Lube-Tech
PUBLISHED BY LUBE: THE EUROPEAN LUBRICANTS INDUSTRY MAGAZINE
No.105 page 1

Fuel economy and lubricants in powertrain systems

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Abstract:
Tightening legislation on CO_2 emission highlights the need for actions from OEMs, Tier suppliers, and lubricant manufacturers to find ways to further improve fuel economy in commercial vehicles. This article examines challenges of fuel economy on development of lubricants used in powertrain systems based on understanding powertrain systems and their tribology systems. Development work indicates that an improved performance, in terms of service life and efficiency of powertrain systems to contribute fuel economy, could be achieved by a careful selection of additives to generate a synergistic effect between additives, additives with metal contact surfaces and additives with sealing materials. Based on the work in GKN Driveline, it is indicated that an improvement of fuel economy could be contributed from a team work between design of new generation of powertrain systems and development of new lubricants in the future.

Introduction:

In Briefing Paper 2015 from ICCT (International Council on Clean Transportation), it is outlined that the transport sector consumes more than half of global oil production, and releases nearly a quarter of all anthropogenic carbon dioxide emissions, (Ref.1). Motor vehicles and engines, especially those fueled with diesel, contribute to ambient air pollution responsible for millions of premature deaths worldwide each year. Consequently, fuel economy and CO_2 standards for new vehicles becomes one of the most important components for the world's future transport.

The world's first fuel economy standards were established in the United States and Japan in 1970s and 1980s. In 1990s, Europe established voluntary CO_2 standards for passenger vehicles that also required vehicle manufacturers to improve the fuel efficiency of new motor vehicles. Since the way to reduce CO_2 emission is to improve the fuel efficiency of the vehicle, it is considered that fuel economy and CO2 standards are interchangeable, (Fig.1, Ref.2 and 3). The updated global fuel economy trends concluded that, while global average fuel economy was improving, more needs to be done to meet the ambitious, yet realistic, target. In the international context, the EU has historically been a front-runner with respect to vehicle emission targets. In recent years, however, most large economies have specified converging CO_2 emission targets for new vehicles (Fig.1, Ref.3). Compared to the EU's 2020 target of 95g/km, the USA (97g/km for 2025 passenger cars), Japan (122g/km by 2020), Canada (97g/km by 2025) and S. Korea (97g/km by 2020) have set similar targets.

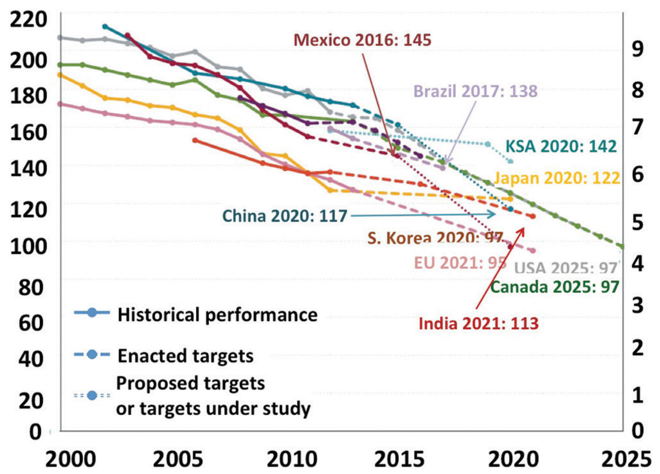

Figure 1. Comparison of global CO_2 regulations for new passenger cars (Ref.3)
Notes: Japan has already exceeded its 2020 statutory target, as of 2013.

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Energy saving in vehicles

Based on analysis of over 100 vehicles by Oak Ridge National Laboratory using EPA Test Car List Data Files, it is reported by U.S. Environmental Protection Agency that estimated energy loss is about 70% in engine, about 5% in parasitic system, 18 to 25% in power to wheels system and 5% to 6% in powertrain, (Fig.2, Ref.4). Report in Handelsblatt Euroforum shows that, by making the same percentage of reduction in weight change, drag coefficients, rolling resistance and energy consumption in powertrain respectively, the best reduction in fuel consumption could be achieved by a reduction in energy consumption in powertrain, (Fig.3, Ref.5). Technologies such as automated manual transmissions (AMTs), double-clutch, lock-up transmissions and continuously variable transmissions (CVTs) can reduce these losses.

