The 14th Annual
FUELS & LUBES ASIA
CONFERENCE

Controlled Architecture Viscosity Modifiers for Driveline Fluids: Enhanced Fuel Efficiency and Wear Protection

Barton J. Schober[a], Richard J. Vickerman[a], Ok-Dong Lee[b], William J. Dimitrakis[a] and Ananda Gajanayake[c]

The Lubrizol Corporation

a. Wickliffe, Ohio, USA
b. Seoul, Korea
c. Kinuura, Japan

PRESENTED AT THE 14TH ANNUAL FUELS & LUBES ASIA CONFERENCE

SEOUL, KOREA, MARCH 5-7, 2008

PUBLISHED BY F&L ASIA, INC.

P.O. BOX 151, AYALA ALABANG VILLAGE POST OFFICE, 1780 MUNTINLUPA CITY, PHILIPPINES

Copyright © 2008 F&L Asia, Inc.

Abstract

Lower viscosity fluids are being used for manual, automatic, and continuously variable transmissions. This is due in part to the belief that they will improve fuel economy. Viscosity specifications are typically based on 100° C viscosity. Actual operating temperatures would be much lower during cold start-up and typical light-duty operation. Temperatures during severe duty, such as towing, would be higher than 100 ° C. Ideally, the start-up and at-use viscosities should be low to improve fuel economy. Under high temperature conditions, the fluid should maintain viscosity to prevent accelerated wear and poor shift performance. Very high viscosity index (VI) fluids are less viscous at low temperatures but maintain viscosity at high temperatures, providing both fuel efficiency and protection. Conventional viscosity modifiers (VMs) such as polyalkylmethacrylates are frequently used in driveline fluids to improve the viscosity temperature response. Formulating with conventional VMs requires balancing the fundamental trade-off between viscosity index, shear stability and low-temperature fluidity. This paper will introduce a new class of viscosity modifiers: controlled architecture polymers. These polymers have a controlled architecture that changes the fundamental relationship previously seen. Driveline fluids can now be developed to have much higher VI and better low-temperature fluidity without sacrificing shear stability. This talk will discuss this new chemistry and demonstrate these advantages. The impact of VI and operating temperature will be demonstrated in automatic transmission fluids. This will be accomplished by testing fluids in a Friction/Torque Testing Rig as well as vehicle testing in the Cold FTP Cycle.

Bio-data

Dr. Barton J. Schober received Bachelors of Science in Chemistry from The State University of New York in 1987 and a Doctorate from the Department of Materials Science at the Pennsylvania State University in 1992. He joined the Lubrizol Corporation in Wickliffe, Ohio, USA where he has worked for 16 years. Bart has held numerous technical research positions as a synthesis chemist, analytical chemist, and manager of the polymer synthesis group in Chemical Synthesis. He is currently a Technology Manager in the Viscosity Modifiers Group responsible for new product development.

Dr. Richard J. Vickerman has been with The Lubrizol Corporation in 1990 where he has held numerous positions within Research and Development including manager of the Friction Modifier group within the Chemical Synthesis Department. He is currently a technology manager in the driveline fluids group and is responsible for strategic research. He holds a Ph.D. in organic chemistry from Case Western Reserve University in Cleveland, Ohio.

William J. Dimitrakis received Bachelors of Science degree in Chemistry from the University of Pittsburgh and an Masters of Business Administration (MBA) form the University of Michigan. He joined The Lubrizol Corporation in 1986 and has held positions in sales, marketing and technical services. He is currently Business Manager for Specialty Viscosity Modifiers

OD Lee is Asia Pacific Regional Business Manager, Viscosity Modifier and responsible for managing overall VM business in AP which includes Engine oil VM, Specialties VM and Pour Point Depressants. OD joined the Lubrizol Corporation in 1995 as a Sales Engineer/Account Manager and moved on to Marketing/Product Management role in 2003. He graduated from Seoul National University in Korea with a BSc degree majoring in Chemistry Education and has since been working on a variety of lubricants and fuel related areas as Lab, Planning & Operation, Technology and Sales either at Lubrizol or at a refinery blender, Hanwha Energy (SK-Inchon Refining Co. now) where he spent 10+ years before coming to the Lubrizol Corporation.

Dr. Ananda Gajanayake is a Mechanical Engineer holding Bachelors of Science of Engineering (Honors) degree from the University of Moratuwa (Sri Lanka) in 1987, Master of Engineering degree from the Asian Institute of Technology (Thailand) in 1991 and Doctor of Engineering degree from the Kyushu University (Japan) in 1999. He worked as a Chief Mechanical Engineer in Ceylon Electricity Board (Sri Lanka) for 7 years and as a Research Engineer (Post-doctoral) in Tonen-General Research Laboratory (Kawasaki, Japan) for 7 years before joining Lubrizol Japan Limited since 2006 for his current position as a Section Manager of Mechanical Testing in Lubrizol International Laboratories Asia-Pacific (LILAP) responsible for engine / driveline testing developments

Introduction

The world is firmly focused on reducing energy consumption and increasingly stringent regulations on CO_2 emissions. One example of regulatory changes is the new US EPA fuel economy test procedures which are required beginning with the 2008 model year, for vehicles sold in the US market. The revised procedures are intended to provide an estimate that more accurately reflects what consumers will experience under real world driving conditions. These changes include testing at higher speeds, more aggressive acceleration and deceleration, hot-weather and cold-temperature testing. The US EPA expects the new procedures will reduce city fuel economy ratings by an average of 12 percent and highway ratings by an average of 8 percent. The addition of low temperature testing creates the opportunity to understand how transmission fluid behavior at low temperatures contributes to efficiency & fuel economy.

