Technology Introduction

Effectiveness of synthetic base oils for automotive shock absorber fluids SustainaLub: balancing reduced environmental impact and ride quality

KATO Shinji, YASUKOUCHI Naoki, ISHIDA Koya

1 Introduction

In recent years, society has increasingly focused on promoting carbon neutrality (hereinafter, "CN") and addressing the SDGs. Consequently, there is a growing demand for automotive parts to deliver even higher environmental performance. This report presents KYB's case study on an initiative to reduce environmental impact using synthetic ester base oils (the formulation details are undisclosed) and the verification of their ride performance. KYB is also designing base oils using bio-based and circular-based raw materials (e.g., vegetable oils, algal oils, and fatty acids derived from recycled oils and fats). These are collectively referred to as "circular-based raw materials". Currently, the base oil design focuses on synthetic ester base oils whose main raw material is plant-derived fatty acids. This design is scalable to allow for the future substitution of monomers derived from algal oil and recycled oils and fats.

Specific measures for reducing environmental impact include using circular-based raw materials and adopting chemically synthesized base oils that suppress CO_2 emissions during manufacturing. For the purpose of this report, these oils are referred to as synthetic ester oils. Other measures include improving biodegradability in case of leakage. These measures require ensuring the basic performance of base oils while reducing environmental impact throughout their entire life cycle. Ensuring their design and verification is a challenge for us.

On the other hand, shock absorber fluid (Photo 1) directly affects the suspension's friction characteristics. These characteristics significantly impact the vehicle's ride comfort and steering stability. Specifically, adjusting the friction response characteristics determines how responsive the shock absorber is to input from the road surface. This directly affects occupant comfort and vehicle stability. Improving ride quality poses a significant technical challenge[1), 2)]. This report demonstrates the effectiveness of new fluid design technology that uses synthetic ester base oils. It does so by quantitatively assessing the friction response characteristics and verifying the improvement in ride quality through vehicle testing. The report proves that this technology effectively balances reduced environmental impact with driving performance.

Photo 1 Shock absorber fluid

2 Background and Objectives of Technology Development

Conventional fluids are primarily composed of petroleum-derived base oils. Concerns have been raised about their environmental impact in terms of biodegradability and CO_2 emissions. Therefore, we decided to use synthetic ester base oils made from circular-based raw materials to develop a fluid that meets the OECD 301F evaluation criteria and can contribute to CN (Fig. 1).

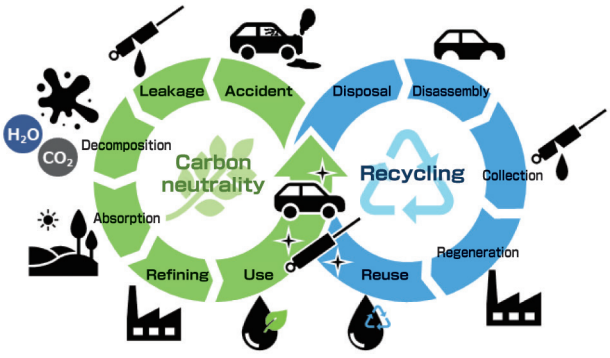


Fig. 1 Initiative to reduce the fluid's environmental impact

Ride quality is primarily affected by the response in the micro-input range (typically experienced on good roads where piston displacement is ±1.5 mm and piston velocity is ± 30 mm/s or less). In this range, the damping force builds slowly immediately after the hydraulic system reverses motion due to oil column stiffness, which is caused by the fluid's compressibility. Due to hysteresis, the damping force tends to be biased toward the acceleration side. Therefore, in the ultra-low-speed and small-amplitude ranges, friction significantly contributes to the total damping force, and the initial suspension response depends heavily on the "rising rate of friction"[1), 6)]. (Figs. 2 and 3).

