Examining the correlation between rheological profiles with fuel economy performance of low-viscosity oils for heavy-duty vehicle fleets

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Contents

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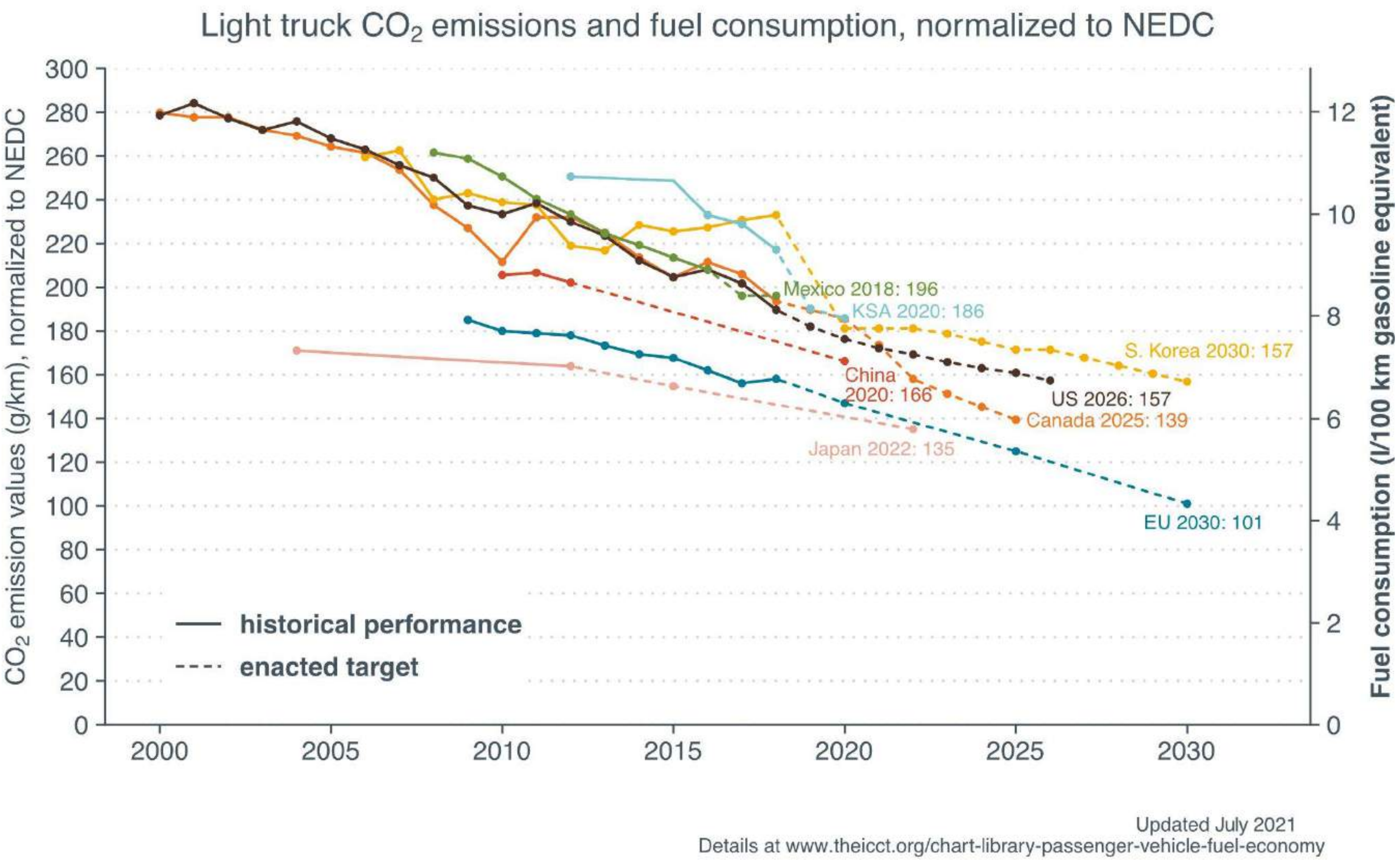
Improved fuel economy and reduced GHG

a global phenomenon



Source: The International Council on Clean Transportation, Zifei Yang and Anup Bandivadekar, 2017, chart update July 2021
https://theicct.org/wp-content/uploads/2021/08/plot_nedc_lcv_SAFEGHG-aug2021.jpg

Engine oil will play the dual role of directly **impacting fuel economy** and **enabling new engine technologies**.

As automotive fuel efficiency requirements increase, OEMs are placing **greater demands** on engine oil lubricants to provide both uncompromised engine protection and reduced friction at low viscosity.

Stringent emission legislation drives more rigorous improvement in fuel economy

Previous and current CO2 emission targets for new HDV

- **CO2 emission reduction targets for HDV (Heavy-Duty Vehicles):**

	Target date	CO2 reduction target (reference year 2019)
Previous 2019 targets	2025	- 15%
	2030	- 30%

	Target date	CO2 reduction target (reference year 2019)
Current 2023 targets	2025	- 15%
	2030	- 45%
	2035	- 65% All new city buses zero-emission
	2040	- 90%

- **Scope of the 2023 CO2 targets:**
  - Trucks : above 5 tons, as well as trailers.
  - City buses and long-distance buses : above 7,5 tons.
  - Exemption : small volume, mining, forestry, agriculture, army, civil protection, fire services ….

EU proposal for significantly stronger CO2 reduction targets in February 2023 with an important expansion of the scope of the regulation.

Newer engines and additive's role

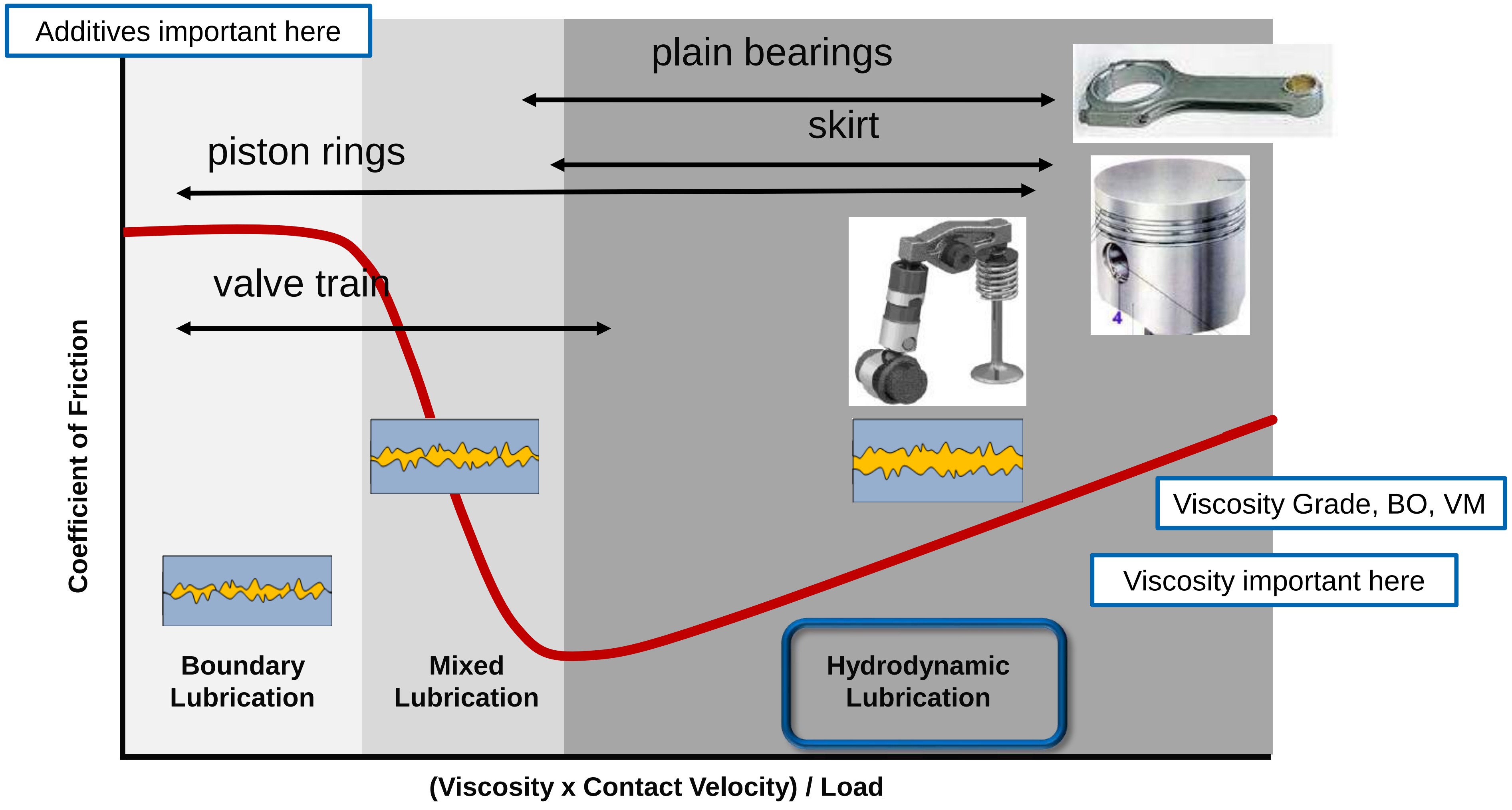
- OEMs have begun making significant **changes to the vehicle** and **engine hardware design** and **technology** to comply with these requirements
  - Move from aluminum pistons to steel pistons, allowing higher combustion pressures and temperatures, improving total efficiency
  - Consequently, engine parts are subjected to **greater thermal stress** and a **higher risk of moving parts** running into a boundary lubrication regime which induces a risk of higher wear levels.
  - Hydrodynamic and mixed lubrication regimes should not be ignored
- Along with optimizing the performance of newer engines, **low-viscosity oils directly affect fuel economy**: the lower the viscosity the greater the fuel economy potential
- Low-viscosity oils cannot compromise on durability or protection that fleet operators are accustomed to from the previous generation of thicker oils
  - That is where **additives play a critical role** in ensuring oxidation stability, wear control, and thermal stress protection in low-viscosity lubricant formulations

