from typical multigrade oil to a "friction-modified" lubricant of lower viscosity. This would lead to an annual CO_2 drop of roughly 3 million tons in the UK. Greater CO_2 savings are clearly possible if optimised lubricants also were used in trucks and in other machinery.

WHAT IS A LUBRICANT?

Car lubricants play four major roles: They control friction and wear in the engine, they protect the engine from rusting, they cool the pistons, and they protect the engine oil in the sump from combustion gases.

Some 75%-95% of a typical engine lubricant is made up of a base oil—a mineral oil that has come directly from a refinery. These base oils can naturally contain straight or branched chains of hydrocarbons—hydrocarbon molecules with aromatic rings attached—or these chains can be produced by further chemical processing of the natural base oil.

The remainder of the lubricant comprises a variety of additives used to improve performance. Typically these include antiwear

Table 1. Typical viscosities of common lubricants as graded according to the Society of Automotive Engineers' (SAE) J300 classification scheme. A multigrade oil described as SAE-15W/40, for example, is a 15 grade at low temperatures and a 40 grade at high temperatures. For an oil to be a 15 grade, the dynamic viscosity has to be less than 3500 mPa.s at -15 C, while the kinematic viscosity of a 40 grade oil must be between 12.5 and 16.3 cSt at 100 C.

Viscosity Grade	Kinematic viscosity at 40 C (cSt)	Kinematic viscosity at 100 C (cSt)	Estimated dynamic viscosity at -15 C (mPa.s)
SAE-20W/50	144.8	17.8	5,870
SAE-15W/40	114.3	14.9	2,940
SAE-10W/30	72.3	10.8	1,900
SAE-5W/30	57.4	9.9	1,090
SAE-0W/20	44.4	8.3	690
SAE-30	91.3	10.8	3,950

additives, corrosion inhibitors, antioxidants, detergents, dispersants, antifoam additives and large polymer molecules known as viscosity modifiers, which are added to improve the viscosity variation of the lubricant with temperature.

Indeed, the viscosity is the most significant physical property of a lubricant. The way in which it varies with temperature, shear rate and pressure determines to a great extent how the lubricant performs in an engine. But the chemistry of the lubricant is also important. The lubricant must be resistant to oxidation, and the lubricant also needs to lay down protective films to combat wear and tear in regions where metallic contact is inevitable.

The behavior of an oil film trapped between two moving surfaces is quantified by the dynamic viscosity, which is measured in units of millipascal seconds (mPa.s). More accurately, the dynamic viscosity relates the shear stress (the shearing force acting on the oil per unit area) and the shear rate (the difference in speed between the two moving surfaces divided by their separation). However, it is often more convenient to measure a quantity known as the kinematic viscosity, which is the dynamic viscosity divided by the fluid density and is measured in mm^2s^{-1}, or centiStokes (cSt).

Lubricants fall into two broad categories: monograde and multigrade, depending on how their viscosity changes with temperature. The Society of Automotive Engineers (SAE) has devised a detailed viscosity classification system. One common lubricant grade is described, according to this scheme, as an SAE-10W/30 multigrade. The first number (10W) refers to the dynamic viscosity measured at low temperatures, while the second number (30) describes the kinematic viscosity at 100 C.

Lower numbers describe "runnier" lubricants. The viscosity of an SAE-5W/30 multigrade, for example, is roughly five times lower than that of an SAE-20W/50 at -15 C. Roughly speaking, the energy lost due to friction in an engine varies as the square root of the viscosity. At -20 C the friction losses of the low-viscosity oil will be approximately half those of the thicker oil, allowing the engine to start more easily.

The viscosity grade of a multigrade oil is different at high and low temperatures due to additives known as viscosity modifiers. SAE-10W/30 has a similar viscosity to the monograde lubricant SAE-30 at 100 C. At lower temperatures, however, SAE-10W/30 is much thinner than the SAE-30 monograde oil. This means the multigrade oil provides protection at high temperatures and yet is runny enough at low temperatures to enable easy engine starting.