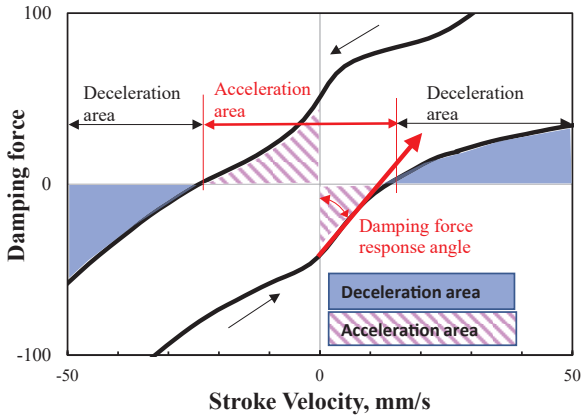


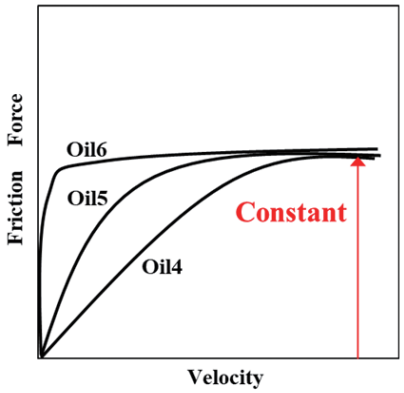
Fig. 2 F-V waveform near zero shock absorber speed

Based on the above mechanism, this initiative adopted a fluid design guideline that focuses on the friction response (i.e., the slope of the build-up of friction force immediately after the hydraulic system reverses motion) (Fig. 3(b)), rather than the magnitude of the friction force[4), 5)]. In other words, only the slope is adjusted, while the magnitude of the friction force is almost maintained, to optimize the initial response in the micro-input range, where hydraulic damping is ineffective. This improves steering stability without compromising the ride comfort. The improvement in this transient region has not been properly determined by conventional damping force evaluation focusing on static characteristics and should be verified quantitatively through bench and vehicle tests[1)]. Furthermore, we conducted driving tests on ice (low μ) to determine the perceived driving characteristics in the micro-input and low-speed ranges.

3 Component Testing and Performance Indicators

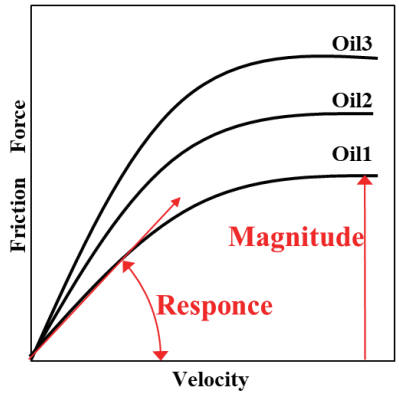
We conducted component testing using a reciprocating pin-on-disk friction test apparatus. With sinusoidal displacement control, we intended to accurately determine changes in friction behavior within the small-amplitude range, with an amplitude of ±0.1 to ±2.0 mm and a maximum speed of 62.8 mm/s.

A strain gauge mounted on the pin shaft measured the friction force, and the oil temperature was controlled at 30°C (Fig. 4).