The automotive industry, responding to consumer pressure and legislative demands, is looking for opportunities to increase the overall fuel economy of their fleets. In addition to more efficient mechanical systems, automotive manufactures are working with the lubricant industry to lower the viscosity of lubricants to increase overall efficiency. Viscosity specifications for automatic transmission fluids (ATFs) have been ca. 7.0 cSt at 100° C. There is a trend to reduce ATF viscosity to below ca. 6.0 cSt at 100° C [1,2,3,4]. Typical operating temperatures in automatic transmissions during cold start-up and light-duty operation are between -20° C and about 80° C. Temperatures during severe-duty intervals, such as towing, can be higher than 100° C. To improve the mechanical efficiency and the fuel economy start-up and at-use viscosities should be as low as practical under normal operating conditions and under high-temperature conditions the fluid should maintain viscosity to prevent accelerated wear and poor shift performance. Very high viscosity index (VI) fluids possess these characteristics and therefore provide both fuel efficiency and improved metal fatigue protection relative to fluids with conventional VI, see Figure 1.

This paper will introduce a new class of viscosity modifier (VM), called controlled architecture polymers, which enable fluids to be formulated with higher VI (~250) and better low-temperature fluidity without sacrificing shear stability. Transmission fluids prepared with both controlled architecture and conventional polymers are compared in low-temperature transmission efficiency.

High VI Fluids with New VM Architecture

ATFs require a fine balance of many performance characteristics to achieve the desired overall performance. VMs used in ATFs are designed to impart the correct temperature/viscosity relationship so the fluid performs adequately within the expected operating temperature range. Until recently there have been only two VM parameters could be adjusted to achieve maximum performance: molecular weight (MW) and the basic polymer chemistry. By polymer chemistry we mean the backbone and side-chain compositions. Higher MW VMs are known to impart high VIs and they also allow the lowest treat rates, so are often advantageous commercially. However, high MW VMs are also more prone to mechanical shearing leading to less thickening and low viscosity fluids. So the MW must be adjusted to give the highest MW possible while still meeting the shear stability requirements of the fluid. This trade-off makes it difficult to maximize both the VI and the shear stability; one traditionally was sacrificed for the other until a suitable compromise was reached.

It is well known that PMAs impart higher VI relative to hydrocarbon VMs, for example poly(*iso*-butylenes) (PIB) or ethylene/propylene copolymers. In Figure 2 it can be seen that a PMA will give much higher VI than PIB with the same shear stability index. Controlled formation of a VMs architecture has been shown to give fluids with significantly increased VI.[5,6]

We have shown that a VM with a star-branched architecture can give very high VI boost while maintaining shear stability, see Figure 2. Table 1 offers a comparison of traditional linear PMA and star-branched architecture in an ATF fluid. In these blends the base oil combination was kept constant to demonstrate the advantages that this architecture imparts. These blends were formulated to approximately the same 100 ^{o}C viscosity. Candidates 1 and 2 use two star-branched VMs which differ in their overall molecular weight.

Table 1 shows that using controlled architecture VM1 results in a blend which gives comparable shear loss to the Standard Formulation. It is worth noting that the 100° C viscosity of Candidate 1 is slightly high, therefore an improvement in the shear stability would be expected if blended to 7.5 cSt. While the shear stability is similar, the viscosity index (VI) is greater and the Brookfield viscosity is lower. Both of these properties are advantageous in ATF formulations. High VI is believed to improve the fuel efficiency and low Brookfield viscosity ensures that the ATF can be pump through the unit at cold startup temperatures.

The thickening of these new VMs is significantly higher than traditional PMA VM. At approximately the same blend shear stability Candidate 1 contains 6.75% polymer whereas the Standard Formulation contains 9.25% polymer. The percent polymer is used to allow direct comparison of the polymer architectures. The VMs are diluted, but the diluent used in all cases was a Group III oil comparable to the blend oils. Therefore little effect is expected from the oil added with the VM.

Candidate 2 demonstrates that further improvement in VI and Brookfield viscosity can be obtained using the higher molecular weight star-branched VM. This comes at the expense of reduced shear stability. However, comparing the thickening and shear stability of blend Candidates 1 and 2 to the Standard Formulation it is clear that the architecture changes the thickening/shear relationship advantageously, see again Figure 2.

For this study we wanted to formulate to the high and low viscosity index extremes in order to demonstrate the efficiency gains that can be achieved with this new technology. However, we also wanted to keep the shear stability comparable as this is a vital parameter when comparing fluid properties. To achieve these goals we allowed the base oil composition to be varied. For the VMs we chose a standard commercial PMA to prepare a lower VI blend and a Controlled architecture (star-branched) PMA to prepare the high VI blend, see Table 2.

In this case the percent active polymer was comparable between the two blends, at 4.6 and 4.7%. The shear stabilities were equal within the variability of the KRL shear test. It is worth noting that the blend with the high VI also has significantly improved the low temperature viscosity (Brookfield viscosity). By starting with a wide VI difference we hope to show the potentially significant improvements in fuel efficiency that is possible. The impact of the VI difference can be seen in the 40° C viscosity difference. The temperature/viscosity relationship was also calculated from the 100° C and 40° C values using the McCoull-Walther-Wright Equation, Figure 3. From this it is clear that very large viscosity differences are expected at even lower temperatures.