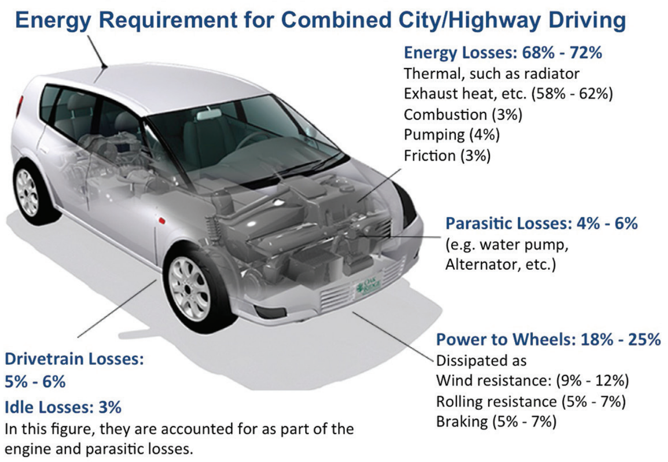


Figure 2. *Energy comparison during driving, (Ref.4).*

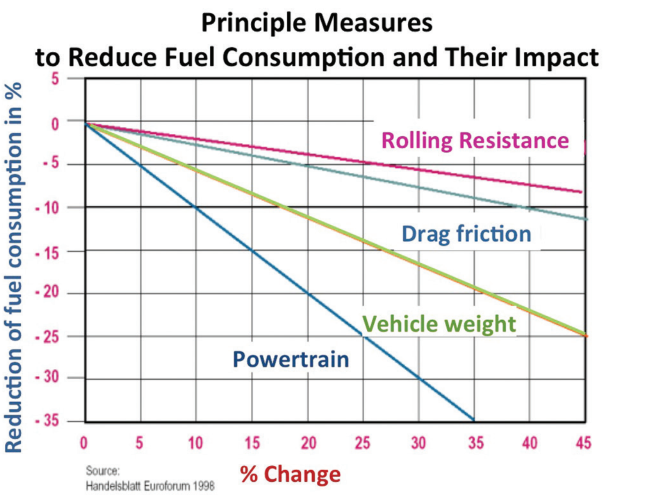


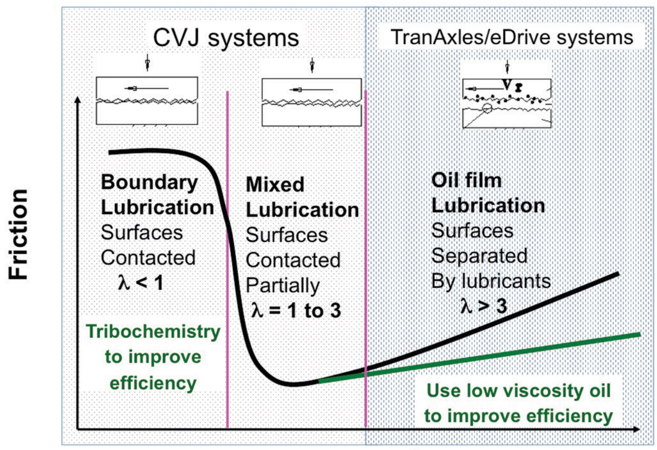
Figure 3. *A reduction of fuel consumption in vehicle from different consideration, (Ref.5).*

GKN Driveline is the world's leading manufacturer of automotive driveline systems to deliver optimum solutions accurately engineered to all specifications in powertrain, including constant velocity joint (CVJ) systems, all wheel driving (AWD) systems, transmissions and axles (TranAxles) systems and e-Drive systems. As a global business serving the leading vehicle manufacturers, GKN Driveline develops, builds and supplies an extensive range of automotive driveline products and systems with an improved efficiency – for use in the smallest ultra low-cost car to the most sophisticated premium vehicle demanding the most complex driving dynamics.

Tribology in powertrain system

Tribology is the science and engineering of interacting surfaces in relative motion. It includes the study and application of the principles of friction, lubrication and wear. In order to have good performance with enhanced life and improved efficiency, it is essential to understand tribology systems, including system requirements, system designs, materials, surface engineering, surface metrology, movement of parts and service conditions etc.