Friction response adjustment

(a) Technology for adjusting friction responsiveness



Friction force adjustment

(b) Technology for adjusting friction levels

Fig. 3 Friction adjustment technologies

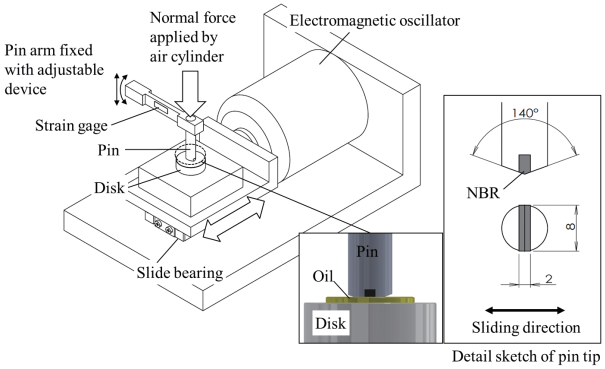
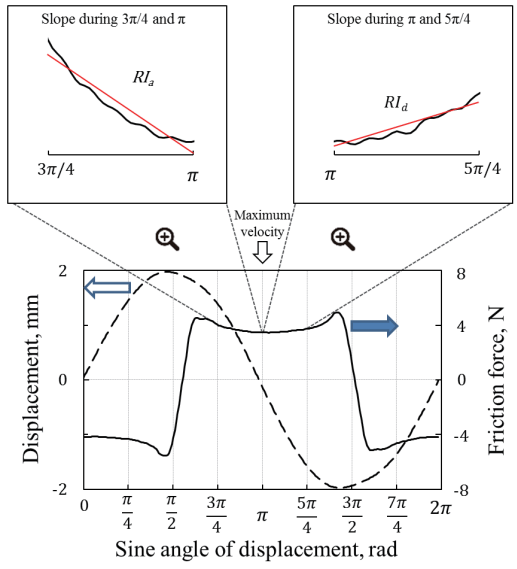


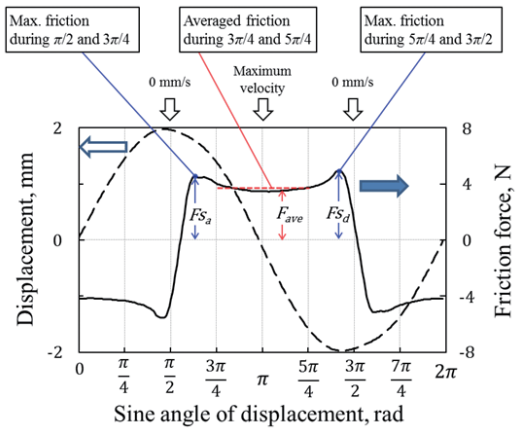
Fig. 4 Schematic diagram of dynamic friction measuring system and test specimen shape

The friction characteristics of the shock absorber fluid were quantified using the following four indices[3), 4)] (Fig. 5).

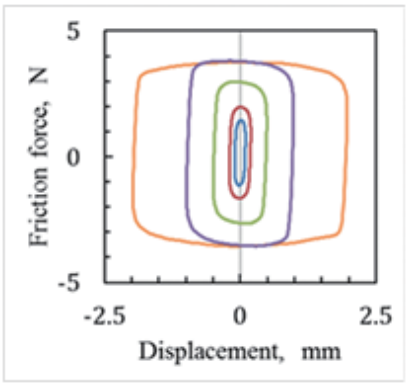
μRMS (average friction), *SI* (friction response), *RI* (roundness index), and *AI* (amplitude dependence)



SI (friction response)



RI (roundness index)



AI (amplitude dependence)

Fig. 5 Indices for evaluating dynamic friction characteristics

These indices made it possible to consider the magnitude of friction (*μRMS*), friction response (*SI*), and other dynamic friction characteristics as key design factors that influence ride quality. Based on the findings from relevant literature, this report focuses on average friction (*μRMS*) and friction response (*SI*), as they are considered strongly correlated with ride comfort. *SI* is an index that quantifies the rate at which friction increases immediately after a change in motion direction. Experimental verification has shown that the index substantially affects the smoothness of the initial response and the driver's perception of road contact[4), 5)].

Details on the friction adjustment technologies, such as the chemical composition and formulation of friction modifiers and design procedures, as well as the derivation and calculation methods, are available in References 1) to 8). Instead, this report focuses on the results of the evaluation indices and evaluation using actual vehicles.

These indices allow us to reflect the responsiveness in the micro-input range, which was difficult to determine with conventional damping force evaluation. This provides a new approach to improving ride quality through fluid design[4), 5)].

4 Vehicle Testing Methods and Analysis Techniques

For the vehicle testing, an accelerometer was attached to the vehicle's shock absorber. The vehicle drove on the test road surface at a fixed speed of 30 km/h. Data was recorded at a high sampling rate. The recorded data was filtered using FFT to calculate velocity and displacement via numerical integration. Then, we evaluated the suspension's response behavior (hereinafter, the "wavelet analysis").