Trend toward lower viscosity heavy-duty engine oils

- The trend toward lower viscosity oils is not new. In December 2016, the industry introduced two new heavy-duty engine oil categories: **API CK-4** and **FA-4**. CK-4 oils; they address the new emission requirements of newer engines but are also backward compatible with older engines using higher viscosity oils, for example, SAE 15W-40.
- **The FA-4 standard specifies thinner oils**, 10W-30 and 5W-30, for heavy-duty applications. These lower viscosity oils are formulated specifically for newer engines designed to comply with stricter standards for fuel efficiency and greenhouse gas emissions.
- While approval and adoption of FA-4 oils have been slow, it has begun picking up in the past two years. Major European heavy-duty OEMs have started using **0W-20 or 5W-20** as their factory fill oils as pressure mounts to increase fuel economy and reduce emissions.

Fuel economy and lubrication conditions

Additives help to provide the right balance in an oil formulation to address **fuel economy while maintaining engine durability protection**

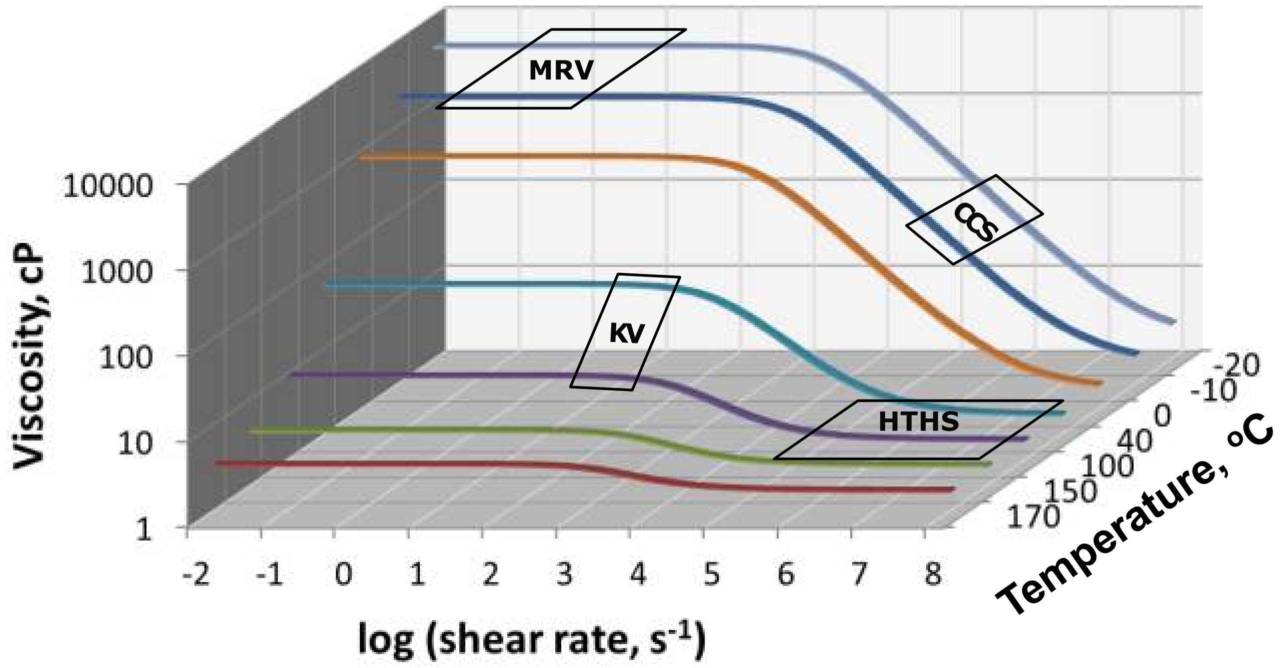


Introduction to rheology
tool to evaluate lubricating oils

- **Typical shear rates**
  - Pumping at cold start: $10^{-1} – 10^{1}$ s^{-1}
  - Oil consumption: $10^{2} – 10^{3}$ s^{-1}
  - Cranking at cold start: $10^{4} – 10^{5}$ s^{-1}
  - Friction in Engine: $10^{5} – 10^{7}$ s^{-1}

T.W. Bates, Oil Rheology and Journal Bearing Performance: A Review. Lub Sci. (2) p159

Rheometers measure viscosity over a wide range of shear rate and temperature.