Experimental

1. Cold AT efficiency rig test

1.1 Test rig configuration

A custom built AT efficiency test rig was used to measure relative torque losses in a 6 speed FR type passenger car automatic transmission unit. The transmission was connected to a drive motor and two absorbing motors in a T-shape configuration, as shown in Figure 4, and was driven at different input revolution / output torque combinations to measure the effect of VM on torque loss and converter slip at several different speeds and loads, as shown in Figure 5.

1.2 Cooling method for AT and ATF and test procedure

Both the automatic transmission and ATF were brought to the low temperature starting condition (below -10° C) by wrapping the transmission with pre-cooled cold-packs and charging pre-cooled (-20° C) ATF to the transmission as shown in Figure 6. With our test rig set-up, we were not able to completely drain the fluid left in torque converter before the start of each test run. When the pre-cooled (-20° C) ATF is charged to the transmission at the start of the test it mixes with the relatively warm ATF left in torque converter. The fluid reaches thermal equilibrium between -10° C and -5° C. Data collection was started at -5° C for all but the simulated idling condition. It took longer to completely mix the fluids and come to a thermal equilibrium under the simulated idling conditions and due to the normal frictional heating during this time the fluid the system did not reach equilibrium until about 0℃. As a result, data collection began at about 0° C. The data shown is an average of two consecutive runs for each test condition.

The test was started by selecting the gear position, input revolution and output torque according to the desired test conditions and the unit was run until the ATF reached a stable final temperature with self-generated heat during operation, which took approximately 30 to 40 min. Table 3 shows the four test conditions simulating different vehicle running modes adapted for this test. These test conditions were chosen by considering medium sized passenger car with a 3.0 liter class engine under what we consider four typical operating conditions representing the normal range of operation. Initially the transmission was spun in first gear at 800 rpm and 8 Nm input torque to simulate the vehicle at idle, then in second gear at 2500 rpm and 13 Nm at simulating a light load (i.e. descending a hill) at 40 km/h (maximum torque is around 55 Nm). Cruising at 60 km/h was simulated by running in fourth gear at 1800 rpm and 40 Nm (maximum torque is around 70 Nm). Finally to simulate driving under a heavy load simulating hard acceleration or launching the vehicle while towing, the unit was run in first gear at 3600 rpm/71 Nm which is nearly the maximum torque (around 75 Nm) for this transmission.

Results and Discussion

The effect of VI increase on AT performance was clearly seen throughout the range of temperatures in all running modes evaluated. Transmission efficiency, torque loss and torque converter slip in Figures 7 - 10. The definitions for each of these terms are as follows:

Torque Loss; (converted into input shaft)
- Input Torque – (Output Torque / Gear Ratio)

– **Slip revolution of Torque Converter**
- Input revolution – (Output revolution x Gear Ratio)

– **Power**
- Input Power
  - Input Revolutions x Input Torque
- Output Power
  - Output Revolutions x Output Torque

– **Power Transmit Efficiency (PTE)**
- PTE = (Output Power / Input Power) x 100 (%)

The transmission ran more efficiently with the higher VI fluid under all the conditions tested. As anticipated, in particularly, the low temperature (cold-start) region of each condition shows the largest efficiency gain of approximately 3 - 4% as shown in Figures 7 - 10, consistent with the larger viscosity differences between low and high VI fluids at the lower temperatures. Moreover, the same efficiency gain persists through the temperature range in vehicle idling as shown in Fig. 7, indicating promising fuel economy benefits while idling in traffic. No direct comparison to actual vehicle fuel economy has been established with this test rig, but increased mechanical efficiency is anticipated to increase fuel economy in an actual vehicle. Future work will concentrate on correlating the VI differences of the ATF to actual fuel efficiency in vehicles run in the FTP cycle, including cold start conditions.

Conclusions

Automotive fuel efficiency is of preeminent concern to OEMs and consumers. This has lead to a general reduction of the 100° C viscosity specification for ATFs. However, ATFs do not typically run at 100° C. It has been demonstrated that higher VI ATFs can achieve higher automatic transmission efficiencies, as measured on a testing rig designed to simulate actual driving torques, loads, and speeds. Under all conditions significant efficiency gains were seen for the high VI fluid compared to typical VI fluid. This high VI was achieved using a new class of VM that used a controlled architecture. High VI was obtained without sacrificing the fluid shear stability. The low temperature viscosity was also improved.

These results indicate that it may not be necessary to reduce the 100° C viscosity of an ATF to obtain high fuel efficiency. Using high VI fluids will allow better efficiency at cold start and normal operating temperatures. The higher 100° C viscosity may improve durability and shift performance under extreme service such as towing. Future work concentrates on correlating these results to vehicle fuel efficiency in the FTP cycle.