WELL-OILED COMPONENTS

In a typical gasoline internal-combustion engine, fuel enters the combustion chamber when an inlet valve opens. This valve then closes, and the piston moves upwards, compressing the fuel-air mixture. When the piston reaches its highest position, the spark plug is activated and combustion occurs, pushing the piston back downwards. The translational motion of the piston is

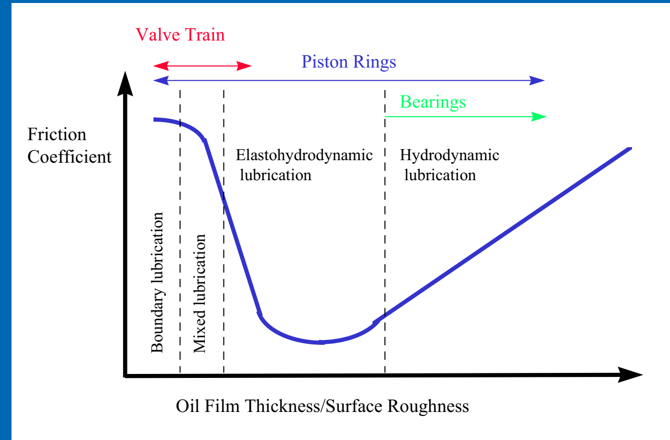

Figure 1. Schematic variation of the friction coefficient as a function of oil film thickness divided by the surface roughness. Four distinct lubrication regimes are observed. Some components, such as the engine bearings, operate mainly in the hydrodynamic lubrication regime, while other components undergo two or more different types of lubrication.

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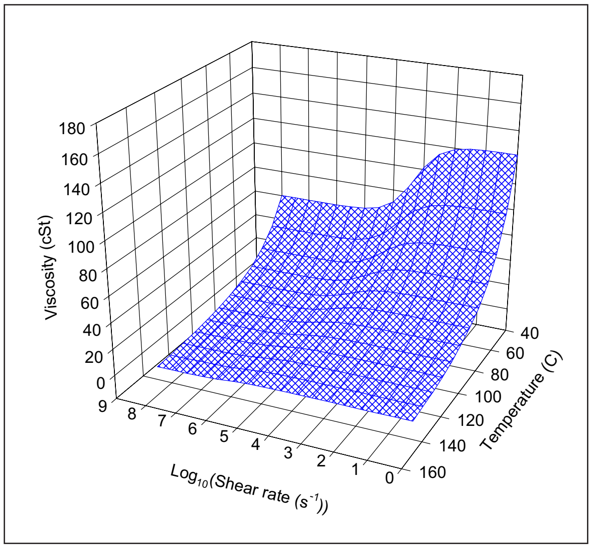

Figure 2. The viscosity of an SAE-10W/50 engine lubricant as a function of shear rate and temperature. In general, the oil becomes thicker at lower temperatures and small shear rates. The viscosity decreases at high shear rates due to the addition of viscosity modifiers, long hydrocarbon molecules that align in the direction of the shearing force.

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then converted into rotational motion via the connecting rod and the crankshaft bearings.

For an engine to work effectively, contact between the cams (which push the valves controlling the inlet and outlet to the combustion chamber) and the tappets must be adequately lubricated so that the components do not wear excessively. A complete oil film must also be formed between the piston rings and the piston liner to prevent wear, to seal the combustion-chamber gases from the rest of the engine and to minimize friction losses. Finally, a thick film of oil must cover the engine bearings so the metal surfaces in the bearing do not come into contact.

Typical engine oil is carefully formulated to protect the valve train, the bearings and the piston assembly, despite the different lubrication requirements of these components. In fact, the thickness of the oil determines its coefficient of friction and defines the distinct regions of lubrication (*see Figure* 1).

Engine bearings and the piston assembly mostly operate in the hydrodynamic regime, where a thick oil film separates the moving metal surfaces so that there is no chance of them coming into contact. When the piston is momentarily stationary, however, the layer of oil covering them can be similar in thickness to the surface roughness of the components. In this "mixed lubrication" region, the metal surfaces intermittently come into direct contact. If the thickness of the oil film is much smaller than the surface roughness then the metal surfaces can rub together repeatedly. This is known as "boundary lubrication." Contact between the cams and tappets in the valve train span the mixed and boundary regimes.

In the elastohydrodynamic lubrication regime, which occurs under high loads with hydrocarbon-based oils, the pressure developed in the lubricant is sufficiently high to elastically deform the metal surfaces on either side of the oil film. This happens because the viscosity of these fluids increases significantly with pressure. The valves and the piston rings also can operate in this lubrication regime.

