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Advanced Hydraulic Fluids Make Mobile Machinery Not Only More Sustainable, but Also More Economical

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Abstract.

Europe is pursuing ambitious climate goals: by 2030, net greenhouse gas emissions are to be significantly reduced—by 65% in Germany compared to 1990. Globally, the pressure to cut emissions and promote sustainable technologies is also increasing. Mobile machinery such as excavators, wheel loaders, and other hydraulically operated equipment is coming into sharper focus, as these machines play a central role in construction, agriculture, and industry.

This technical study explores how advanced hydraulic fluids can contribute to achieving these goals. By using shear-stable viscosity index improvers based on polyalkylmethacrylates, fluids can be formulated to maintain high efficiency across a wide temperature range. This not only leads to energy savings of up to 20%, but also to a measurable reduction in CO_2 emissions.

In addition to the environmental impact, the economic perspective is also examined: despite higher initial costs, these fluids offer a positive long-term return on investment—through reduced energy consumption, extended component life, and lower maintenance costs.

The study is based on Evonik's many years of experience in developing and testing such high-performance fluids. Using technical data and case studies, it demonstrates how modern fluid technology can contribute to the sustainable transformation of mobile hydraulics.

Keywords: Hydraulic systems, Hydraulic fluids, Viscosity index improvers, Polyalkyl methacrylate (PAMA), Reduced energy consumption, Total cost of ownership (TCO)

1. INTRODUCTION

In mobile hydraulic machinery, the total cost of ownership has become one of the most critical competitive factors. For machine owners and operators, fuel or energy costs and maintenance requirements play a decisive role in daily operations.

Rising fuel prices, stricter emissions requirements, and uncertainties in the supply of energy and raw materials have intensified the pressure to reduce energy losses in hydraulic systems. As a result, hydraulic efficiency and fluid performance are no longer secondary topics — they directly determine operating cost, machine uptime, and competitive positioning in the mobile equipment market.

At the same time, mobile machinery contributes significantly to global energy consumption and CO_2 emissions. Even incremental improvements in hydraulic efficiency, fluid formulation, and component durability can therefore offer substantial potential for reducing operating costs and environmental impact across large fleets.

The reasons for this are high fuel and energy cost and uncertainties in the supply of energy [1, 2] and raw materials (Figure 1.1).

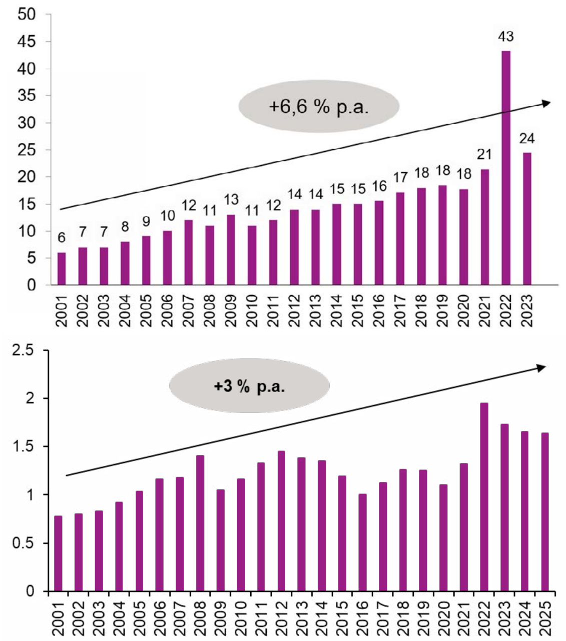

Figure 1.1. Electric energy price in €cent/kWh over time in the 21st century [3,4] and diesel retail price in €/l [5] in Germany.

Efficiency improvement potentials have been repeatedly demonstrated in the mobile machinery and industrial sector [6,7]. However, the implementation of energy efficiency measures is often slow, and several hurdles need to be overcome. The low acceptance, despite economic advantages, is attributed to a number of obstacles, which have been investigated by numerous studies [8]. A well-known obstacle mentioned in several surveys is the lack of resources, time, and educated staff. Additionally, the effort required for the planning and implementation of energy efficiency measures represents a further barrier.

The optimization of construction sites in terms of up time process efficiency is not only a business requirement, but also a decisive step on the way to a climate-neutral society. A bundle of measures is available, which differ significantly in terms of investment costs and complexity [8]. A simple measure to achieve both, cost and emission reduction, is to increase the energy efficiency of the hydraulic system by choosing a suitable hydraulic lubricant. This approach does not require hardware design modifications and can therefore be easily applied to existing hydraulic driven machines. Since hydraulic oils are changed regularly anyway, the associated effort is also low.