References

1) Dardin, A.; Hedrich, K.; Müller, M.; Topolovec-Miklozic, K.; Spikes, H., “Influence of Polyalkylmethacrylate Viscosity Index Improvers on the Efficiency of Lubricants” SAE Paper 2003-01-1967

2) Umamori, N.; Kugimiya, T., “Study of viscosity Index Improves for Fuel Economy ATF” SAE Paper 2003-01-3256

3) Kurosawa, O.; Matsui, S., Komiyya, K; Morita, E.; Kawasaki, Y. “Development of the Fuel Saving Low Viscosity ATF” SAE Paper 2003-01-3257

4) Yamamori, K.; Saitou, K.; Kobiki, Y.; Ogawa, A., “Development of New Automatic Transmission Fluid for Fuel Economy” SAE Paper 2003-01-3258

5) Filippini, B. B., Schober, B. J., Dimitrakis, W. J., Visger, D. C., “Multigrade Hydraulic Fluids with Improved Properties via Novel Viscosity Modifiers”, STLE Presentation, 8 May 2007.

6) Callais, P; Schmidt, S; Macy, N., “Effect of Controlled Polymer Architecture on VI and Other Rheological Properties” SAE Paper 2004-01-3047

Table 1 – ATF blends comparing Controlled architecture VMs to PMA VM in a typical ATF formulation.

	Standard Formulation	Candidate 1	Candidate 2
Group III Base Oil, 3 cSt @100	70	70	70
Group III Base Oil, 4 cSt @100	30	30	30
Performance Package	7.7	7.7	7.7
Pour Point Depressant	0.15	0.15	0.15
PMA VM	**9.25 Actives**		
Controlled Architecture VM1		**6.75 Actives**	
Controlled Architecture VM2			**4.70 Actives**
Viscosity at 100 (cSt)	**7.53**	**7.61**	**7.48**
Viscosity at 40 (cSt)	33.97	32.88	27.64
VI	**199**	**212**	**260**
20 H KRL (Viscosity Loss)	**13%**	**15%**	**20%**
-40C Brookfield Viscosity (cP)	**9920**	**8770**	**7090**

Table 2 – ATF blends prepared to test the effect of VI on fuel efficiency

	Low VI	**High VI**
Group III Base Oil, 3 cSt @ 100	51.6	78.3
Group III Base Oil, 6 cSt @ 100	30.3	
Performance Package	11.4	11.4
PMA VM	4.6 (actives)	
Controlled Architecture VM		4.7 (actives)
Viscosity at 100 C (cSt)	7.0	7.0
Viscosity at 40 C (cSt)	33.0	26.1
Viscosity Index	**183**	**251**
20 H KRL Viscosity Loss	16%	17%
Brookfield Visc at -40 C (cP)	11,900	5,040

Table 3 Test conditions for AT test rig

Step	**Description**	**Gear position / Input rpm / Input torque**
1	**Heavy load running / towing**	**1st gear / 3600 rpm / 71 Nm**
2	**Idling**	**1st gear / 800 rpm / 8 Nm**
3	**Light load running at 40 km/h**	**2nd gear / 2500 rpm / 13 Nm**
4	**Normal cruising at 60 km/h**	**4th gear / 1800 rpm / 40 Nm**
Test-time: until final stable sump temperature was reached.		

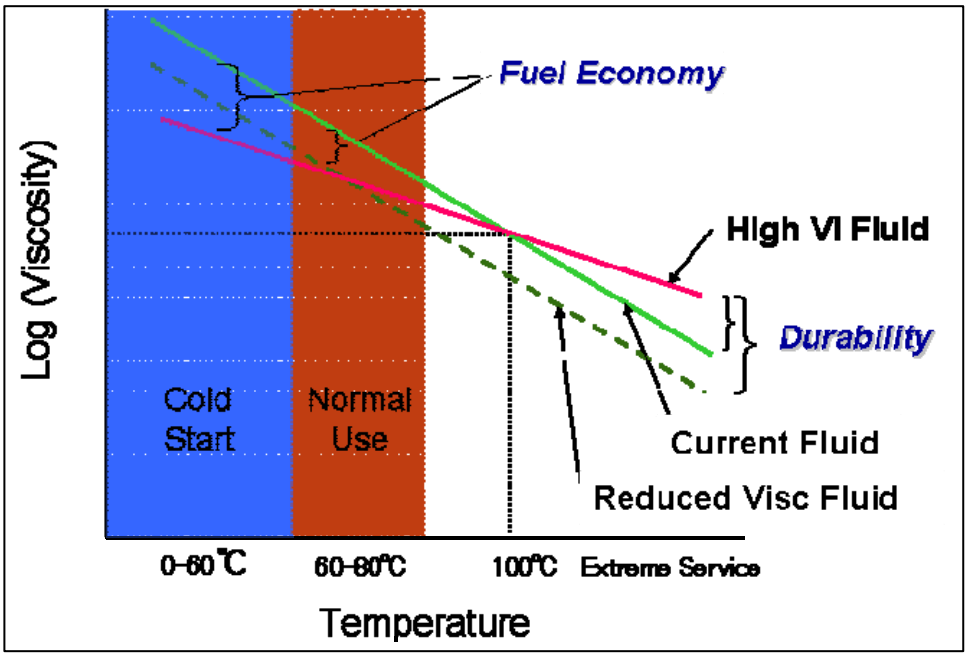


Figure 1 – Fluids may be formulated to the same 100° C viscosity. However, the fluid with the higher VI will have lower viscosity at the transmission's normal use temperature. It will have much lower viscosity at cold temperature startup. These lower viscosities would be expected to improve the efficiency of an automatic transmission fluid. At the same time, the high VI allows the fluid to maintain high viscosity at high temperatures.