Courtesy of TA Instruments

Instrumentation

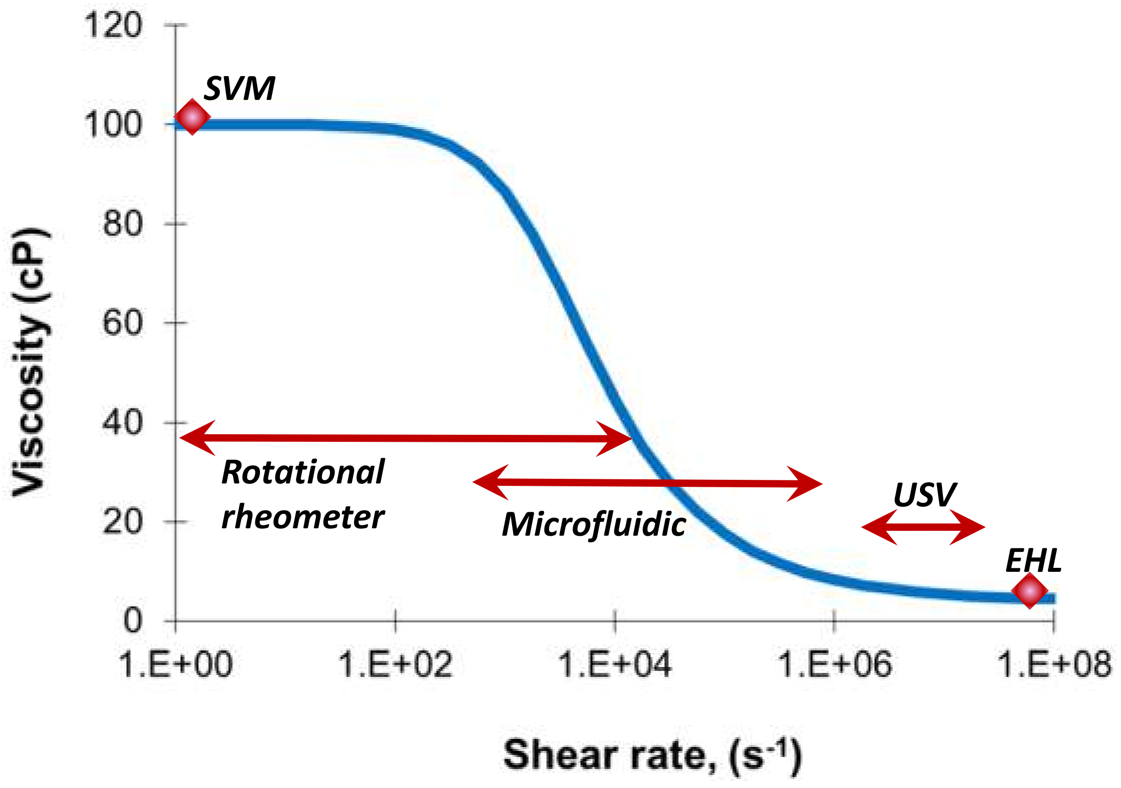
measuring different shear rate regimes

Stabinger Viscometer (SVM)

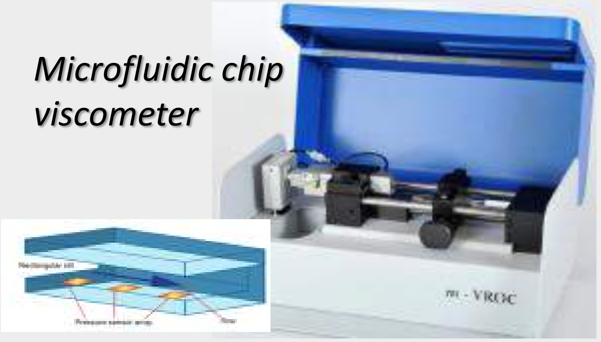
Courtesy of Anton Paar

Rotational rheometer

Courtesy of Anton Paar



Microfluidic chip viscometer



Courtesy of RheoSense

Ultra Shear Viscometer (USV)

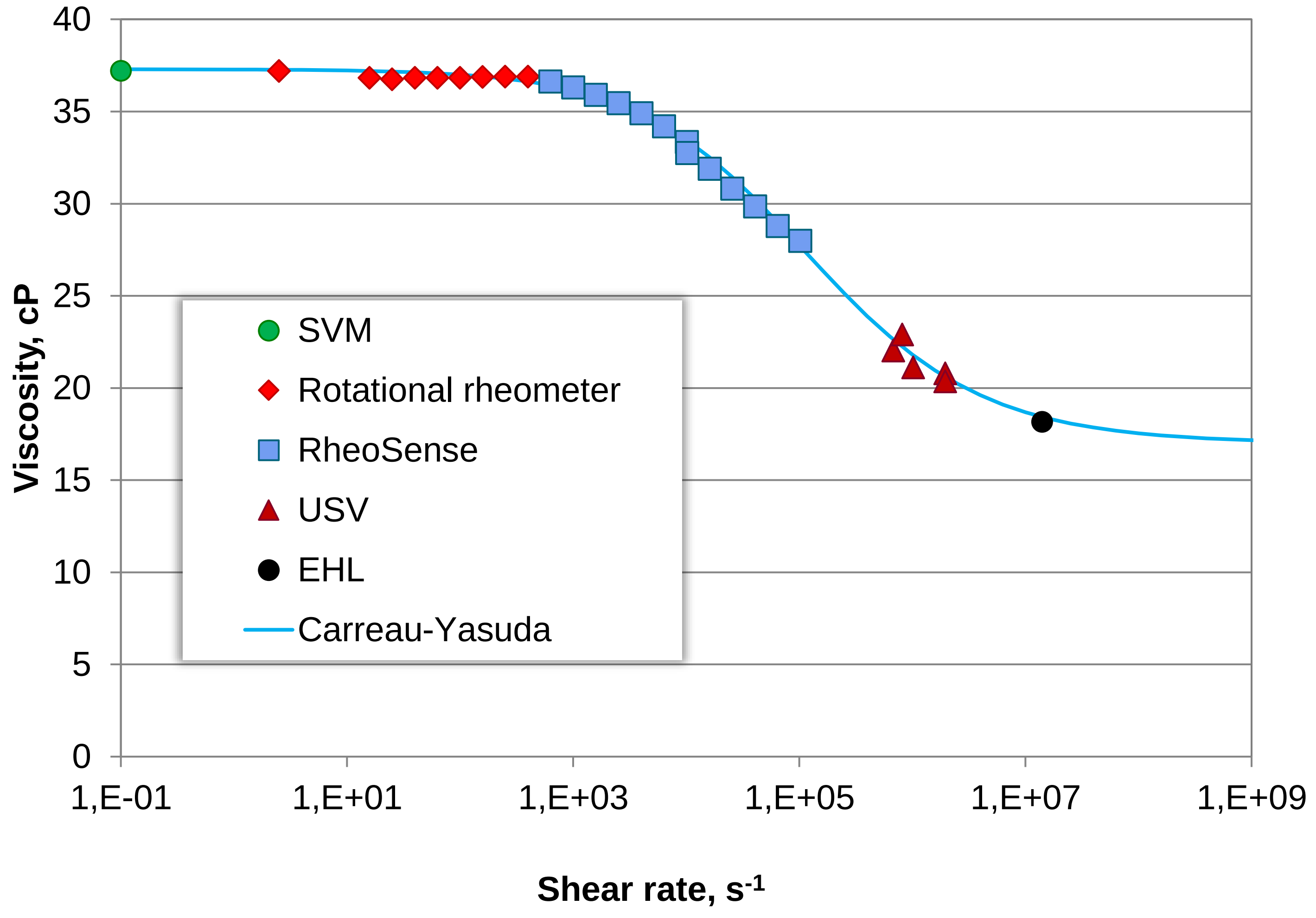
Courtesy of PCS Instruments

ElastoHydrodynamic Lubrication (EHL)

Courtesy of PCS Instruments

Rheological profile combination of all data

- Combining reliable data from difference sources used to plot the full viscosity curve at a given temperature.
- Carreau-Yasuda model used to describe experimental data
- In next slides, results of fitted model will be discussed.