2. HYDRAULIC OILS IN MOBILE MACHINES

Hydraulic fluids are widely used in industry. Their properties result from the choice of base oils and the selection and combination of suitable additives. Viscosity has a great influence. In principle, it is possible to reduce hydromechanical losses by using low-viscosity fluids and thus (theoretically) increase the efficiency of the machine, unless volumetric losses in hydraulic systems increase too much as a result of this measure. With very low viscosities there is a risk that no sufficient lubricating film will be formed in contact points that are subject to high temperatures leading to increase of mixed friction and increase of wear. This risk is avoided by reducing the temperature dependence of the viscosity of the lubricant – i.e. increasing the viscosity index (VI) – by using suitable VI improvers and/or base oils with high VI. An additional risk of simply lowering the viscosity is to increase the chance of an external leakage in older machines at elevated temperatures where fluids with low viscosity index will have dramatically reduced viscosity.

For hydraulic applications, it has been shown that both, viscosity index and shear stability of the fluid are decisive for the level of efficiency [6,7]. Figure 2.1 demonstrates the opposing characteristics of mechanical and volumetric efficiency in hydraulic equipment [6,7]. A low viscosity reduces internal friction and has a positive effect on the mechanical. The opposite is true for volumetric efficiency, which decreases as viscosity decreases. Overall efficiency is the combination of both efficiencies.

The aim is to minimize both, the "Total Cost of Ownership" (TCO) and the “GreenHouse Gas” (GHG) emissions, two parameters that are linked via the lifetime, reliability, and efficiency of equipment.

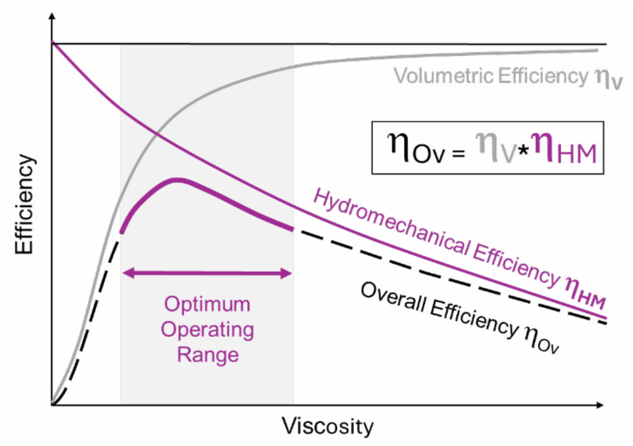

Figure 2.2. Correlation of efficiency and viscosity in a hydraulic pump [6,7]

3. VALIDATION OF FUEL AND ENERGY SAVINGS

Figure 2.1 describes a step-by-step approach to validate effects of an oil changes in hydraulic systems. An oil change can be an easy way to reduce overall cost in terms of savings on maintenance, energy consumption, and GHG emissions. The procedure to realize oil changes in mobile and stationary hydraulics was investigated and demonstrated for various systems (excavators, wheel loader, skid steer loader, tractor).

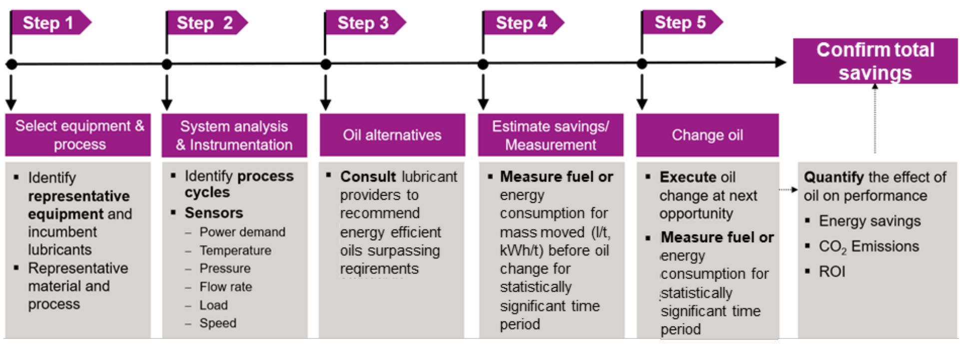

Figure 2.3. Universal step by step approach to execute oil changes and confirm fuel or energy savings.