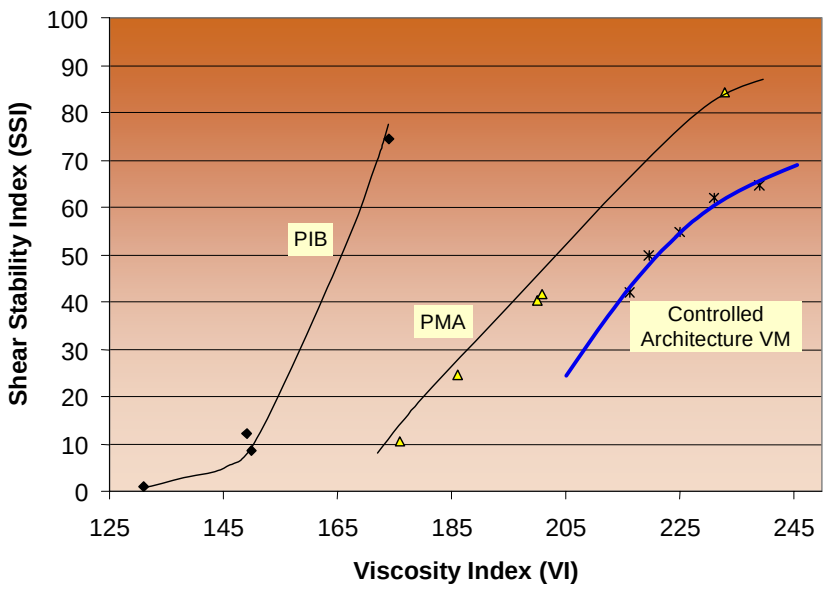


Figure 2 – Fluids blended to the same 100° C viscosity in 4 cSt Group II oil can be compared by plotting their shear stability index against the blend VI. Generally it is desired to have the highest VI with a minimum shear stability index required. PMAs impart a lot of VI for a given shear stability index. However, controlled architecture PMAs give even higher VI for the same shear stability index.

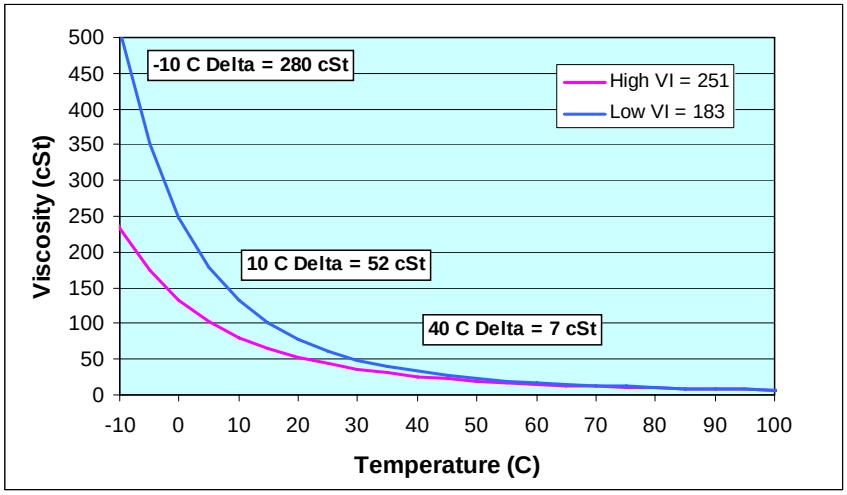


Figure 3 – Extrapolated low temperature viscosities for the high and low viscosity ATFs.

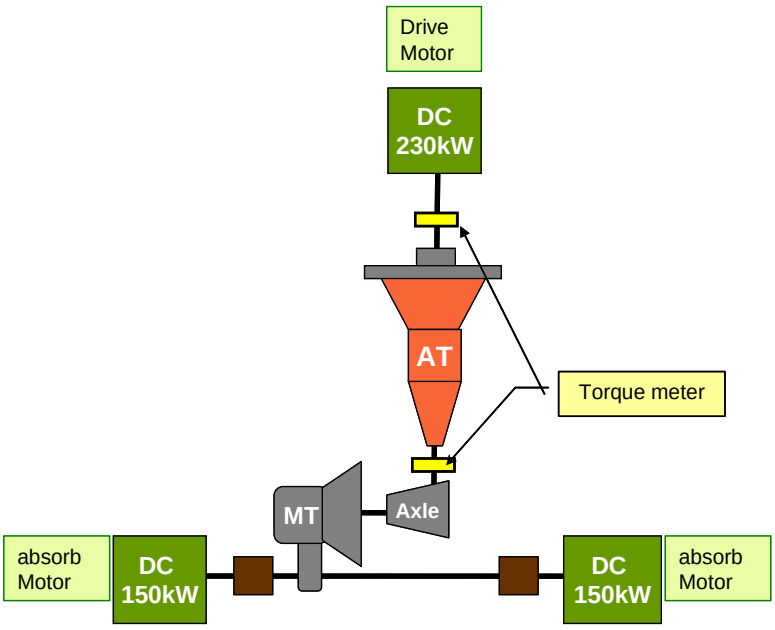


Figure 4 – Automatic transmission test rig configuration

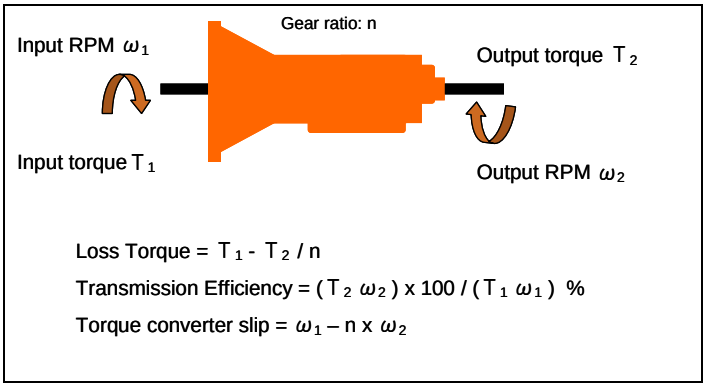


Figure 5 - Measurements and performance indicators.