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Internal Combustion Engine:
a collection of tribometers and rheometers

- **Valvetrain (1)**
  - boundary and mixed regime
  - high contact pressure ~ 1 GPa
  - high shear rates ~ 10^8 s^{-1}
  - lower viscosity → higher friction
- **Piston ring and liner (2)**
  - entire lubrication regime
  - lower contact-pressure
  - high shear rates ~ 10^6 -10^7 s^{-1}
  - lower viscosity → higher FM impact
- **Crankshaft (3)**
  - hydrodynamic regime
  - moderate shear rates ~ 10^4 -10^5 s^{-1}
  - higher viscosity → lower friction
- **Oil pump (4)**
  - hydrodynamic regime
  - Low shear rates

Valvetrain (1)

(2) (3) (4)

Nothing operates at exact HTHS conditions (150^oC at 10^6 s^{-1})

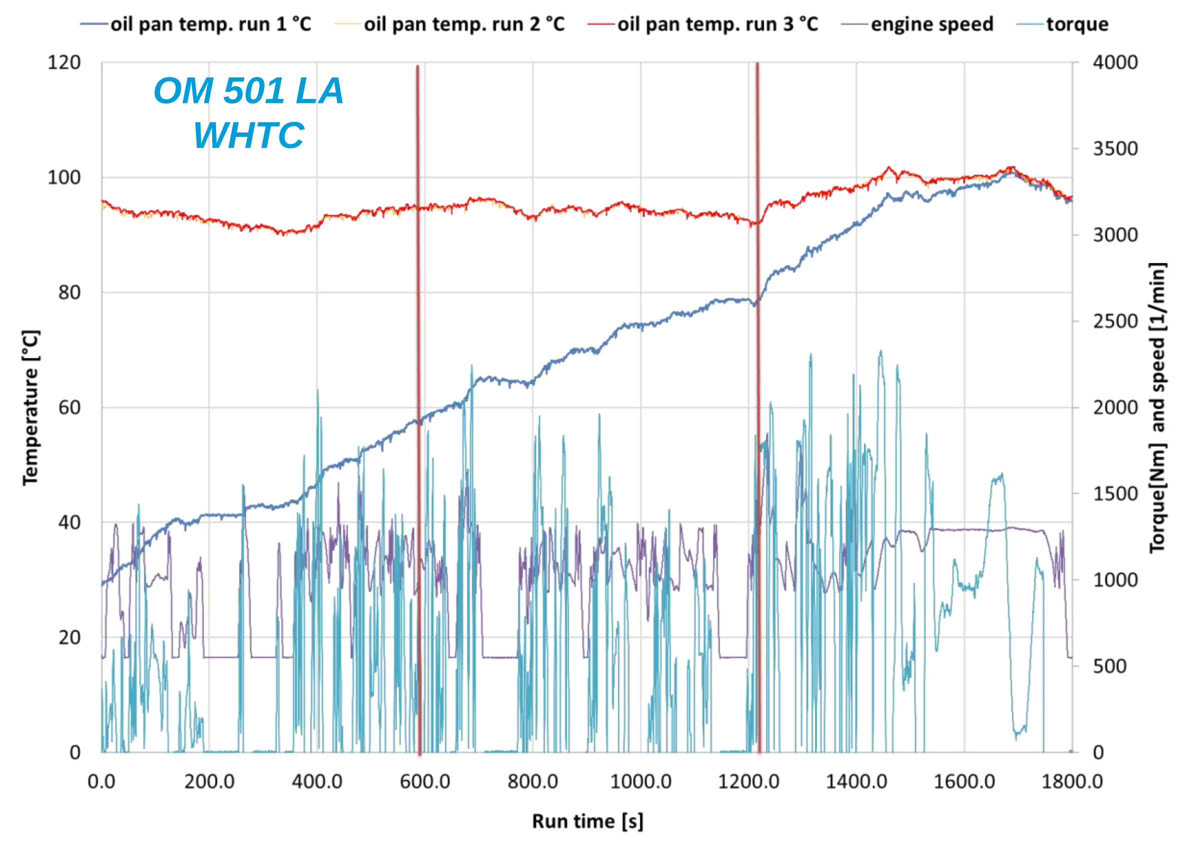
Fuel economy engine tests:
Detroit Diesel DD13 & OM 501 LA

Detroit Diesel DD13 engine used with EPA Supplemental Emissions Test (SET) cycle

DD13 SET

Mode	Engine Speed	Load, %
1	Low idle	0
2	A	100
3	B	50
4	B	75
5	A	50
6	A	75
7	A	25
8	B	100
9	B	25
10	C	100
11	C	25
12	C	75
13	C	50

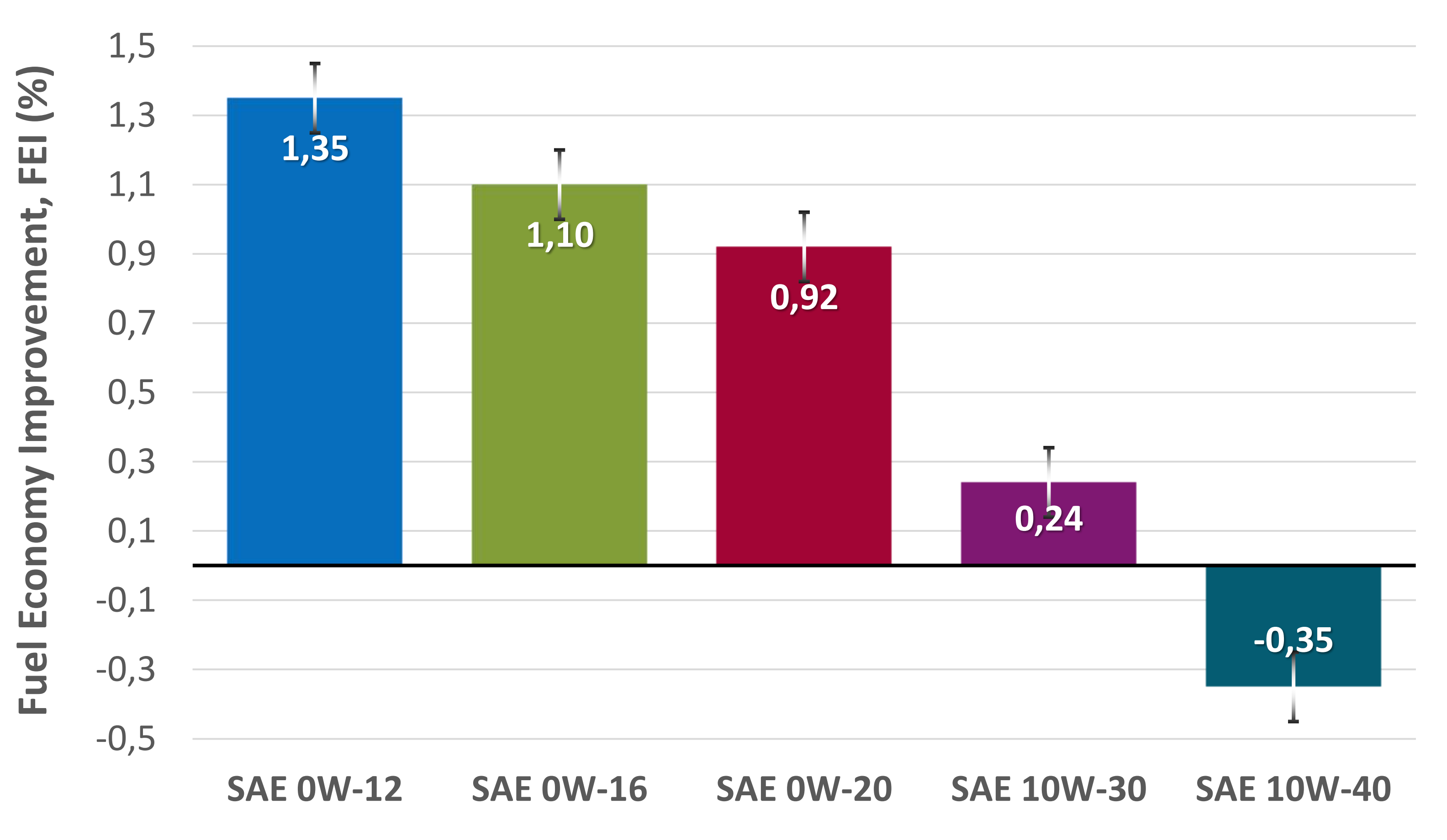
Mercedes-Benz OM 501 LA engine used with World Harmonized Transient Cycle (WHTC)