In this article, the authors present an overview of observed effects depending on the fluid rheological properties and describe in more detail the effects of fluid in an excavator operation.

The field trial employed a medium-class hydraulic crawler excavator representative of machines in the 23–26 ton operating-weight range. According to published technical data for machines of this class, such excavators typically exhibit an operating weight between 23,400 and 26,050 kg and are powered by a diesel engine rated at approximately 129 kW (≈175 HP). The excavator used in the study incorporates a conventional hydraulic architecture consisting of three hydraulic cylinders controlling the boom, a single cylinder for the stick (arm), and an additional single cylinder for bucket articulation. Interchangeable digging buckets with nominal capacities of 0.75 t, 1.25 t, and 1.75 t were utilized to assess loading behavior and cycle efficiency under varying tool masses. This configuration is representative of typical quarry-class loading equipment.

To support the excavation cycles and evaluate downstream productivity effects, the test setup also employed a 25-ton class dump truck for material hauling and a wheeled loader for auxiliary material handling and site servicing. The integration of these machines enabled a controlled assessment of how changes in hydraulic fluid formulation influence the excavator's energy efficiency, loading dynamics, and overall productivity across a complete loading–hauling cycle.

The trial was conducted in a stone quarry environment in Gimbsheim, Germany, where conditions allowed repeatable and consistent measurement. An on-site truck scale facilitated accurate mass determinations for each truckload, enabling quantification of fill mass, bucket productivity, and cycle uniformity. The test material consisted of gravel stone with an approximate particle size of 1 inch, providing a homogeneous granular medium suitable for comparing hydraulic performance under realistic working conditions.

This instrumentation framework ensured a controlled, measurable, and representative evaluation of hydraulic system behavior in real-world quarry operations.

The experimental program consisted of seven test oils including reference fluid, each subjected to 31 operational test cycles per day, executed in three independent replicates to ensure statistical robustness. A reference oil was incorporated systematically throughout the campaign—at the beginning, midpoint, and end of each daily sequence—to monitor drift and establish baseline repeatability. Additional reference runs were scheduled immediately after the first test oil, after the machine's return to site, and at the conclusion of the final oil evaluation, providing a continuous calibration framework across the multi-day campaign. The order of oils was selected pragmatically to accommodate site logistics and thermal behavior, recognizing that operational temperatures naturally increased over the day, typically rising from 50 °C to 70 °C. Hydraulic oil temperature control was further refined by enforcing 100% cooling-fan duty via CAN-bus command, complemented by a deliberate reduction of the cold-air suction-hose cross-section, enabling tighter regulation of thermal boundary conditions during each test run.

Each oil was evaluated over a four-day operational block, followed by a dedicated operator test on day five, after which the machine underwent a one-day flushing and refilling procedure before transitioning to the next fluid. Two operators participated in the study, with both operators performing tests each day to reduce operator-specific bias. Operator sequencing was predefined and maintained consistently, applying the same order on days 1 and 3 as on days 2 and 4. For each oil, 16 test sequences per operator were executed, ensuring balanced exposure of each hydraulic fluid to varying operational styles and workloads. The 16 test sequences were distributed between moving, truck loading and digging cycles.

A stringent oil-flushing procedure was implemented between fluids to prevent cross-contamination. This process comprised four complete flushing cycles, performed with the excavator's boom and arm fully extended to maximize hydraulic-volume exchange, followed by one full refill of fresh test oil. The viscosity of the filled oil was measured at both the beginning and end of each test period to document potential degradation or shear-related viscosity loss over the operational interval. Collectively, this methodology provided a highly controlled and repeatable framework for quantifying the influence of hydraulic-fluid formulation on excavator performance, thermal stability, and cycle efficiency.