Lubricants also are used in other important components in a vehicle such as the gearbox. This is a challenging environment where pressures routinely exceed 10^9 Pa and the gears operate in the elastohydrodynamic lubrication regime. Moreover, in many cars, the gear lubricant is filled once and then never replaced during the vehicle's lifetime. Researchers at Torotrak, in Leyland, England, are currently developing novel transmission systems that are effectively gearboxes with an infinite range of gearboxes. These continuously variable transmissions are designed to improve a vehicle's fuel efficiency by enabling the engine to operate at more efficient speeds and load. These novel transmissions require lubricants with high friction coefficients.

Greases are also commonly used to lubricate the constant velocity joints that connect the axles to the drive wheel while allowing the suspension to move up and down. These joints are critical components in many current models of four-wheel-drive and sports-utility vehicles and they therefore require high-performance greases.

MEASUREMENTS SMOOTH THE WAY

Most engine manufacturers design their components to operate with oils and greases within a certain viscosity range. Therefore, it is important to measure the properties of lubricants accurately. The kinematic viscosity of an oil is usually determined under low shear rates, simply by measuring the time the meniscus takes to flow vertically downwards, under gravity, between two marks on a capillary tube. Different diameter capillary tubes are used for thinner or thicker oils.

Meanwhile, the dynamic viscosity is usually measured under high shear conditions and at the high temperatures typical of those found in bearings and other critical contacts in engines. Instruments in which a thin film of oil is trapped between two surfaces moving relative to each other carry out these measurements. For example, in a rotating cylinder viscometer, the dynamic viscosity is estimated from the shear torque produced on a stationary inner cylinder by a rotating outer cylinder. Another instrument that is used for measuring the dynamic viscosity of very small quantities of lubricant comprises a conical surface rotating against a flat plate.

These measurements also can tell us something about how the viscosity varies with shear rate. Our group at Shell Global Solutions and others, including Jagadish Sorab, at Ford Motor Co., have fitted such data to realistic equations that describe how the viscosity varies with both temperature and shear rate as shown in Figure 2. We have found the viscosity of a typical engine lubricant decreases at high shear rates. The reason is the large polymer molecules used as viscosity modifiers line up in the direction of the shear force at high shear rates. This alignment reduces the "thickening" effect that these polymers have when they are randomly aligned.

Indeed, non-equilibrium molecular-dynamics simulations of model lubricants carried out at Shell in the early 1990s clearly showed how the molecules line up when a high shear rate is applied to the fluid (*see Figure* 3). This effect, however, is temporary. The viscosity returns to its previous value when the shear rate is reduced.

Crucially for automotive applications, these types of experiments also have revealed how the viscosity of a lubricant varies with pressure. For example, the viscosity of a typical lubricant at 500 MPa can be between 10,000 and 100,000 times higher than that at atmospheric pressure. Not to mention, the viscosity increases exponentially with pressure. This exponential variation is known as Barus's law and is valid at pressures up to a few hundred megapascals. At very high pressures (2-4 GPa), however, this simple relationship tends to overestimate the increase in viscosity. Instead the lubricant becomes glass-like and behaves more like a solid than a liquid, deforming the metal surfaces on either side of the lubricant elastically—this is the elastohydrodynamic lubrication regime.