In GKN transmissions/axles systems and e-Drive systems, the tribology system is mainly working in a regime of full oil film lubrication conditions, (Fig.4). In this regime, two surfaces are fully separated by an oil film. A reduction of oil viscosity could decrease the internal shear force between oil molecules as a result of reducing friction and improving efficiency, (Fig.4). However, after a reduction of oil viscosity, the oil film thickness could decrease as a result of potential risk of surface damage under high pressures. At the same time, a protection of contact surfaces from surface damage becomes an important factor during starting movement in systems. Therefore the use of special additives is required.



$$L_b = \eta \frac{v}{Ra_t P} = \frac{h}{(R_1^2 + R_2^2)^{1/2}} \longrightarrow \lambda$$

Figure 4. *Key areas where GKN products perform.*

In modern CVJ systems, key parts perform in a regime of boundary lubrication conditions because the pressures are up to 8 GPa on the point contact surfaces in ball types of CVJs and 4 GPa on the line contact surfaces in tripod type of CVJs. At such high pressures, contact surfaces could be prevented from wear and cold welding with low friction by selecting proper anti-wear and extreme pressure additives and friction modifiers in greases as lubricants. Development of CVJ greases indicates that MoS2, MoDTP and MoDTC are widely used to reduce friction in order to improve efficiency for the fuel economy. ZDTP is used as a typical anti wear additive. Sulphurised esters/olefins and organic phosphate are used as extreme pressure additives, (Ref.6). Pursuit of a synergy between additives plays one of the most important rules in development of new generations of lubricants in powertrain systems because good performance could be achieved by active tribochemical reaction, (Ref.7). The synergy becomes important, not only between additives, but also between additives and metal contact surfaces inside CVJs. Additives could react with metal surfaces tribo-chemically to form a complex surface layer, (Fig.5). That might, be with MoS2 in nano scale and/or a complex organic compound with iron, sulphur, phosphate, oxygen, Zn, Mo…, (Ref.8).

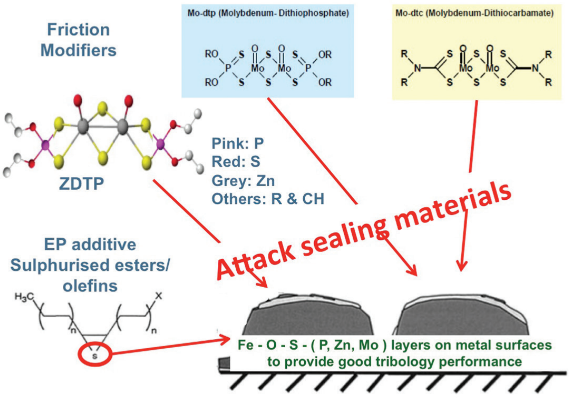


Figure 5. *Tribo-chemistry in tribology performance.*

Research shows that, if the additives are chemically active, they could generate the surface layer fast and stronger in different systems. For instance, as an anti-wear additive, a tribochemical reaction takes place on metal surfaces with ZDTP. It generates a complex surface layer to prevent the surfaces from wear. However, the quality and quantity of surface layers are dependent on the additive molecular structures and metal composition.

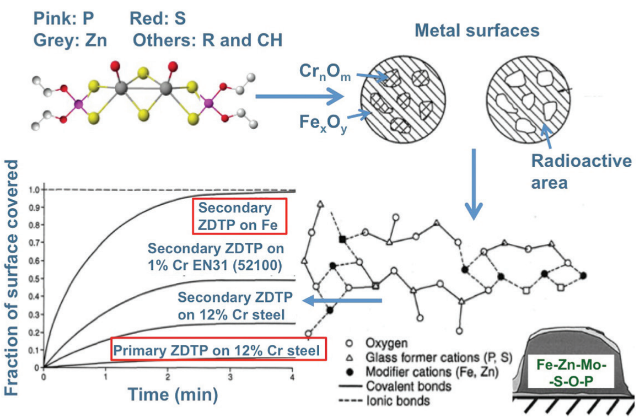


Figure 6. *Influence of metal surface characteristics on surface layers from tribo-chemical reaction.*

In Fig.6, it is seen that much smaller surface areas are covered for a combination of primary ZDTP with 12% Cr steel comparing to others, (Ref.9). At the same time, the chemically active additives could attack sealing materials badly. If the sealing system fails, CVJ system would also be out of order. Consequently, an understanding of tribology systems in powertrain products is one of the keys to develop lubricants for improving fuel economy.