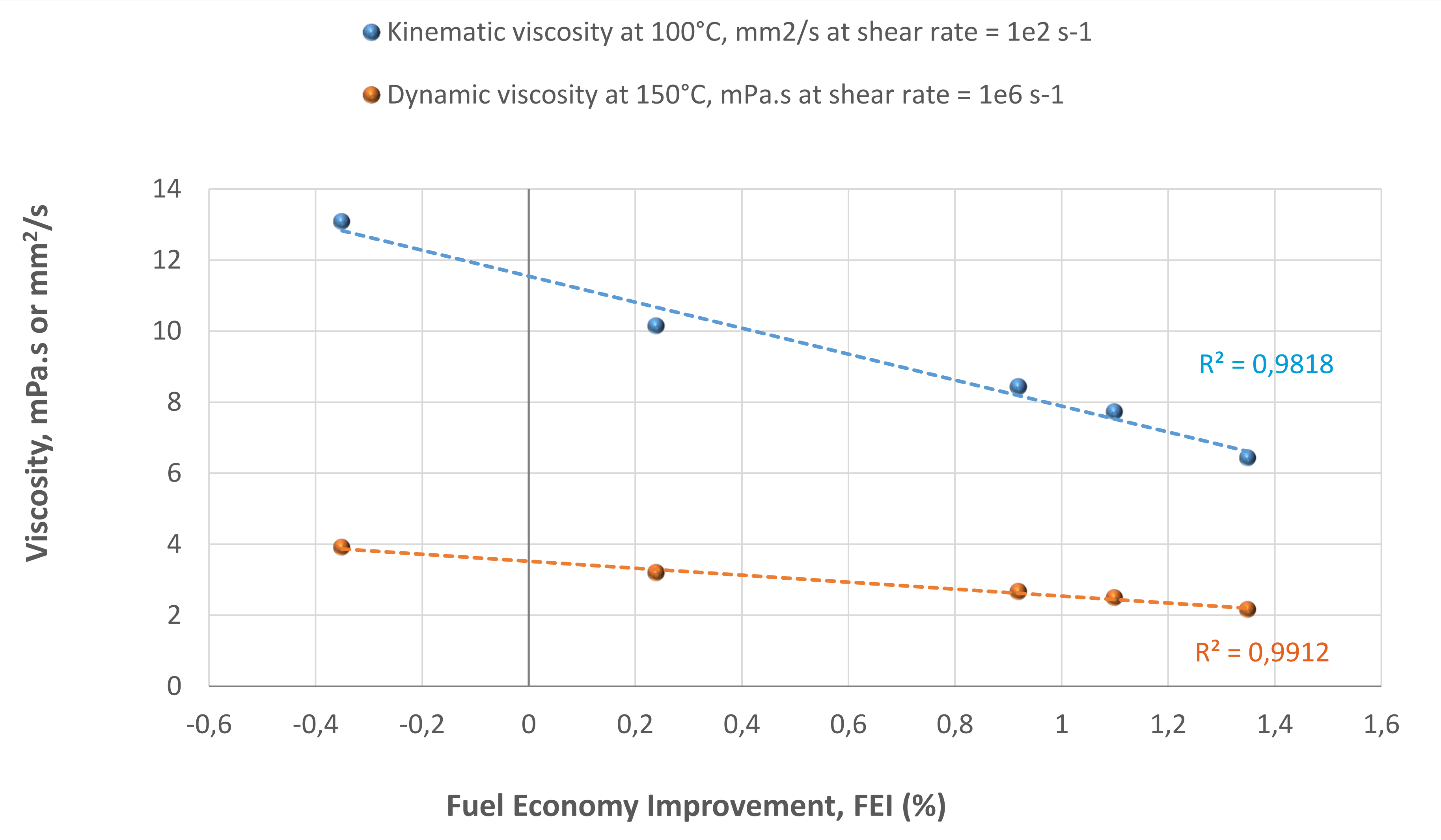
[Emission Test Cycles: Heavy-Duty Supplemental Emissions Test (SET) (dieselnet.com)](https://dieselnet.com/standards/cycles/esc.php)
https://dieselnet.com/standards/cycles/esc.php

FEI of multigrade oils tested in DD13

- Different multigrade oils tested in DD13 engine in steady state driving cycle.
- Lower viscosity grade oils show higher fuel economy performance.

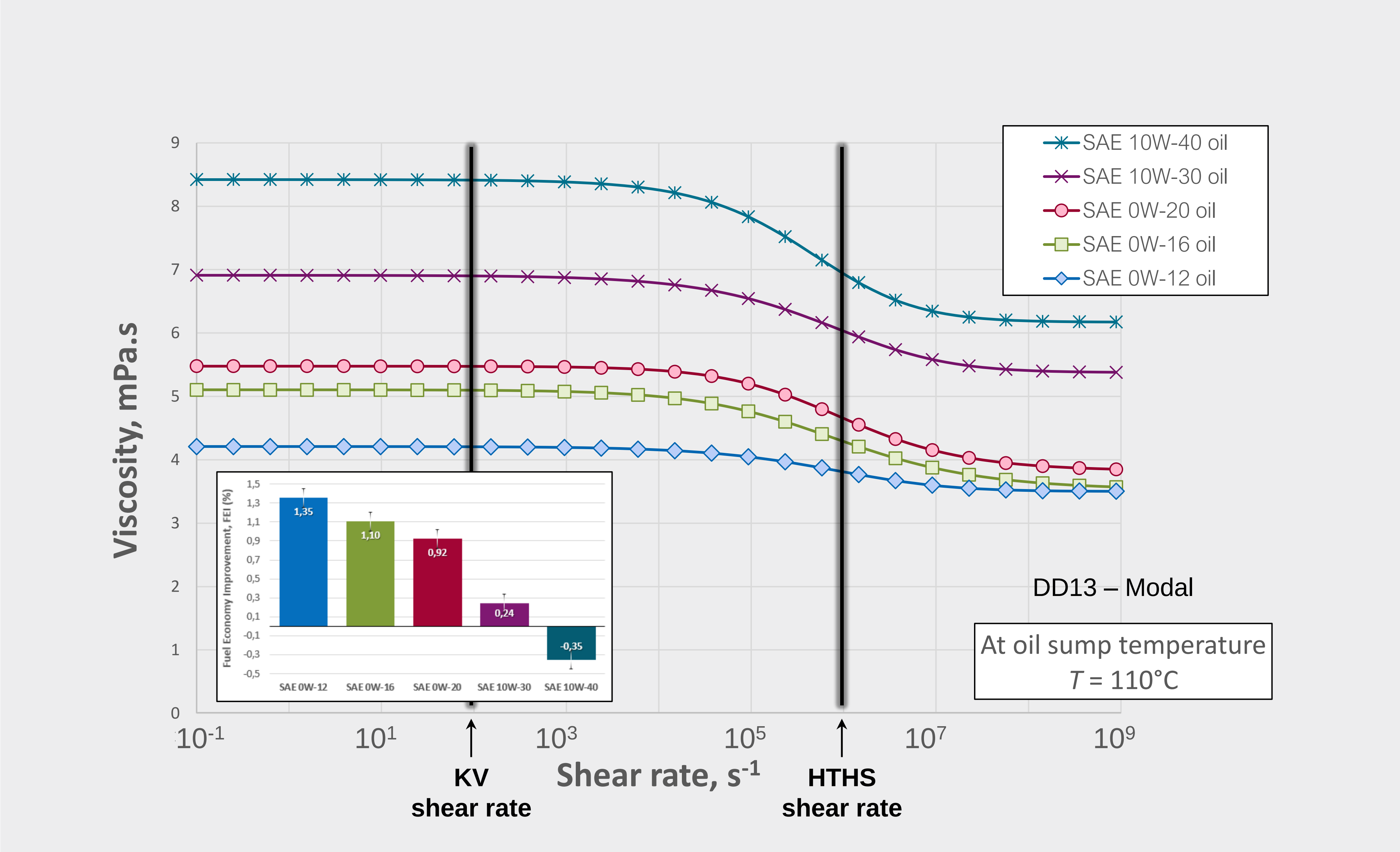


FEI correlation with viscosity of multigrade oils



For tested multigrade oils, good correlation between FEI and viscosity at one temperature and one shear rate, example: kinematic viscosity at 100°C, and HTHS viscosity at 150°C.