4. TESTED FLUIDS

The hydraulic fluids evaluated in this study consisted of formulations built on a standard hydraulic fluid anti-wear/oxidation inhibitor (DI) additive package, combined with base oils spanning API Group II, Group III, and Group IV quality levels. The product matrix was intentionally designed to see if the influence of base-oil quality and viscosity-index (VI) performance on hydraulic efficiency, including fluids blended with second-tier high-VI Group III stocks as well as maximum-VI formulations relying on Group IV (PAO) components can be elaborated. The set included conventional mono-grade fluids (ISO VG 46 and ISO VG 68) with moderate viscosity indices (VI 105 and VI 98, respectively), as well as a series of high-VI multigrade formulations engineered to deliver enhanced viscometric stability: VG 32 VI 189, VG 46 VI 112, VG 46 VI 155, VG 46 VI 167, and an ultra-high-VI VG 25 VI 285 fluid (see Figure 4.1). These exhibited viscosity indices ranging from 112 to 285, covering the practical performance envelope from improved cold-start viscosity control to advanced shear-stable elastomer-friendly multigrade behavior. Kinematic viscosities at 40 °C and 100 °C varied accordingly, from 26.0 to 71.2 cSt at 40 °C and 7.08 to 9.13 cSt at 100 °C, reflecting the tailored grade-dependent rheology. Shear stability, measured in a 40-minute ultra sonic test (ASTM D5621) viscosity loss, ranged from 0.45% in the mono-grade VG 68 to 15% in the ultra-high-VI VG 25, capturing differences in polymeric thickener architecture, treat rate, and mechanical shear sensitivity. Collectively, this hydraulic-fluid matrix provided a broad and controlled variation in base-oil structure, viscosity grade, and viscosity index improver properties, enabling systematic assessment of how fluid formulation influences excavator hydraulic efficiency, thermal behavior, and operational productivity.

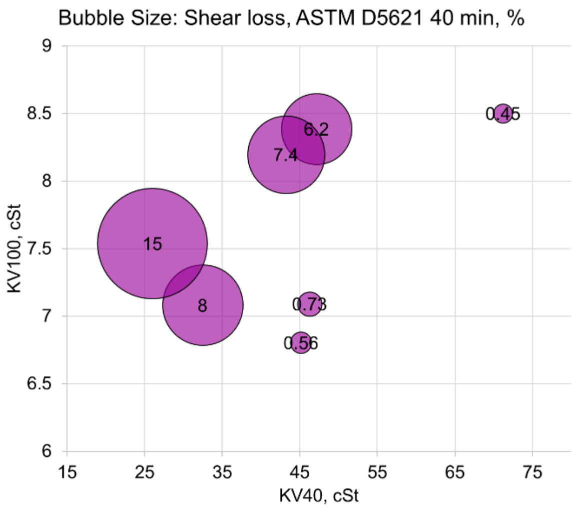

Figure 4.1. Overview of the rheological properties of seven tested fluids.

5. RESULTS

5.1. Performance Outcomes Across Viscosity Grades and Viscosity Indices

The weighted overall efficiency improvement (45% digging + 45% truck loading + 10% traveling) results (Figure 5.1) reveal a clear stratification of fluid performance driven primarily by viscosity grade (KV40) and viscosity index (VI). The reference monograde ISO VG 46 (KV40 = 45.16 cSt, VI = 105) establishes the 0% baseline. Deviations from this baseline strongly follow the expected physical mechanisms: reductions in viscosity grade paired with sufficiently high viscosity index produce substantial improvements in hydraulic efficiency, whereas increases in viscosity grade or insufficient VI lead to penalties. This is illustrated by the poorest-performing fluid, ISO VG 68 (KV40 = 71.2 cSt, VI = 98), which shows a −6.1% efficiency decrease due to elevated hydromechanical losses at higher viscosity. Conversely, the highest-performing fluids—ISO VG 22 with 285 VI and ISO VG 32 with 189 VI — demonstrate improvements of +13.6% and +10.7%, respectively, underscoring the strong advantage of pairing relatively low kinematic viscosity at 40°C with very high VI to minimize frictional losses while preserving pump leakage control at elevated temperatures.