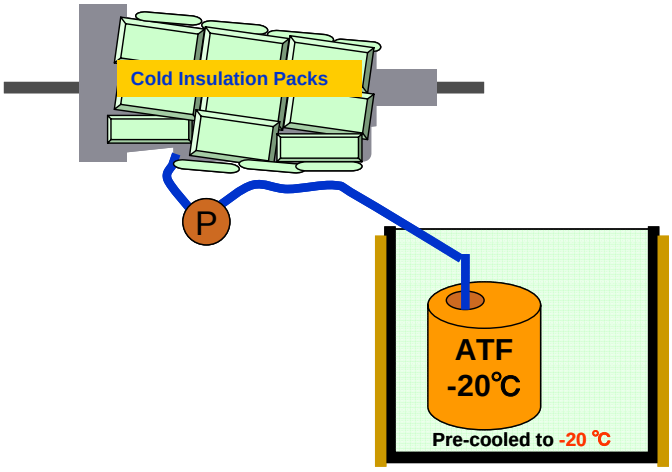


Figure 6 - Cooling strategy for AT and ATF

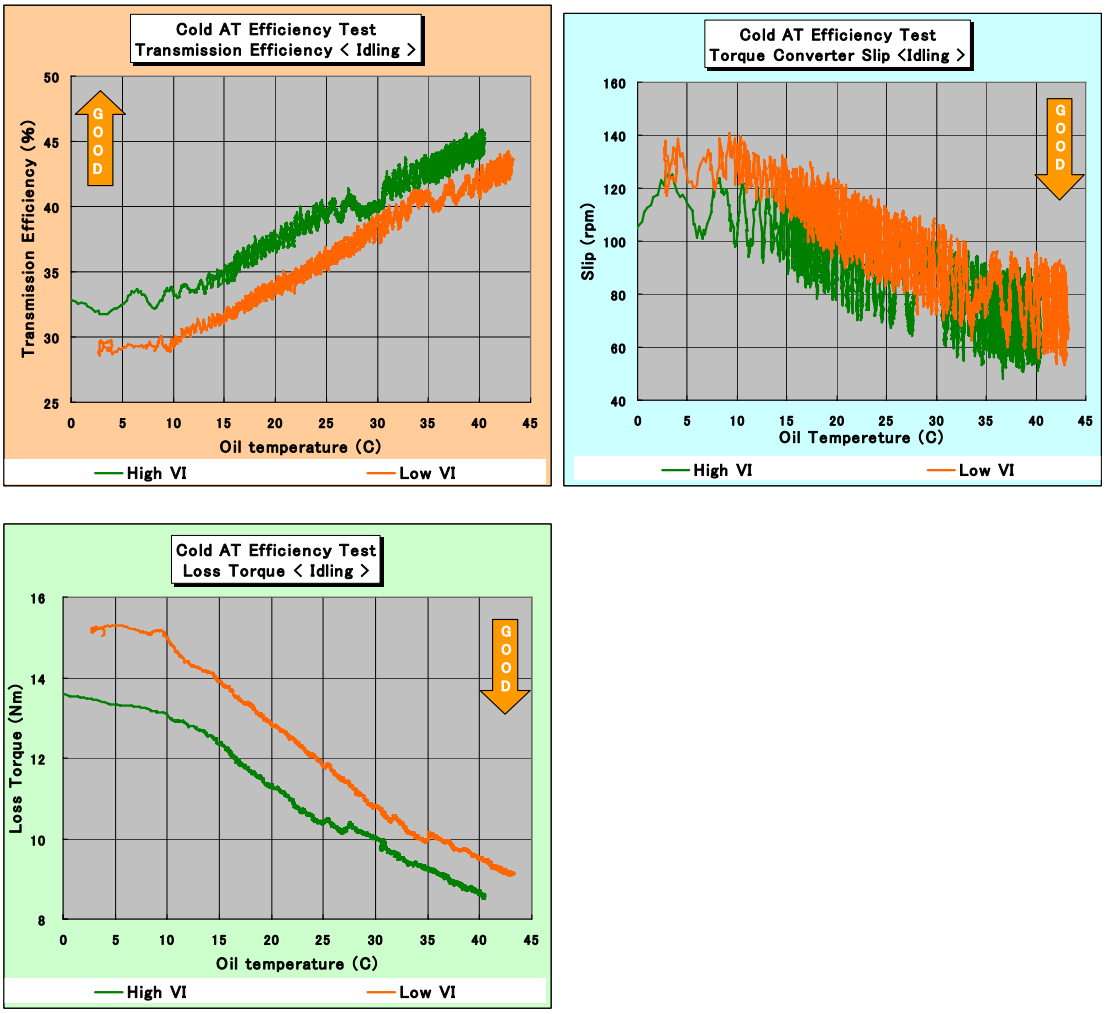