Challenge for new generation of lubricants in powertrain systems

Challenge from durability in new design related to fuel consumption

GKN Driveline is a technology orientated company. In the 2000s, GKN developed new countertrack technology. Independent engineering analysis has proved that GKN's countertrack technology improves fuel economy by an average of 0.2 mpg on a typical front wheel drive mid-size vehicle. This results in a CO_2 emission reduction of 1 g/km. With new countertrack technology, GKN is able to increase the efficiency over 1%. For special vehicle segments such as SUV's, case studies have shown that countertrack technology can lead to CO_2 emission reductions up to 3 g/km.

Fig.7 shows a basic concept of GKN countertrack technology.

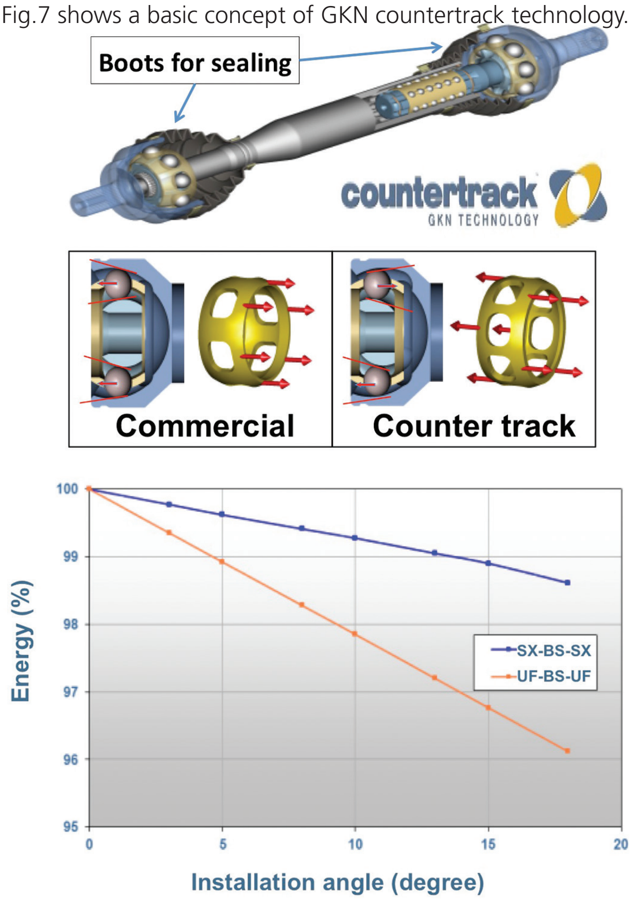


Figure 7. *GKN Driveline countertrack technology (SX) and efficiency improvement.*

In commercial design, all of balls are pushed in one direction toward to front of CVJ systems where the force on the cage and balls is balanced with opposite directions in GKN countertrack technology. Consequently, a different tribology system occurs in GKN countertrack technology. At the same time, due to 8% reduction in package size, there is an increase in the contact pressure, from 4 GPa in the current commercial generation to 8 GPa in new countertrack technology. With this large increase in contact pressures, a challenge of improving durability of CVJs appears for development of lubricants.

Fig. 8 shows a new generation of grease developed by GKN Driveline in the 2000s. With a good understanding of the tribology systems in a new design, this new generation of grease performs with a great improvement in the life of CVJs during back to back tests on GKN bench test rig using same batch of CVJs to fulfil GKN requirement for OEM applications. In fundamental study, it is interested to see that the new generation of grease provides an improvement in the life of CVJs where a large increase exists in Last Non-Seizure Load (LNSL) and Welding Load in 4 ball tests in laboratory, (Fig.8).