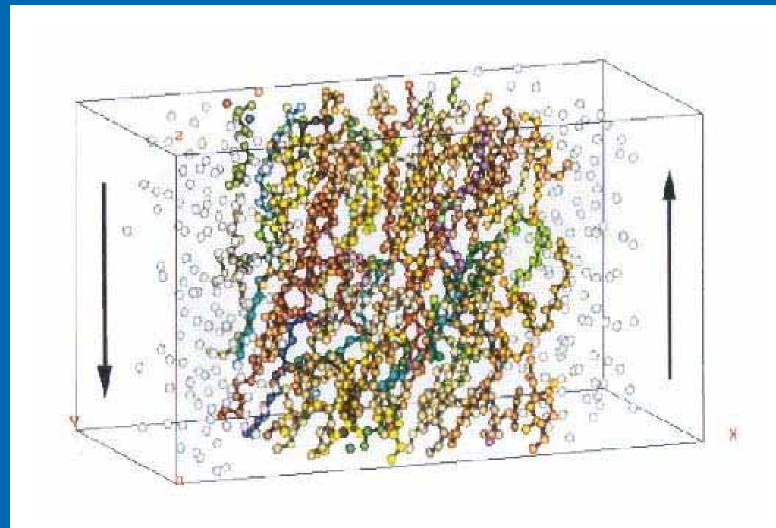

Figure 3. Non-equilibrium molecular-dynamics simulations confirm that the hexadecane molecules in this model lubricant temporarily align in a shear field.

ELASTIC EFFECTS

Other optical and mechanical techniques have been developed to investigate the behavior of oils and greases in the elastohydrodynamic region. One of the most common instruments used for this purpose is the so-called ball-on-plate-rheometer, which has been used extensively by Dr. Hugh Spikes' group at Imperial College in London. Essentially, the instrument consists of a steel ball that is pressed against a transparent rotating disk made of glass or sapphire. As the disk rotates, the thickness of the oil film between the two components is measured by shining light through the transparent disk and monitoring the resulting interference fringes shown in Figure 4(a). When the ball is pressed lightly against the disk, the surface remains

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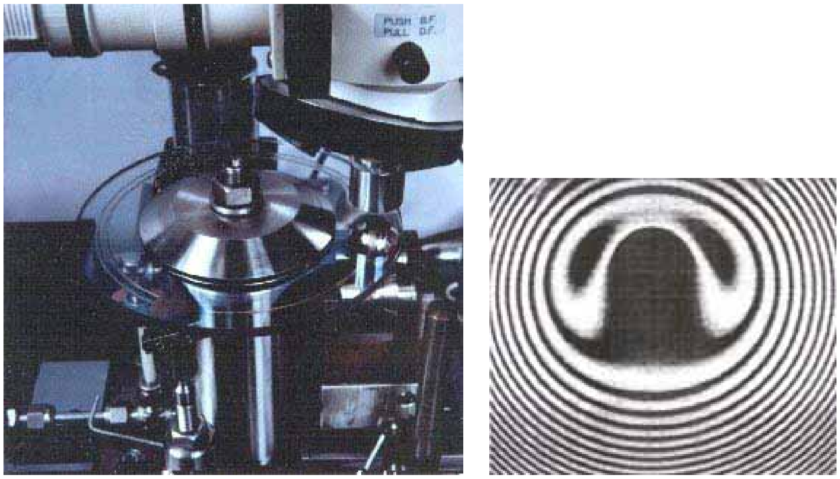


Figure 4. (a) A ball-on-plate rheometer used to measure the properties of lubricants in the elastohydrodynamic region. A steel ball is pressed against a transparent rotating disk made of glass or sapphire. As the disk rotates, the thickness of the oil film between the two components is measured by shining light through the transparent disk and monitoring the interference fringes. (b) This characteristic pattern of interference fringes shows that the thickness of the oil film at the center of the contact is approximately constant, while the film at the edges is thicker.

unaltered and a series of concentric circles is observed. However, if the ball is pressed hard against the disk, then the plate deforms elastically, as shown by the characteristic horseshoe-shaped interference pattern in Figure 4(b). This shape indicates the thickness of the oil film at the center point of the contact is approximately constant, while the increase in the number of fringes outside the central region demonstrates the film is thicker at the edges. In this elastohydrodynamic region, the flat central region behaves in a similar way to a ball of Plasticine pressed against a flat surface, with the difference that the surfaces return to their original shape when the pressure is removed.

Elastohydrodynamic lubrication occurs in gears, in valve trains and in the rolling-element bearings found in wheel hubs, which have to cope with large radial and thrust loads with minimum friction. The ball-on-plate-rheometer is, therefore, ideal for evaluating the performance of lubricants under the realistic conditions found in many machine components.

Other methods for measuring the viscosity of lubricants under high pressures include the falling ball experiments pioneered by Dr. Bo Jacobsen (now at Lund University in Sweden) and co-workers in 1985. In these experiments a steel ball is dropped either vertically, or more commonly at an angle, onto a plate smeared with a drop of oil or grease. Pressures of up to 7.5 GPa can be created in the lubricant film in this way. And the coefficient of friction can be determined from either the motion of the ball after contact or from force transducers on the surface. Different lubricants have different friction coefficients because of the way the viscosity varies with temperature, shear rate and pressure and also due to the different combination of lubricant additives.