This method enabled us to identify high-frequency vibrations that occurred immediately after a change in motion direction. These vibrations were difficult to detect using conventional damping force evaluation methods. Thus, we established an analytical framework for quantitatively evaluating the effect of differences in friction response on ride quality. Note that this analysis aims to accurately identify differences in responsiveness within the micro-input range. This method is particularly effective for examining correlations with *SI* [1), 6)].

5 Vehicle Test Results and Ride Feel Evaluation

We confirmed that there is a clear difference in vehicle response and sense of road contact due to differences in the fluid's friction characteristics (*SI*), even when the damping force characteristics are the same. *SI* is not a simple indicator where "higher is better" or "lower is better." Rather, it is crucial to adjust the *SI* to fall within an appropriate range.

5. 1 Test Overview

This study compared three formulations (1), (2), and (3) of the fluid with fixed vehicle, damper, and valve specifications. Table 1 and Fig. 6 show the average friction (*μRMS*) and friction response (*SI*) for each formulation.

Wavelet analysis (CWT, asphalt) was used to compare the three formulations ((1), (2), and (3)).

Conditions: Asphalt-paved test course at a constant speed of 30 km/h, Vehicle: Toyota Corolla Sport. The only variable was the fluid.

The on-road sensory evaluation (on ice, low μ) compared the formulations (2) and (3).

Conditions: Vehicle: Toyota Yaris (one vehicle with the same specifications for each formulation); Outside temperature: -5℃; Weather: Sunny; Road surface: Ice (low μ).

Table 1 Fluid friction characteristics for vehicle testing

Symbol	Base oil and formulation	Average friction (μ_{RMS})	Friction response (*SI*)
(1)	Mineral oil and conventional formulation	Low	Low
(2)	Mineral oil and latest formulation	Medium	High
(3)	Synthetic ester base oil + friction modifier	Low	Medium

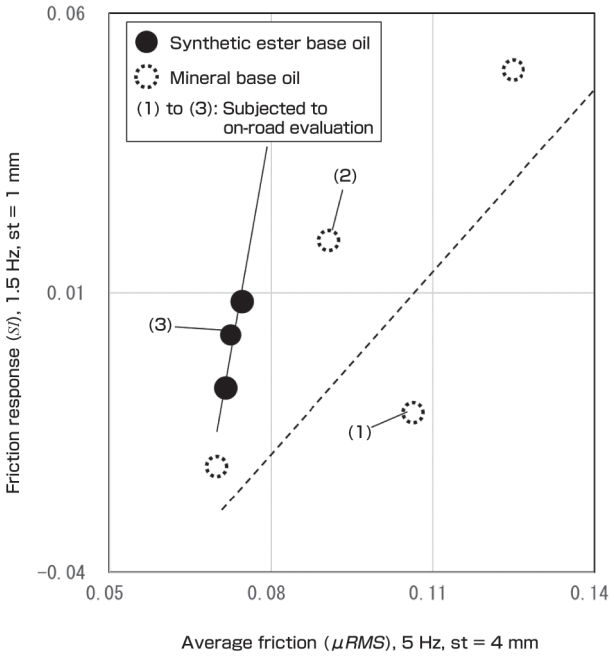


Fig. 6 Relationship between average friction (*μRMS*) and friction response (*SI*)

5. 2 Analysis Results

Fig. 7 shows the results of the wavelet analysis (CWT, asphalt, 30 km/h, Corolla Sport). Compared with the conventional formulation (1), the latest formulation (2) and the formulation with the synthetic ester base oil and friction modifier (3) showed a tendency for the high-frequency components in the 100-250 Hz range to decrease. This is likely due to the suppression of the acceleration peak immediately after a change in motion direction by optimizing the friction characteristics, particularly the friction response (*SI*). Thus, the analysis demonstrated that the magnitude (*μRMS*) and rising rate (*SI*) of friction are reflected in the actual driving response.

Furthermore, we compared the 100-250 Hz range in formulations (1), (2), and (3) to determine the characteristics before and after optimizing the friction response.