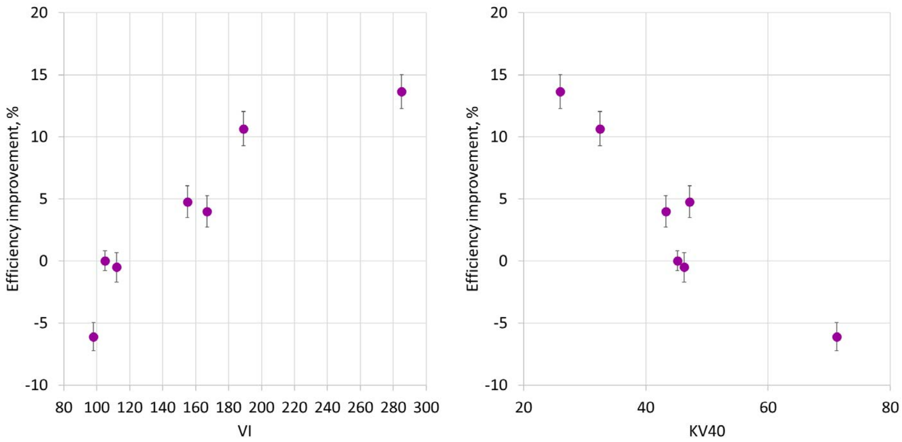

Figure 5.1. Efficiency improvement of test fluids with varying viscosity index (VI) and kinematic viscosity at 40°C (KV40) compared to the ISO VG 46 Monograde fluid in a combined cycle 45% digging + 45 % truck loading + 10 % traveling.

5.2. Influence of Viscosity Index (VI) on Efficiency

VI emerges as a decisive factor in the test results, exerting a strong positive influence on overall efficiency also when viscosity grade is held relatively constant. Among the ISO VG 46-based fluids, an increase in VI from 105-112 VI to 167 VI boosts efficiency from −0.5…0% baseline to +4.0…+5%, despite no significant differences in KV40. These results emphasize that VI governs the fluid's ability to maintain optimal viscosity as the temperature rises during operation. High-VI fluids prevent excessive thinning, thereby sustaining both lubrication, internal/external sealing effectiveness in pumps and actuators.

5.3. Effect of Viscosity Grade Reduction

The data strongly support viscosity-grade reduction—provided VI is sufficiently high. Fluids with markedly reduced KV40, such as 285 VI ISO VG22 (KV40 = 26 cSt) and 189 VI ISO VG 32 (KV40 = 32.5 cSt), consistently deliver the largest efficiency gains: +13.6% and +10.7%, respectively. These improvements are attributable to significantly lower hydrodynamic losses in pump, valve components and pipes, allowing hydraulic actuators to cycle faster and with reduced energy consumption. However, these gains only materialize because VI values are high (VI = 285 and VI = 189), preventing the fluid from becoming too thin during operation that it compromises volumetric efficiency or pump protection. In contrast, fluids with moderate KV40 but insufficient VI—such as 105…112 VI—experience efficiency losses or negligible gains due to poorer thermal viscosity retention.

5.4. Role of Shear Stability in Maintaining Volumetric Efficiency

Shear loss, measured via ultrasonic shear thinning (ASTM D5621, 40 min) for fluids, having the viscosity index improvers (VIIs) ranged from 6.2% to 15% across the fluids. This type of shear loss correspond to the middle to high tier type of the VIIs used in hydraulic fluids. The results confirm that low to moderate shear loss supports efficient hydraulic operation by preventing excessive polymer breakdown and preserving the volumetric-efficiency advantage conferred by high VI. For example, 167 VI (shear loss = 7.4%) and 155_VI (6.2%) both maintain efficiency increases near 4–5%, however the fluid with 155 VI outperformes the fluid with 167 VI while even having slightly higher KV40, indicating that shear stability remains additional decisive factor to boost efficiency as already noted earlier [6]. The overall trend shows that lower shear loss helps sustain volumetric efficiency, in high-VI fluids where fluid temporary thinning or permanent breakdown would otherwise erode the sealing benefit.

6. Implications on the Total Cost of Ownership and Avoided Emissions

Adopting a multigrade hydraulic fluid (ISO VG 46, VI 155) in place of a monograde ISO VG 46, VI 105 yields a measurable improvement in total cost of ownership and a material reduction in emissions over a single drain interval. Under the realistic assumption of a fleet of five machines, each consuming 26 L/h of diesel and filled with 900 L of hydraulic fluid, with a 2,500 h drain interval—the empirically observed 5% efficiency gain translates directly into lower fuel use during digging, loading, and travel. Priced at €1.60 per liter of diesel, the fleet-wide fuel saving over one interval amounts to €20,883. Against this benefit, the higher upfront cost of the multigrade—€4.50/L versus €2.00/L for the monograde—requires an additional €11,250 to fill the fleet (Δ€2.50/L × 900 L × 5 machines). Even after accounting for this premium, the upgrade produces €9,633 in net savings within the same service cycle. Typically high quality premium hydraulic fluids with high viscosity index bring an extended oil drain interval, which is not accounted for in the analysis here. Because fuel savings accrue with every operating hour, the investment reaches break-even well before the end of the interval—at roughly 1,350 operating hours per machine—after which all further savings are realized as pure financial gain. The environmental dividend is equally tangible: by avoiding the combustion of 13,050 L of diesel over the interval, the fleet prevents approximately 35 t of CO_2 emissions on a tank-to-wheel basis, contributing directly to Scope 1 reductions without any hardware changes or operational retraining. Mechanistically, these outcomes reflect the superior balance of mechanical and volumetric efficiency delivered by the higher-VI formulation: reduced viscous losses at operating temperature accelerate hydraulic cycles, while sufficient viscosity retention and controlled shear thinning preserve sealing and pump health. In practical terms, switching to ISO VG 46 VI 155 delivers a rapid-payback, low-risk pathway to lower operating costs and meaningful carbon abatement, realized entirely within a single drain interval.