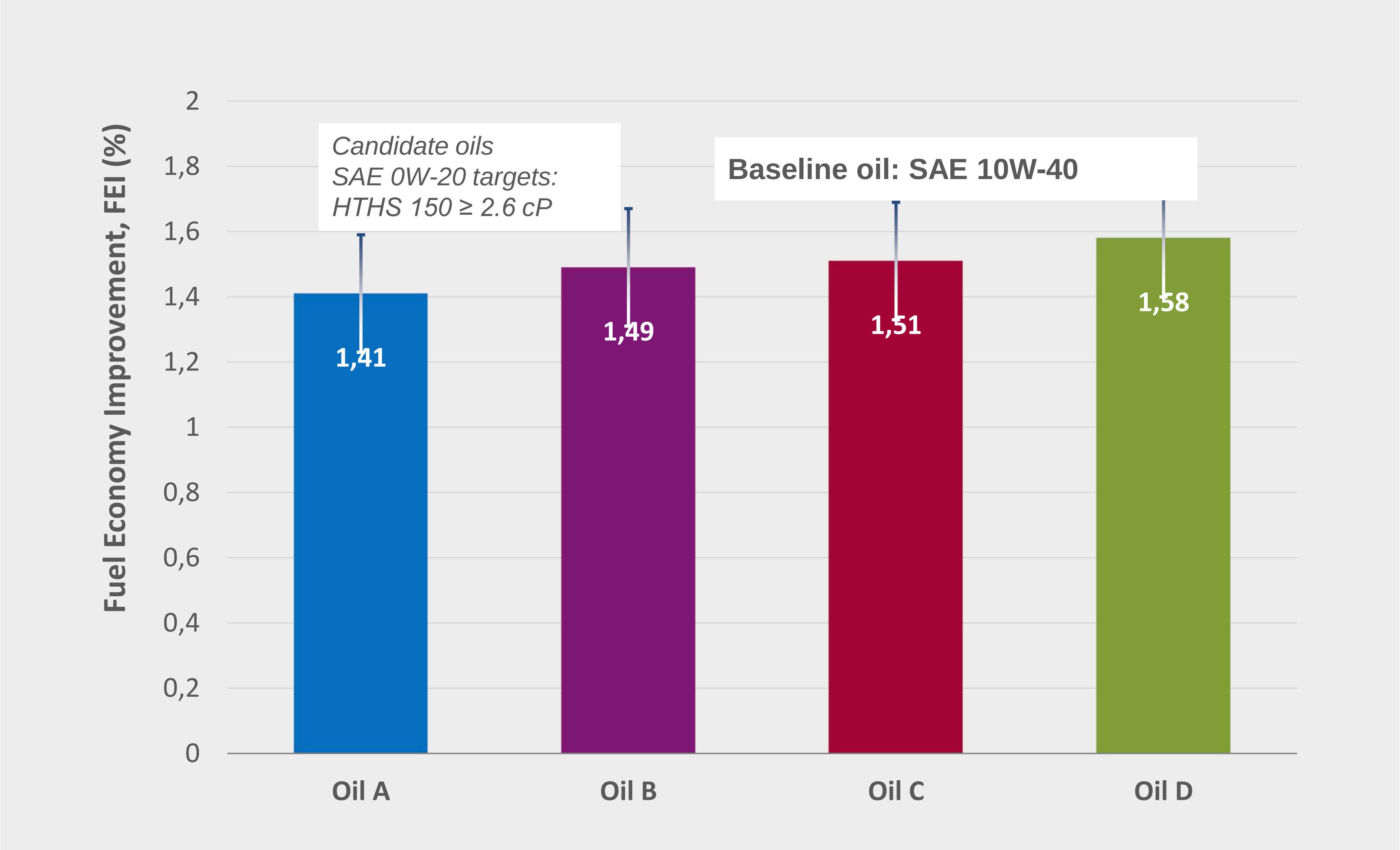
Rheological profile of multigrade oils



As expected, lower viscosity grade oils show higher fuel economy performance.

Rheological profiles of oils correlate well with FE performance of oils.

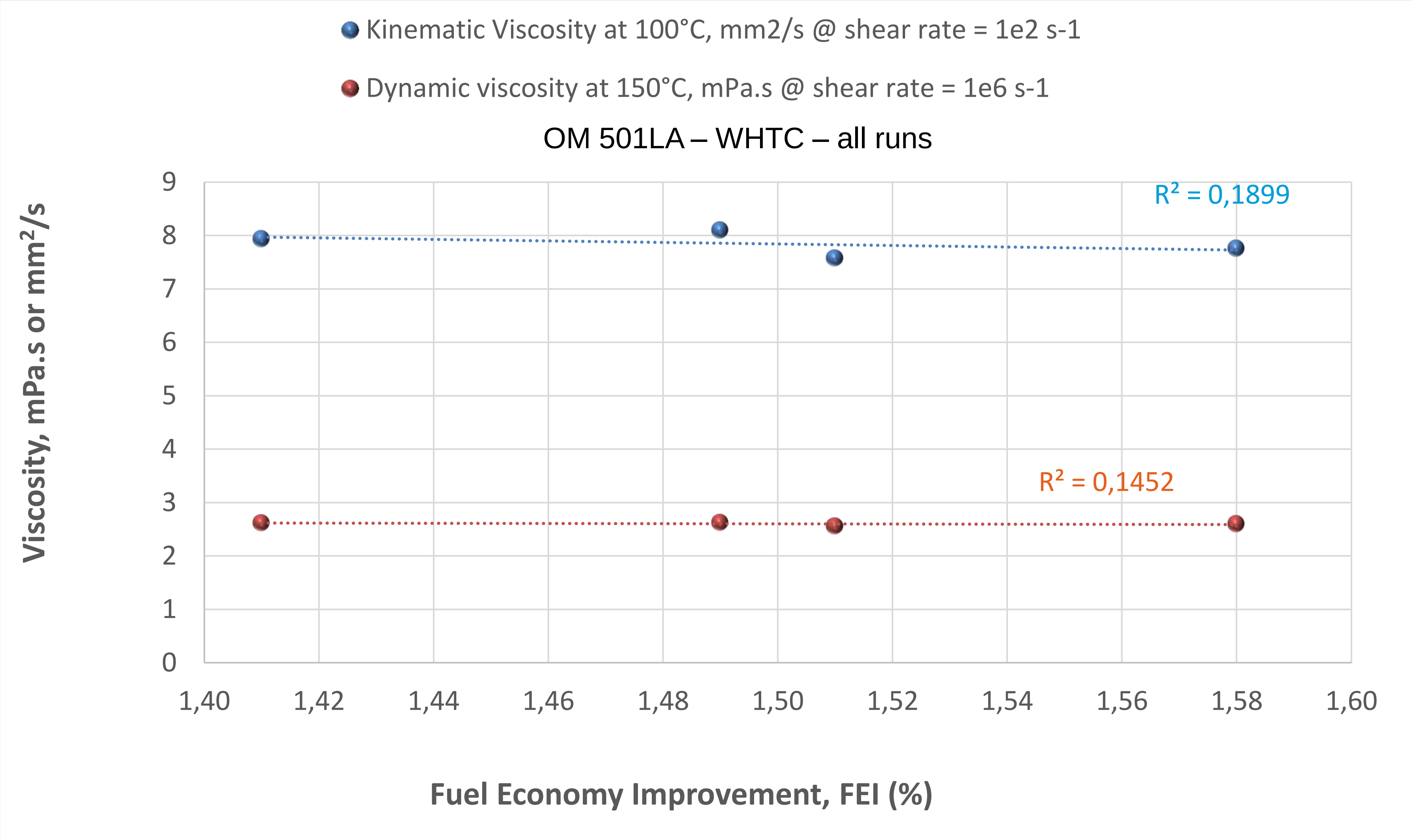
FEI of 0W-20 oils tested in OM 501 LA



Same SAE 0W-20 oils tested in OM 501 LA engine in WHTC transient driving cycle.