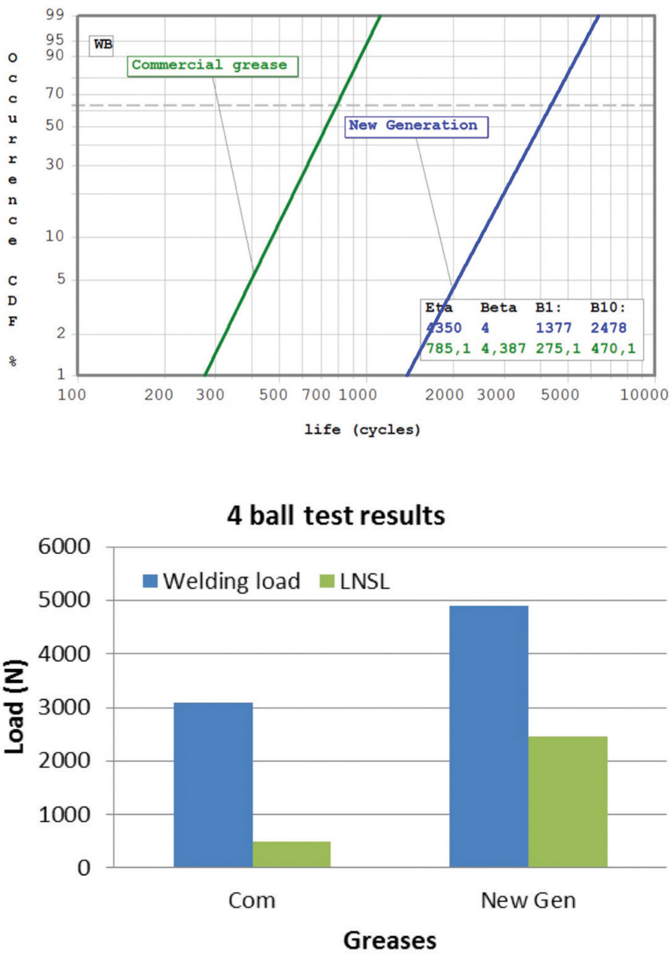


Figure 8. *Improvement of CVJ life from understanding requirement in new tribology system.*

Challenge from efficiency related to fuel consumption

As mentioned in (Fig.3), a large reduction in fuel consumption could be subjected from a reduction in energy loss in powertrain system. With a complexity in tribology systems in CVJs, movement of parts inside CVJs would be in different conditions dependent on loads, surface conditions, temperatures and speeds. Consequently, understanding tribology systems to achieve low friction in design of grease formulation plays one of the most important roles in improving fuel economy in CVJ systems.

Fig. 9 shows an influence of GKN greases on efficiency of fixed ball type of CVJs. At 15 degree working angle in the same fixed ball type of CVJs, a reduction of about 32% in energy loss could be achieved in GKN standard tests using the advanced grease to replace the commercial grease. In the advanced grease, a synergic effect was investigated and designed between physical and chemical additives in grease formulation where an additive package mainly based on physical lubricants is designed in the commercial grease.

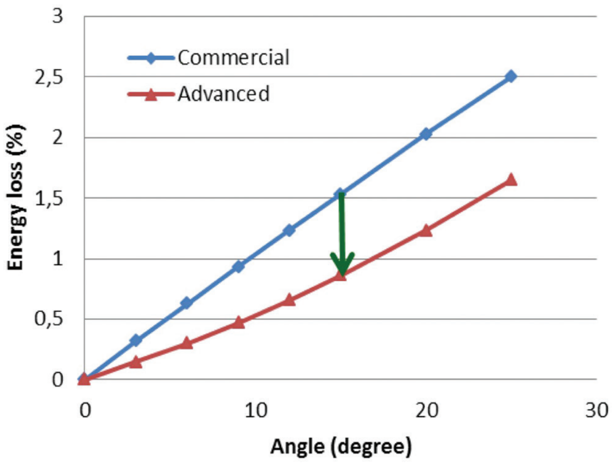


Figure 9. *Efficiency of fixed ball type of CVJs.*

Inspection shows that contact surfaces of inner races and outer races would become smooth in the fixed ball type of CVJs after use for a long period under heavy conditions, (Fig.10).

Figure 10. *Contact surface of outrace after CVJ tests.*

Laboratory study shows that, under 3.7 GPa pressure, GKN advanced grease has similar friction behaviour to the commercial grease on smooth contact surfaces, (Fig.11). When changed the surface conditions in to ground surfaces with Ra = 0.6 µm, the advanced grease shows a large reduction in friction from the synergic effect after a running period under 2.7 GPa pressure.