Figure 7. Transmission performance at Idle

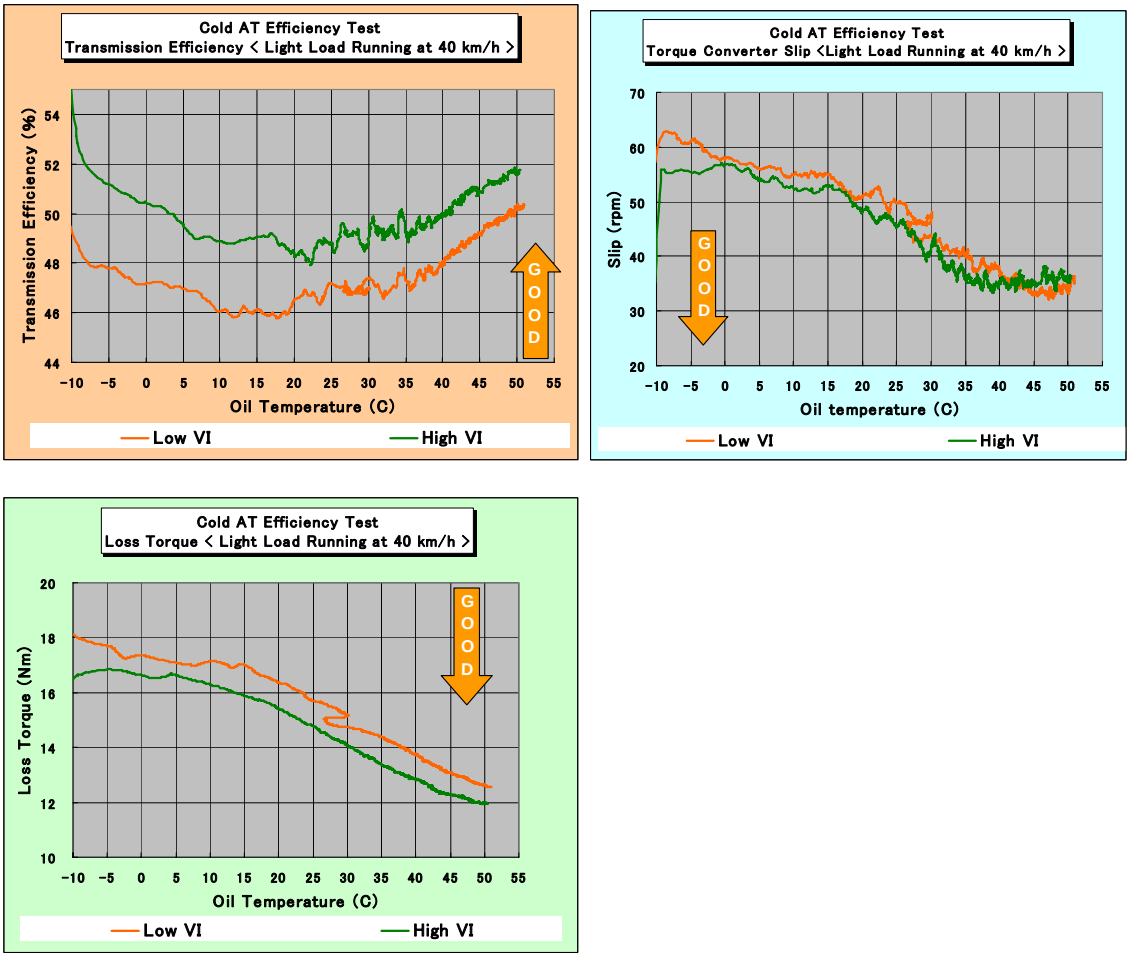
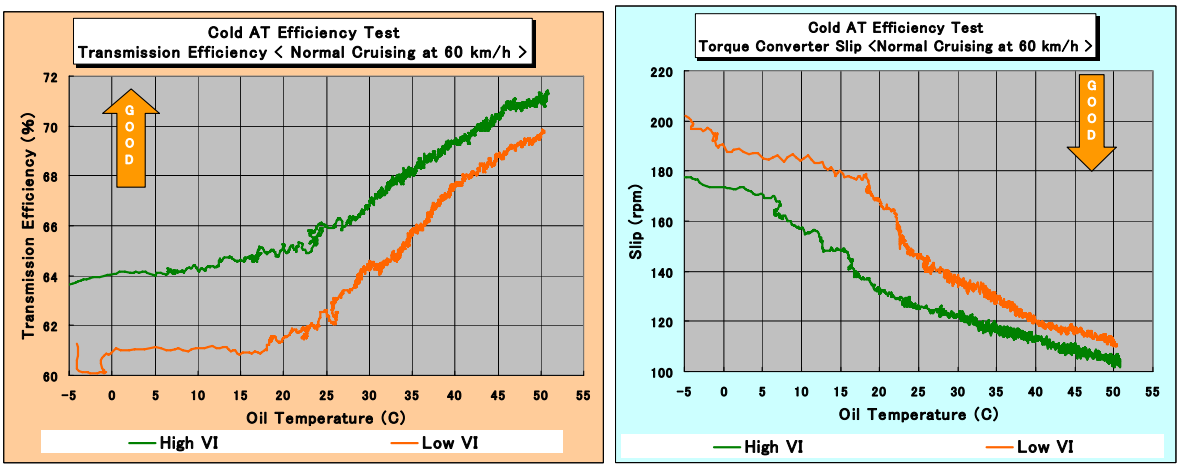