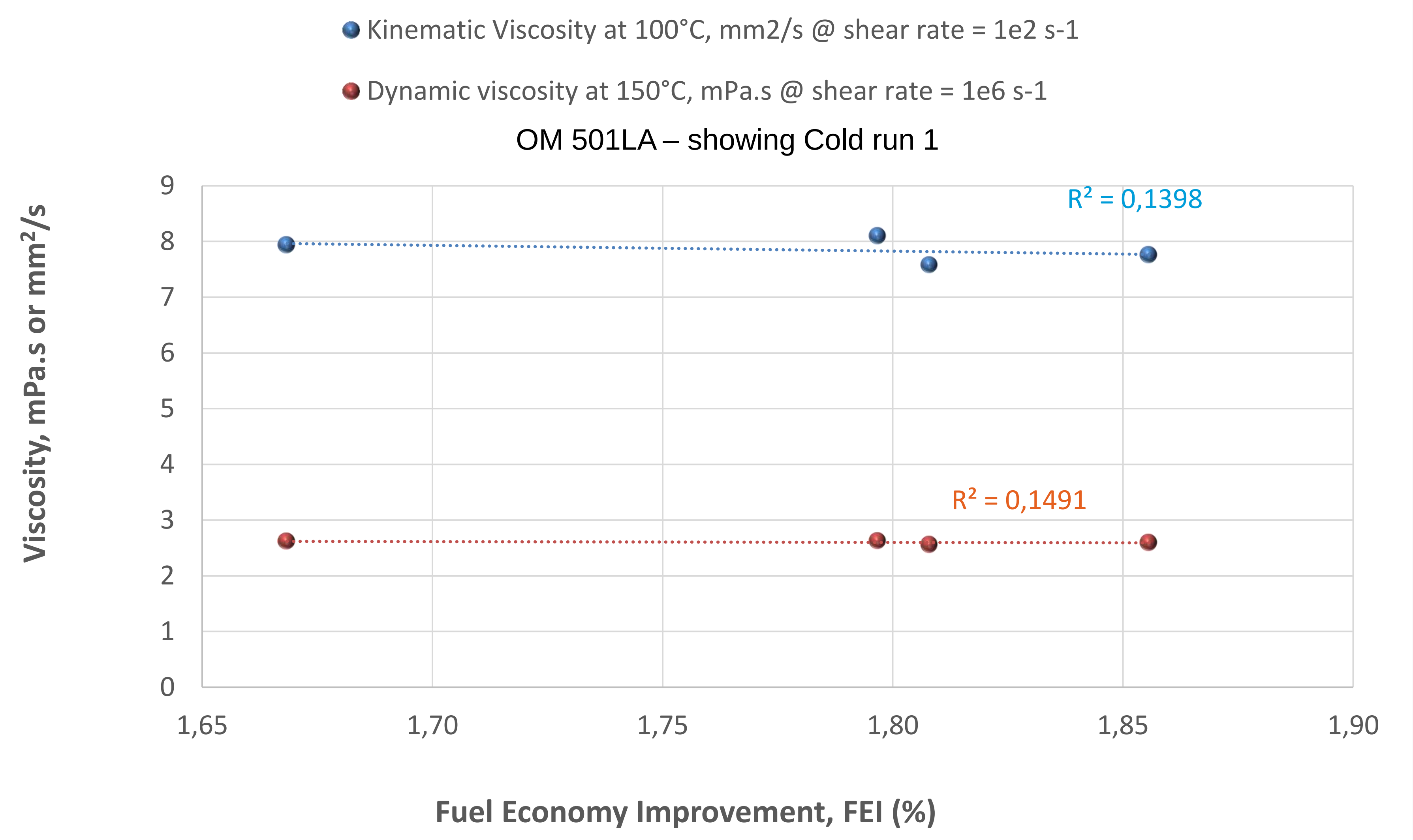
0W-20 oils made with different viscosity modifiers, have same HTHS at 150°C.

FEI correlation with viscosity of SAE 0W-20 oils



For same viscosity grade oils, weak correlation between FEI and viscosity at one temperature and one shear rate, example: kinematic viscosity at 100°C, HTHS viscosity at 150°C.

FEI correlation with viscosity of SAE 0W-20 oils



For same viscosity grade oils, weak correlation between FEI and viscosity at one temperature and one shear rate, example: kinematic viscosity at 100°C, HTHS viscosity at 150°C.

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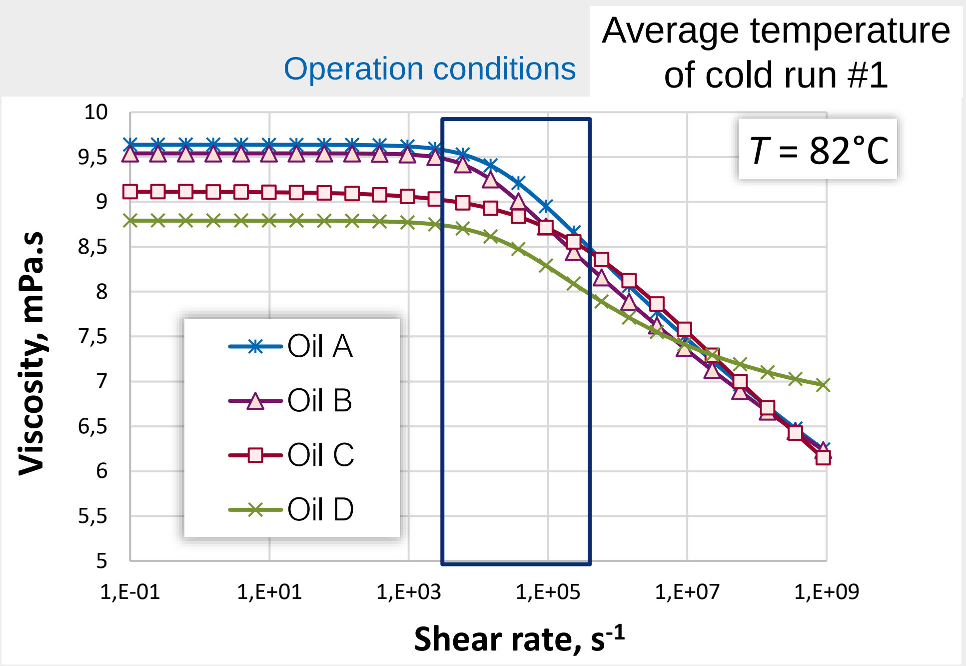
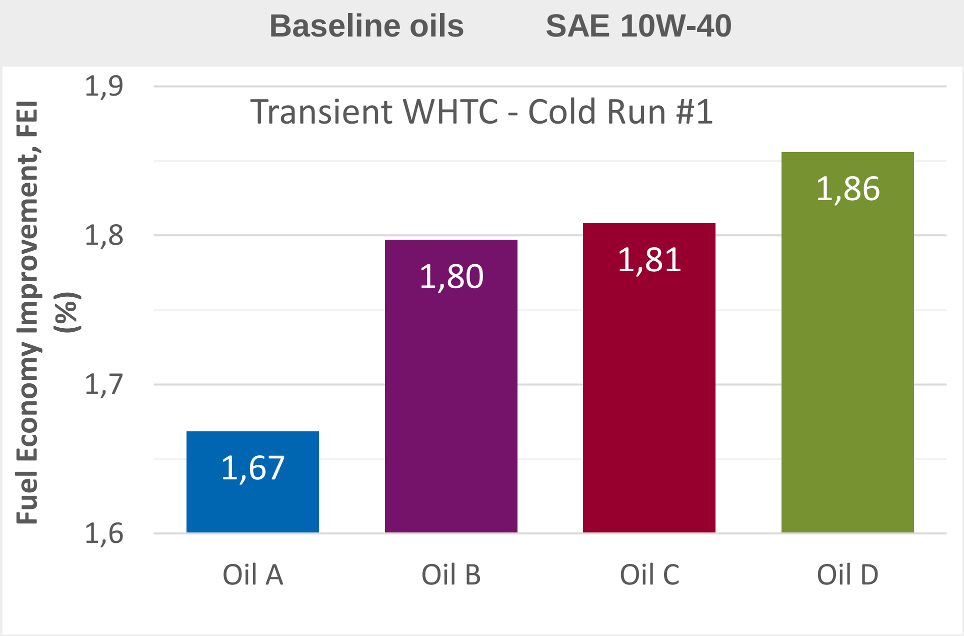
Correlation between rheology and FE engine test