5. 3 Sensory Evaluation Results

On ice, where the road surface friction coefficient (μ) is low, differences in road holding performance can be easily reflected in sensory evaluations. Driving on ice involves high-frequency inputs due to fine surface irregularities and repeated slip-and-grip cycles. Meanwhile, the piston speed remains near zero for a relatively long time. This results in a weaker rise in hydraulic damping force. Consequently, differences in friction response are likely to appear immediately after a change in motion direction.

Evaluation results

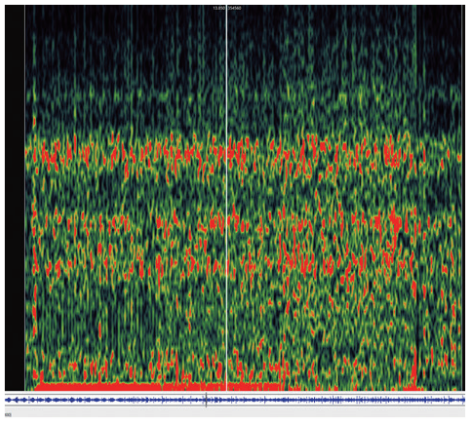
In the sensory evaluation (no quantitative measurements were taken), professional drivers commented that the initial response felt natural, that the sense of road contact was improved, and that it felt like driving on a completely different set of tires. General users commented that bumpy roads felt smoother, steering was better, and the car felt more stable. Thus, the differences in friction response were clearly perceived as distinct (Table 2).

5. 4 Conclusions

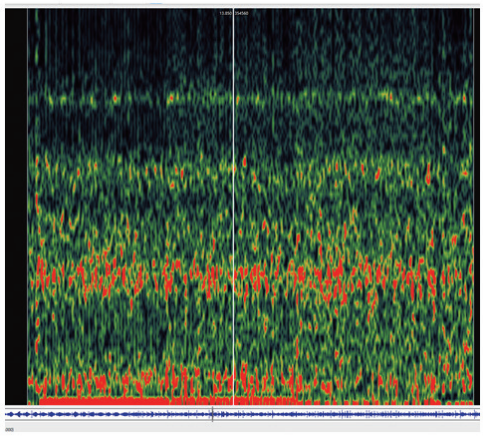
(1) *SI* has an "optimal range." Too high an *SI* tends to lead to worse ride comfort, while too low an *SI* is likely to result in a weaker sense of road contact. Fine-tuning during actual driving is essential to finding the optimal point.

(2) Simply lowering the average friction (*μRMS*) does not solve problems. While lowering *μRMS* certainly contributes to ride comfort, simultaneous optimization with friction response (*SI*) is key.

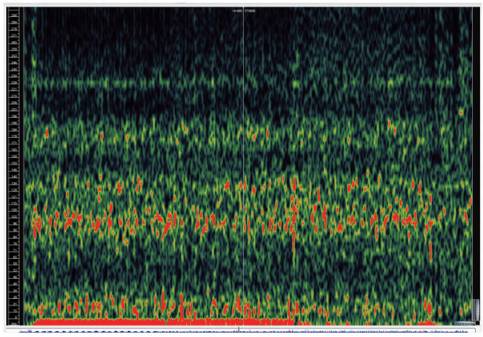
(3) The formulation (3) (synthetic ester base oil and friction modifier) is significant. The combination does achieve the design range of low average friction and moderate response. This formulation strikes a balance between the magnitude and rising rate of friction response, which was previously difficult to achieve. This formulation provides significant environmental and driving performance benefits.