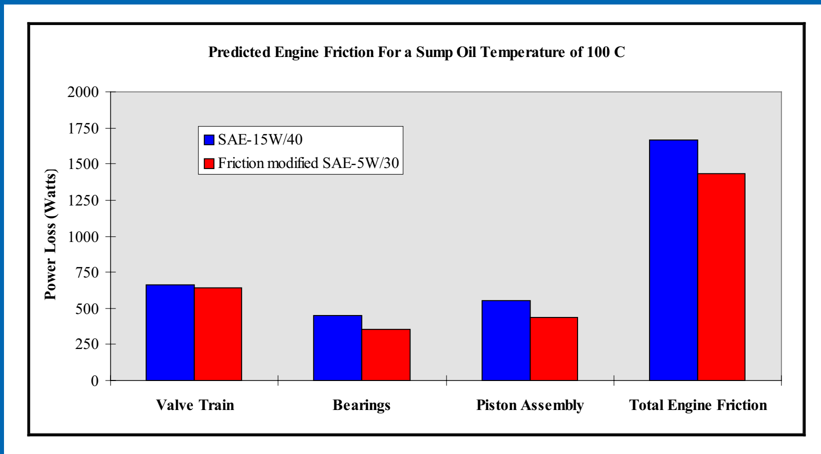
It is worth mentioning that many lubricants also exhibit elastic effects. In other words, their behavior cannot be fully explained just by assuming they are purely viscous fluids. Grease, for example, is viscoelastic. Under certain conditions it behaves as a viscous fluid when it flows freely in a pipe under an applied pressure. On other occasions it behaves like a solid prior to flowing. Most other commercially available lubricants also exhibit viscoelastic behavior.

Rheometers also can be used to measure viscoelastic properties as well as viscosities. However, little is known about how the viscoelastic properties of lubricants vary with temperature, pressure and shear rate because these measurements are difficult to make for commercial lubricants that are only weakly viscoelastic. Several researchers such as Shell's Brian Williamson and Ken Walters at the University of Wales in Aberystwyth speculate that viscoelastic lubricants can be advantageous for the lubrication of bearings under extreme conditions.

GREASE-LIGHTNING SIMULATIONS

With the increased computer capacity that has become available over the last decade, it is now possible to accurately model the performance of lubricants in engines, gearboxes and other components. If we know the minimum thickness of the oil film, we can predict the durability of the component and the power loss due to friction. Thus, this capability can help researchers who are designing new lubricants predict how a machine's performance is related to lubricant viscosity and how it will be affected by temperature, shear rate and pressure.

The theory of elastohydrodynamic lubrication was first developed by Dr. Duncan Dowson at Leeds University and others in the 1950s when computer simulations were not possible. In elastohydrodynamic lubrication, both the fluid equations and the elastic deformation of the surfaces have to be modelled, and these complicated simulations can now be performed on modern