SAE 0W-20 oils tested in OM501LA – WHTC





Candidate oils

SAE 0W-20 targets: HTHS 150 ≥ 2.6 cP

Difference between oils, only, in their VM types

Rheological profiles of oils have good correlation with their FEI, suggesting dominant hydrodynamic regime in the engine with given driving conditions

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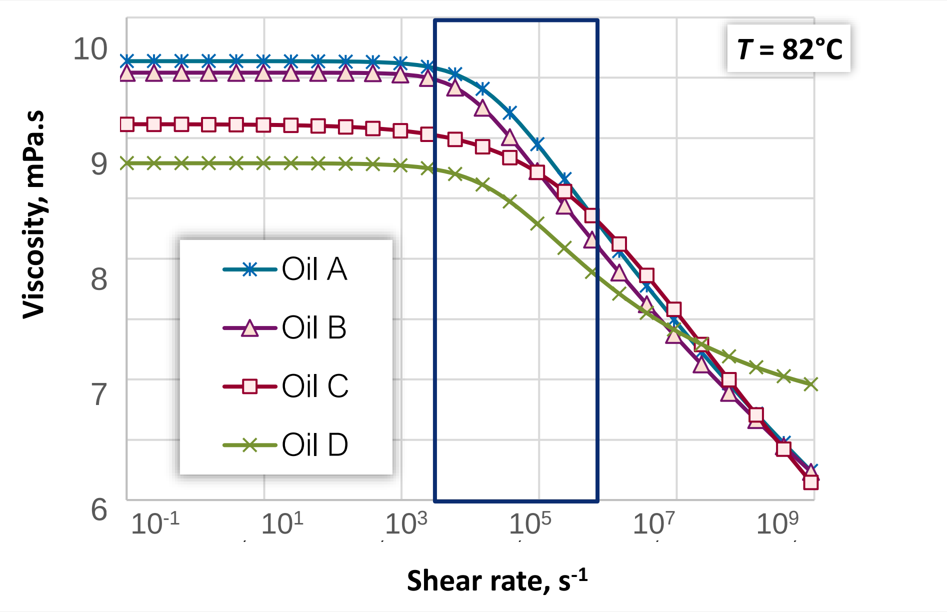
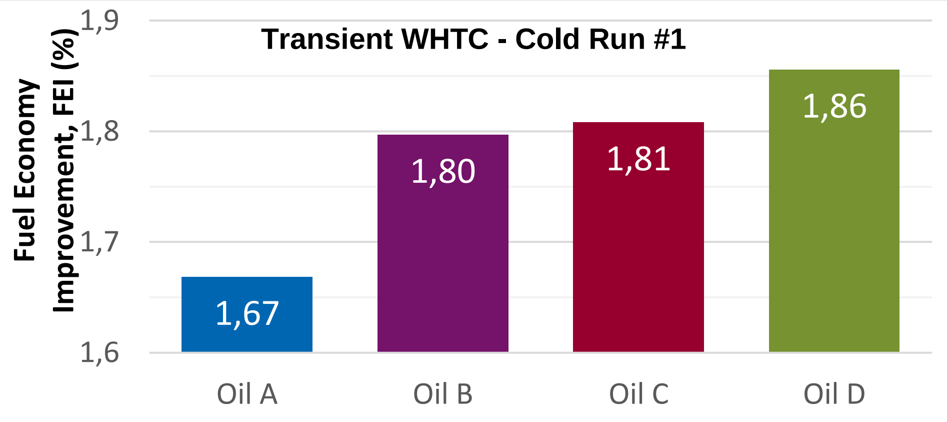
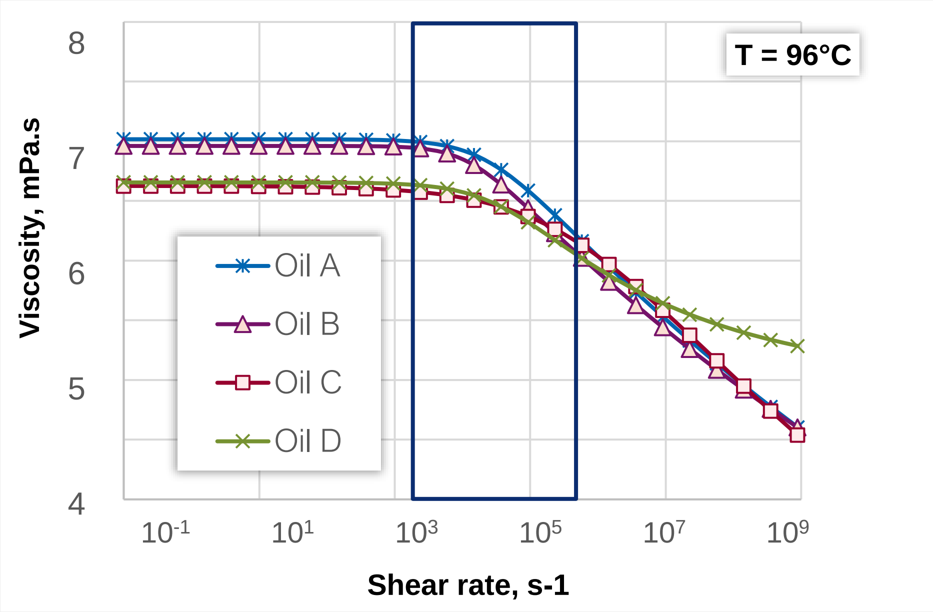
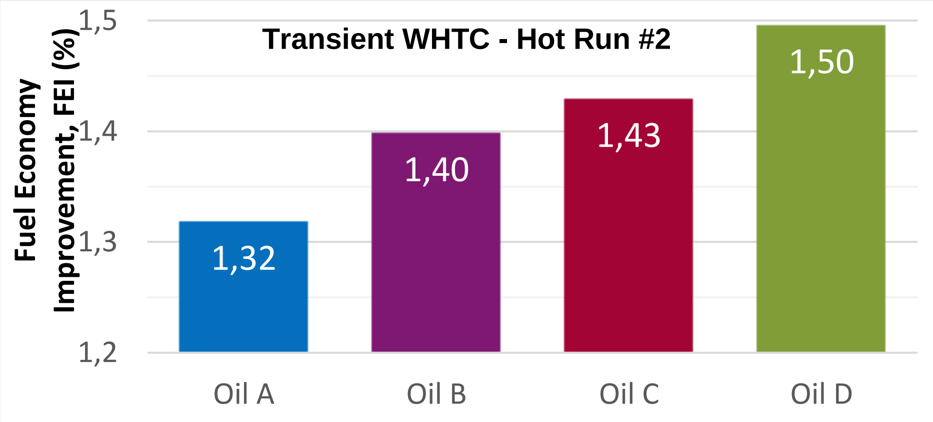
SAE 0W-20 oils tested in OM501LA – WHTC









Rheological profiles of oils have **good correlation with their FEI**, suggesting dominant hydrodynamic regime in the engine with given driving conditions

Concluding remarks

- Developed **rheological methods** show how rheology can describe different viscometric attributes of lubricating oils and can be used to predict relative fuel economy performance of oils in an engine under driving conditions with dominant hydrodynamic regimes.
- Rheology is **an effective tool** in development of more fuel-efficient engine oils.
- Using **lower viscosity grade** lubricants can help reduce fuel consumption
- **Chevron Oronite** continues to conduct research aimed to optimize Viscosity Modifiers and additive packages for fuel economy savings