Figure 8. Transmission performance at 40 km/h under light load



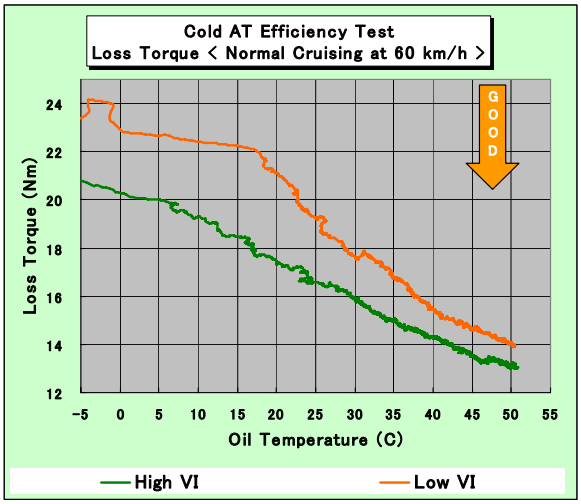


Figure 9. Transmission performance at 60 km/h under normal load

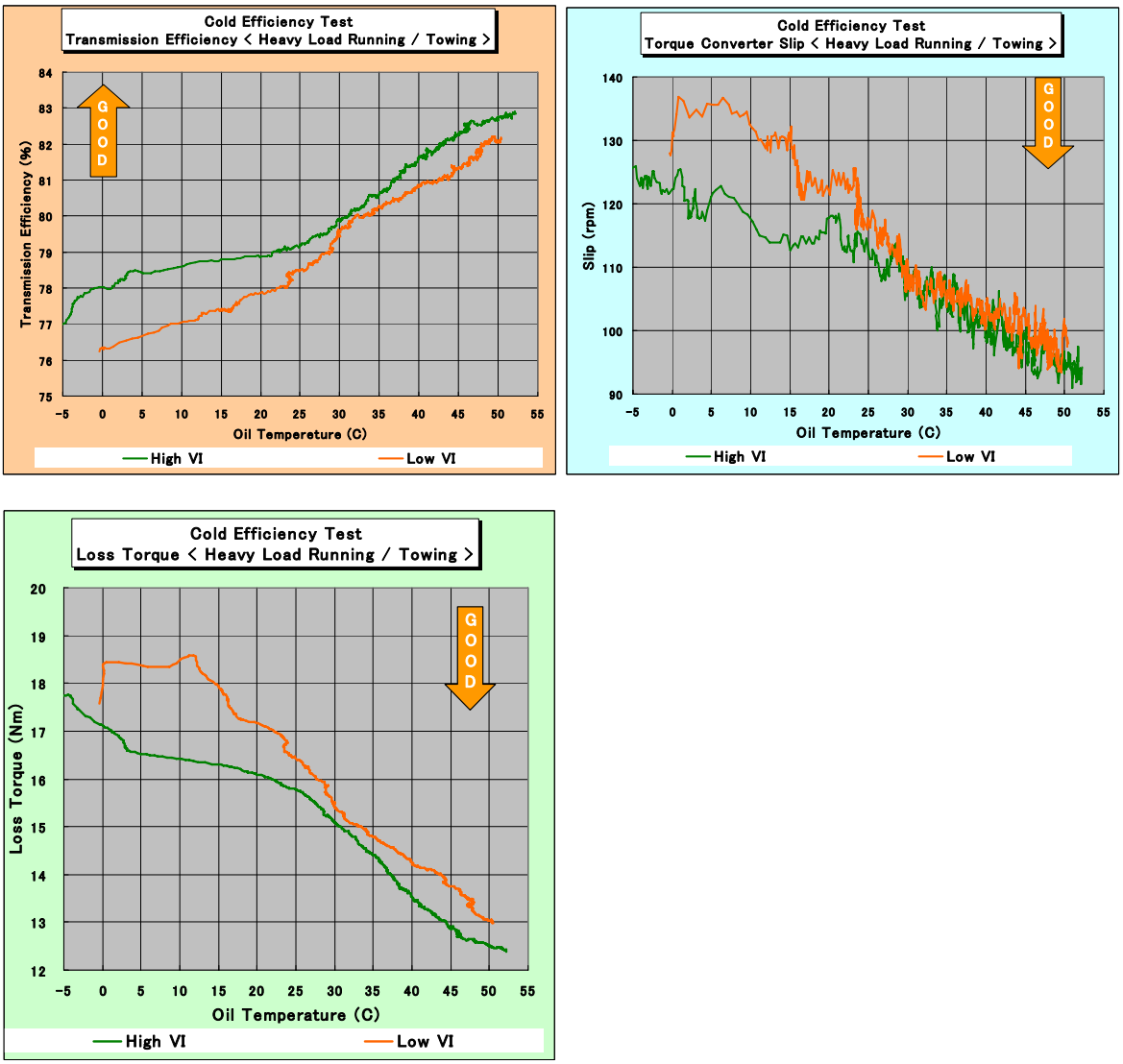


Figure 10. Transmission performance under heavy load