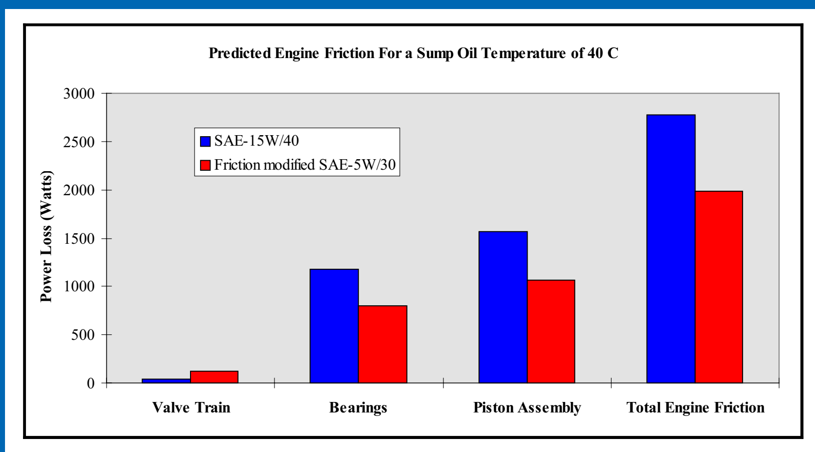


Figure 5. Computer models are now being used to predict the power lost due to friction in each engine component. The results can also be combined to estimate the total losses in this two-liter European gasoline engine operating at 100 C (top) and 40 C (bottom), and under medium load, at a speed of 2,500 revs/minute. Physicists and engineers can study the effects of two different lubricants, a friction-modified SAE-5W/30 (red) and a standard SAE-15W/40 grade (blue) at the different temperatures. The losses are higher at lower temperatures due to the losses that occur in the hydrodynamically lubricated components such as the bearings and the piston assembly. On the other hand, losses in the valve train decrease with the lower temperatures. The predicted difference in friction between the two different temperatures, around 40%, would correspond to a difference in fuel consumption of around 12% (this is why cold starts are bad for fuel consumption). The difference in friction between the two lubricants, at a given temperature, is smaller, but it is still possible to improve fuel consumption by up to 5% by moving to a lower viscosity, friction-modified engine lubricant. It is not always easy to demonstrate the fuel economy benefits in a vehicle field test due to other factors, such as weather conditions, engine conditions and driver behavior, which can be more significant than the effect of the lubricant.

computers relatively quickly. Meanwhile, hydrodynamic lubrication in plain bearings and piston rings can be analyzed in seconds. Modelling mixed and boundary lubrication is more difficult since we require a detailed understanding of the roughness of the surfaces as well as of the lubricant properties. In general, the output of the models is the minimum thickness of the oil film and the losses due to friction.

Many groups have accurately estimated the minimum oil film thickness in an elastohydrodynamic contact. However, estimating the friction coefficient has proved to be much more problematic due to the large variation of viscosity with pressure, which is not always accurately known. Recently, Shell's Laurence Scaleshas showed it is worth investing the effort to find accurate relationships between viscosity, temperature, pressure and shear rate because they allow both the minimum oil-film thickness and the friction coefficient to be estimated. To do this, however, requires at least eight parameters to describe the lubricant behavior.

But by combining models for the plain bearings, the piston assembly and the valve train, researchers have found they can model the lubrication conditions in a complete in-

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ternal combustion engine. Since the bearings and piston rings are lubricated predominantly in the hydrodynamic regime, a lubricant with a lower viscosity should lead to a thinner oil film and, thus, lower friction. However, the valve train operates in the mixed-boundary lubrication regime, which means lower friction can only be obtained with thicker lubricants. Engine friction models enable us to study the trade-off between viscosity, additive chemistry and friction and, therefore, help us select the optimum lubricant to improve a vehicle's fuel economy (*see Figure* 5).

FUTURE CHALLENGES

There are many challenges in developing the lubricants of the future. Cars are becoming more powerful, drivers would like to change the engine oil less frequently, and manufacturers want to reduce the losses due to friction still further. In order to develop lubricants that satisfy these customer demands, physicists and engineers have to understand the performance of the lubricant in more detail.

First, we need to fully understand the role that the elastic properties of lubricants play under extreme conditions. To do this we will need to measure the viscoelastic properties of lubricants at different temperatures, pressures and shear rates and develop suitable rheological models. Our current models are based on solution of the Reynolds' equation, which assumes the oil film is of the order of a few microns thick and the components are a few millimeters across. A more serious shortcoming of the Reynolds' equation is that it assumes elastic effects are not important.

The second major challenge is to better incorporate chemistry into physical models. After all, lubricants change chemically during their time in an engine. Simply speaking, a fresh lubricant is like a pure hydrocarbon. Over time it oxidizes and chemically degrades to form alcohols, ketones, aldehydes, acids and esters. These chemical changes can lead to viscosity increases and acid build-up, which can affect the lubrication performance.

CONCLUSIONS

Tribologists are playing an increasing role in addressing the environmental problems of pollution and global warming by developing more energy-efficient lubricants, which also last longer between oil drains. A better understanding of lubricants and lubrication requires both insight from tribological modelling and careful experimental measurements. The progress that is being made in lubricant research today will undoubtedly play a part in safeguarding the natural environment for many generations to come. **<<**

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