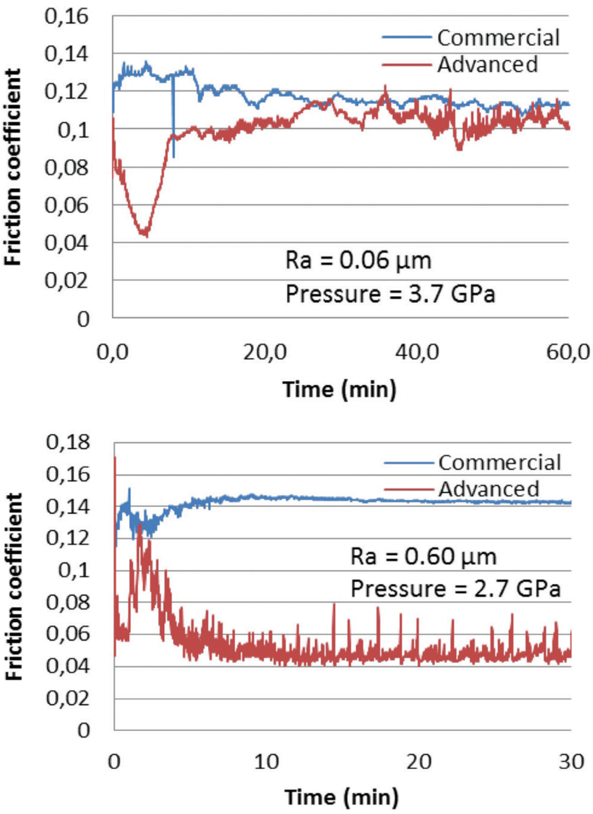


Figure 11. *Friction behaviour under different test conditions. Notes: ribology tests performed at 80°C with 1.5 mm stroke and 40 Hz frequency on SRV test machine.*

Challenge from compatibility with sealing materials related to reliability

Greases are sealed by boots made from rubbers or thermoplastic elastomers (TPEs) in CVJ systems for life. A failure of boots would result in the end of CVJ life. In one way, in order to improve performance of lubricants, an enhanced additive package is required in formulation. In another way, the additives for enhancement of grease performance could attack the polymer chains to deteriorate the properties of boot materials as a result of reducing the life of boots.

Fig.12 shows a correlation between molecular weights (MW) of TPEs, their property change in laboratory tests and the normalised life of CVJ boots in bench tests. When TPEs contact with lubricants at high temperatures, chemical and physical interactions could take place so that a reduction in molecular weights occurs dependent on different lubricants, temperatures and durations. GKN work indicates a tendency in which a reduction appears in the life of CVJ boots where the molecular weight of TPEs decreases. Consequently, a control of molecular weight change from interactions between lubricants and polymer materials plays one of the most important roles for CVJ life.