7. Broader Field Experience and Generalization of Results

The excavator study presented here represents only one example within a much broader body of long-term field evidence. Over more than 20 years of active field-trial work, Evonik has collaborated with equipment owners and OEM partners to evaluate high-VI hydraulic fluids across a wide range of mobile machinery, operating environments, and hydraulic duty cycles. These long-duration studies—performed under real-world loading, digging, carrying, and travelling conditions—demonstrate that the qualitative efficiency- and productivity-enhancing mechanisms observed in the excavator trial are consistent, reproducible, and not machine-specific.

Across various equipment types—including skid steer loaders, compact and small-size excavators, mid-size excavators, and modern electronically controlled mid-size excavators—the introduction of high-VI, shear-stable multigrade fluids has resulted in clear operational gains. Depending on machine type and work mode, efficiency improvements have ranged from 6% up to 35%, and productivity improvements from 6% up to 25–35%. These effects have been observed under diverse hydraulic tasks: excavation, loading and carrying cycles, grading, travelling, and mixed operation. Importantly, the comparisons span a variety of baseline fluids—conventional ISO 46 HM monogrades, moderate-VI ISO 46 industrial fluids, and OEM 10W hydraulic formulations—demonstrating that the relative advantage of a higher-VI, thermally robust fluid holds regardless of the starting point.

A consistent pattern emerges from these long-term trials: fluids with higher viscosity index and carefully controlled shear stability maintain optimal viscosity under highly dynamic temperature and load conditions, thereby improving both mechanical and volumetric efficiency. This leads to faster hydraulic response, reduced pump losses, improved actuator speed, and more effective transmission of engine power into productive work. Crucially, these performance gains are achieved without any hardware modification. Machines require no changes to pumps, valves, filters, cooling systems, or control logic—operators continue to work exactly as before, while the hydraulic system benefits from the improved viscometric behaviour of the fluid alone.

Equipment type	Skid Steer Loader	Compact Excavator	Small-size Excavator	Mid-size Excavator	Modern Mid-size Excavator	
Type of work	Loading, carrying & dropping	Trench digging	Loading, carrying & dropping	Digging, grading, travelling & idling	Digging	
Ref. fluid	ISO 46 VI 140*	ISO 46 VI 140*	10W genuine oil	ISO 46 HM	ISO 46 HM	
Tested fluid	ISO 68 VI 200*	ISO 68 VI 200*	ISO 46 VI 195*	ISO 46 VI 170**	ISO 46 VI 157*	ISO 32 VI 190*
Efficiency Improvement	**up to 14%**	**up to 15%**	**up to 30%**	**up to 35%**	**up to 6%**	**up to 12%**
Productivity Improvement	**up to 16%**	**up to 14%**	**up to 25%**	**up to 35%**	**up to 6%**	**up to 14%**

* shear stable fluid
** very shear stable fluid

Improvement in Efficiency and Productivity obtained through high VI shear stable fluid and appropriate ISO grade in all trials

Figure 7.1. Generalized view on mobile equipment hydraulics field trial results at Evonik across the applications.

The combined evidence of two decades of field trials provides strong confirmation that the improved efficiency demonstrated in the excavator case study is representative of a broader principle: high-VI, shear-stable multigrade fluids enable both economically and environmentally superior operation of mobile hydraulic equipment, enhancing productivity while simultaneously reducing fuel consumption and emissions. This makes fluid-based efficiency improvement an immediately deployable, low-risk, and cost-effective lever for sustainable performance enhancement across the mobile hydraulics sector.

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