(1) Mineral oil of conventional formulation (low average friction)



(2) Mineral oil of latest formulation (high response)



(3) Synthetic ester base oil (medium response)

Fig. 7 Vehicle test comparison of frequency range through wavelet analysis (before and after SI optimization)

Table 2 Summary of drivers' comments (on roads with low μ)

Driver	Topic	Representative comments (quoted)
Professional (multiple)	Smooth driving	The weight transfers properly and the steering responds well. Steering is smooth even when turning the wheel slowly.
Professional (multiple)	Improved responsiveness	Initial responsiveness is linear and moderate. The steering responds even to the slightest input.
Professional (multiple)	Perceived improvement in tire performance	It feels like I'm driving on a different set of tires.
Professional (multiple)	Improved grip limit	It doesn't reach its grip limit right away.
General user (multiple)	Smooth driving	Bumpy roads feel smoother. It responds exactly as it should.
General user (multiple)	Improved responsiveness	It responds well even to light steering inputs. Slalom speed has increased.
General user (multiple)	Improved steering	Handling is excellent. It does exactly what I want it to.
General user (multiple)	Lower vibration	Vibrations are well-controlled.
General user (multiple)	Vehicle stability	It feels stable.

(Note: Personal name undisclosed; Source: Internal Evaluation Slide "Drivers' comments (Experience on roads with low μ)")

6 Environmental Performance

We verified that the shock absorber fluids we developed are biodegradable using an OECD 301F-based evaluation. Using a base oil made from circular-based raw materials allows us to contribute to CN.

Furthermore, these fluids are designed for easy recycling and reuse, improving the efficiency of after-use treatment and reuse processes. Thus, the fluids are advantageous for reducing environmental impact and recycling resources.

These fluids were used in vehicles that participated in the 2024 BAJA 1000 (Photo 2) and the 2025 Rally Hokkaido. While possessing the environmental performance, these fluids consistently delivered stable driving performance, even under the harsh operating conditions, proving their practicality and sustainability. Participating in these rallies was a significant step toward future implementation in society. Going forward, we will promote the use of these fluids and establish a recycling scheme. Our goal is to create a technological foundation for further implementing CN.

Photo 2 Vehicle that participated in BAJA 1000 (LEXUS LX600 "OFFROAD" TEAM JAOS 2024 ver.)

7 Future Prospects

This technology can be applied to more than just passenger cars. It can also be used for various hydraulic products, including construction machinery, railways, and ships. We believe that friction response control technology will be fundamental to future predictive modeling and design standardization, contributing to the realization of a sustainable mobility society.

Furthermore, hydraulic equipment manufacturers' research and development of hydraulic fluids leverages their expertise in both mechanical structures and material properties. This initiative combines mechanical and material technologies, which can only be achieved by specialized manufacturers. Against this backdrop, KYB will continue to develop hydraulic fluids that integrate environmental sustainability and differentiated technologies, achieving a balance between product performance and sustainability.

8 In Closing

This initiative presented a fluid design guideline centered on friction response control for developing shock absorber fluids using synthetic ester base oils. This approach achieves both ride quality and environmental performance. By focusing on the build-up of friction rather than its magnitude, we have successfully increased responsiveness within the micro-input range. The developed fluids have also received high ratings in vehicle testing. Through a tribological approach, the characteristics of friction behavior, which had not been fully clarified in the past, are becoming clear [7]. Wavelet analysis (CWT, 30 km/h, Corolla Sport) on an asphalt-paved test course revealed that formulations with optimal friction response (*SI*) reduce high-frequency components in the 100-250 Hz range and suppress the acceleration peak immediately following a change in motion direction. This indicates that including the "magnitude" and "rising rate" of friction in the design parameters clearly affects frequency range evaluations. This results in a reduction of high-frequency vibrations, which may also lead to lower noise, vibration, and harshness (NVH). Furthermore, we believe this feature can also contribute to the advanced quietness required in the electric vehicle (EV) era.

On the other hand, during vehicle testing on ice (low μ) with a Toyota Yaris vehicle (identical specifications, with only the fluid replaced), when the input was small and the piston remained near zero speed for an extended period, the differences in friction response immediately after a change in motion direction were clearly perceived as distinct. Professional drivers commented that the initial response felt natural and that the sense of road contact improved. They said it felt like driving on a different set of tires. Nonprofessional drivers commented that bumpy roads felt smoother, handling was better, and the car felt more stable. Thus, the differences in friction response were clearly perceived as distinct. This improved sense of road contact may contribute to improved driving stability and safety [3]. *SI* is not a simple indicator where "higher is better" or "lower is better." Rather, it is crucial to adjust the *SI* so that it falls within the appropriate range. Additionally, testing implied that lowering average friction (μRMS) improves ride comfort, but simultaneous optimization with *SI* is key.