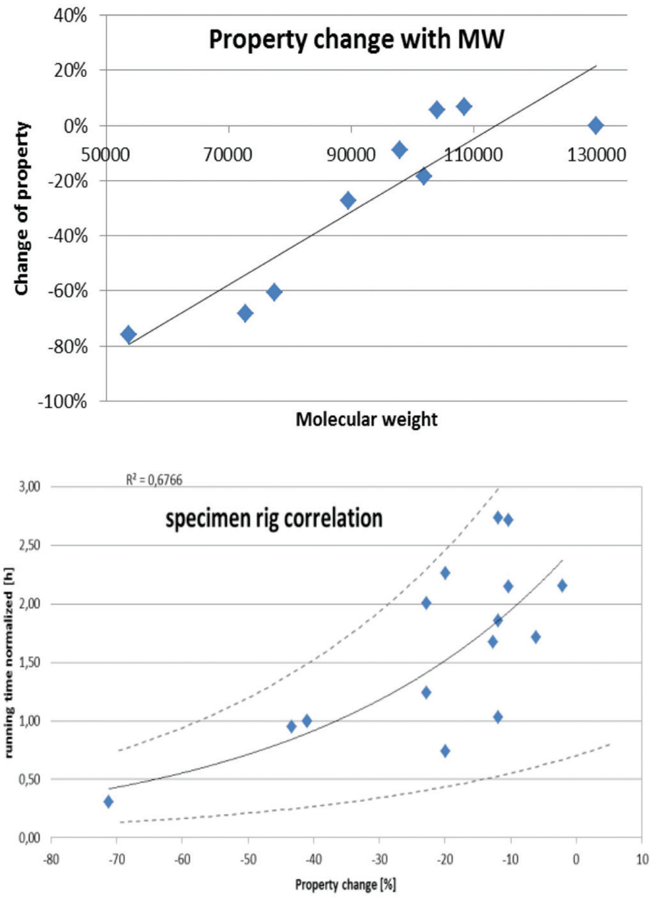


Figure 12. *Effect of molecular weight change on boot life.*

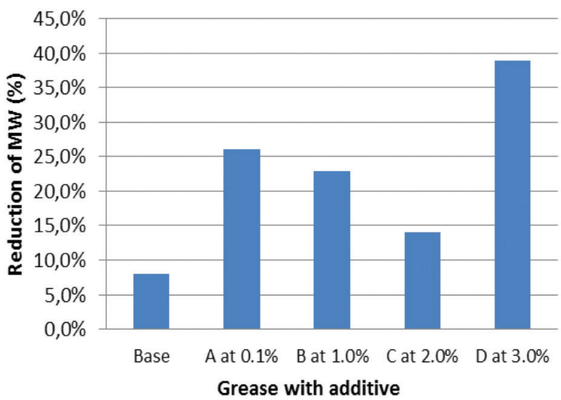


Figure 13. *Additive effect on sealing materials*

Fig.13 shows an effect of 4 different additives on changes of molecular weights of a particular TPE material during interactions in laboratory compatibility tests when mixing them in same basic grease respectively. In the compatibility tests, samples of TPEs were immersed in greases and placed in an oven at 125°C for 336 hours. Molecular weights were measured after compatibility tests. Investigation shows that four additives in different quantities could contribute a similar level of EP performance in the greases. However, the worst performance was observed in the compatibility tests after adding additive D at 3wt%. An improvement was observed by use of additives A, B and C. Considering 0.1wt% of additive A was used in the formulation with a large reduction of about 26% in molecular weight after the compatibility test, the additive A might be considered as the worst additive.

Lubricants for fuel economy in new generation of powertrain systems

As mentioned before, an ambitious target of improving fuel economy has been set up for 2025, (Fig.3). Powertrain systems play important roles in fuel economy. A good lubricant in powertrain systems could contribute a reduction in fuel consumption of vehicles. Consideration of designing new lubricants with special requirement from OEM and market development is important for R&D work in automotive industry.

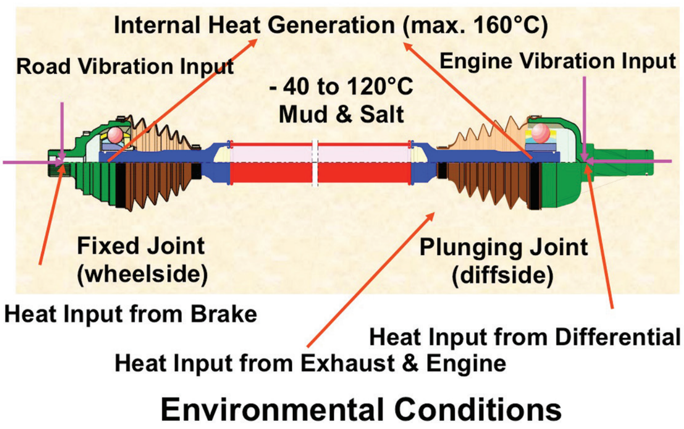


Figure 14.

From a tendency of designs in new vehicles, it is seen that powertrain systems could serve at much more severe conditions. For instance, in CVJ systems, the service temperatures could be change from a range between -40 and 120°C in to -45 and 180°C, see (Fig.14). At same time, it is required to provide an improved reduction in noise, vibration and harshness during power transmission. In order to meet the demand from OEM customers, first of all, it is essential to consider use of oils in greases with improved qualities. Secondly, it might be considered to use additives more stable at high temperatures, but more active at normal temperatures, in order to generate tribochemical surface layers for low friction and anti-wear behaviour at normal temperatures and to prevent the lubricants from deterioration at high temperatures.

Cost is one of the most important issues in the automotive industry. It is clear that high qualities of oils and additives result in an increase in cost. It is not possible to improve the quality of lubricants without any increase in cost. Consequently, work as a team with design of new generation of powertrain systems is one of key factors to fulfil OEM requirement for improving fuel economy.

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