In particular, the formulation (3)-low average friction and medium response, achieved by combining synthetic ester base oils and friction modifiers-demonstrated a balance between the magnitude and rising rate of the friction response. This balance was difficult to achieve with conventional mineral oil-based formulations. This formulation pioneered a new design domain that contributes to the simultaneous achievement of ride comfort and road contact (steering stability). This provides significant benefits in terms of driving performance, in addition to the environmental advantages of synthetic esters.

This technology was recognized for its contribution to improved shock absorber friction control and performance, winning the FY2022 Engineering Award from the Japanese Society of Tribologists (JAST) [8].

Based on this technology, we developed SustainaLub, a new shock absorber fluid. SustainaLub is the result of technical development aimed at achieving environmental and driving performance with an eye toward future practical application. The product represents KYB's unique engineering concept [9].

Furthermore, we considered ease of recycling and reuse from the formulation design stage with an eye toward social implementation and resource circulation. Our goal is to further achieve CN by establishing a recycling scheme. In the future, we plan to accelerate the implementation process and develop SustainaLub as a sustainable mobility technology that paves the way for new possibilities in automotive tribology.

References

1) KATO Shinji: "The Effects of Shock Absorber Fluids on Vehicle' Ride Comfort and Steering Performance," Monthly Tribology, 35(5), 27-31, 2021.
2) NAKANISHI Hiroshi: "Technical Trends and Tribology of Shock Absorber," Journal of Japanese Society of Tribologists, 54 (9), 598-603, 2009.
3) KATO, SASAKI: "Study of Evaluation Index Characterizing Dynamic Friction Characteristics in Shock Absorber," Journal of Japanese Society of Tribologists, 64(1), 55-62, 2019.
4) S. Kato and S. Sasaki: Effects of hydraulic oil and lubricant additives on dynamic friction properties under various reciprocating sliding conditions, Friction, 8 (2), 471–480, 2020.

5）KATO Shinji: “Research on Friction Characteristics of Shock Absorber Lubricants,” KYB Technical Review No.45, 22-29, 2002.
6）S. Kato and N. Samadi: The Power of Oil–Influence of Shock Absorber Oil on Vehicle Ride and Handling Performance, 11th International Munich Chassis Symposium, 93–107, 2020.
7）KATO Shinji, SASAKI Shinya: “Study on the Influence of Shock Absorber of Friction Characteristics of Reciprocating Sliding on Sensory Characteristics of a Vehicle,” Journal of Japan Society for Design Engineering 54(4), 253-264, 2019.
8）KATO Shinji: “Improving the Performance of Automotive Shock Absorbers through Tribology - Techniques for Evaluating Dynamic Friction Characteristics and Control Technologies,” Journal of Japanese Society of Tribologists, 68(11), 778-781, 2023.
9）KATO Shinji: “KYB: Carbon-Neutral Shock Absorber Oil, with Tribology as a Core Technology – Interview with Shinji Kato of KYB Corporation,” Editor: Journal of Economic Maintenance Tribology/Lubrication Technology Inc. (706), 29-33, 2024.

Authors

KATO Shinji

Joined the company in 1987. Dedicated Department Manager, Product Development Office, Engineering Headquarters, Automotive Components Operations. Took present post after working as Materials Engineering Sect. Manager, Basic Technology R&D Center.

ISHIDA Koya

Joined the company in 2019. Product Development Office, Engineering Headquarters, Automotive Components Operations. Engaged in development of shock absorber fluids.

YASUKOUCHI Naoki

Joined the company in 2006. Dedicated Section Manager, Product Development Office, Engineering Headquarters, Automotive Components Operations. Engaged in development of shock absorber fluids.