IET – Feb 24

Lubrication demands for Electric vehicles: do we still need lubricants and if so, then where are they needed?

Presented by Dr Rich Baker

TriboTonic

Tribology and Petroleum Support

My Journey

Academic Journey

1991-1998

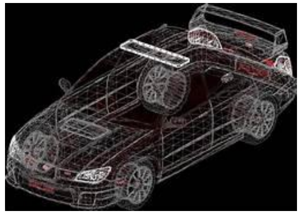
- BSc Maths
- MSc Mech Eng
- PhD Mech Eng

IET Journey

The Institution of Engineering and Technology

- Joined IET – via Tribology Network 2012
- MIET - 2015
- Chair Tribology Network – 2015-18
- CC-TPN member 2018-20
- LN Committee 2020-

Professional Journey



Taught 3D-CAD to Automotive Engineers — 1998-2000

Industrias Alegre S.A.

Senior Design Engineer UK, Germany and Spain — 2000-03

PCS Instruments

Technical Sales and Marketing in a Tribology Company — 2003-19

TriboTonic — Tribology and Petroleum Support

Setup TT – distribute Tribology and Petroleum products across Europe — 2019-?

Agenda

- Brief Introduction to Tribology
- Lubricants and Additives in ICE’s
- EV History
- Lubricants in EV’s
- Testing of Greases for EV’s
  - Existing vs future testing/methods
- Conclusions/Discussion

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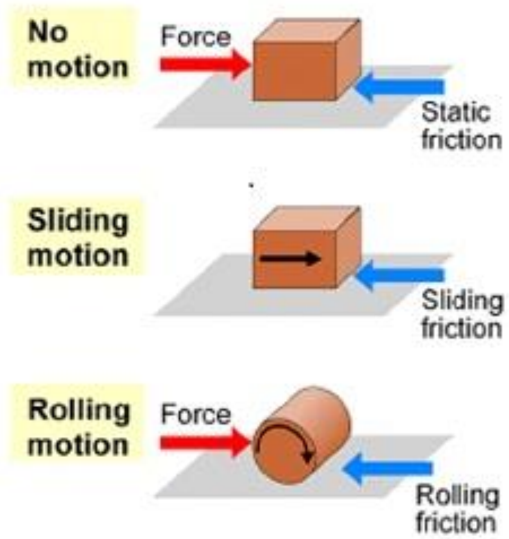
What is Tribology

- Tribology is 'The science and engineering of':

Friction



Wear

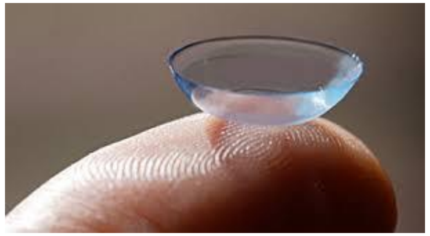
Lubrication

Bringing together scientific and engineering principles

- Material science
- Surface engineering
- Mechanical engineering
- Chemical engineering
- Chemistry
- Physics
- Food Science etc. . .

to engineer and optimise **contact surfaces in relative motion**

Tribology is Everywhere



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Friction Coefficients

Complicated Interfaces

Materials	μ_s	μ_k
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Copper on steel	0.53	0.36
Rubber on concrete (dry)	1.0	0.8
Rubber on concrete (wet)	0.3	0.25
Wood on wood	0.25-0.5	0.2
Glass on glass	0.94	0.4
Teflon on Teflon	0.04	0.04
Teflon on steel	0.04	0.04
Waxed wood on wet snow	0.14	0.1
Waxed wood on dry snow	0.10	0.04
Metal on metal (lubricated)	0.15	0.06
Ice on ice	0.1	0.03
Synovial joints in humans	0.01	0.003
Very rough surfaces		1.5

REF - http://www.hadron.physics.fsu.edu/~crede/TEACHING/PHY2048C/Calendar/W6_D1/Friction%20Coefficients.htm

Why Tribology? - Origin of the Word

Tribology comes from two Greek words:

- "tribos" : "rubbing"
- "ology" : "the study of"

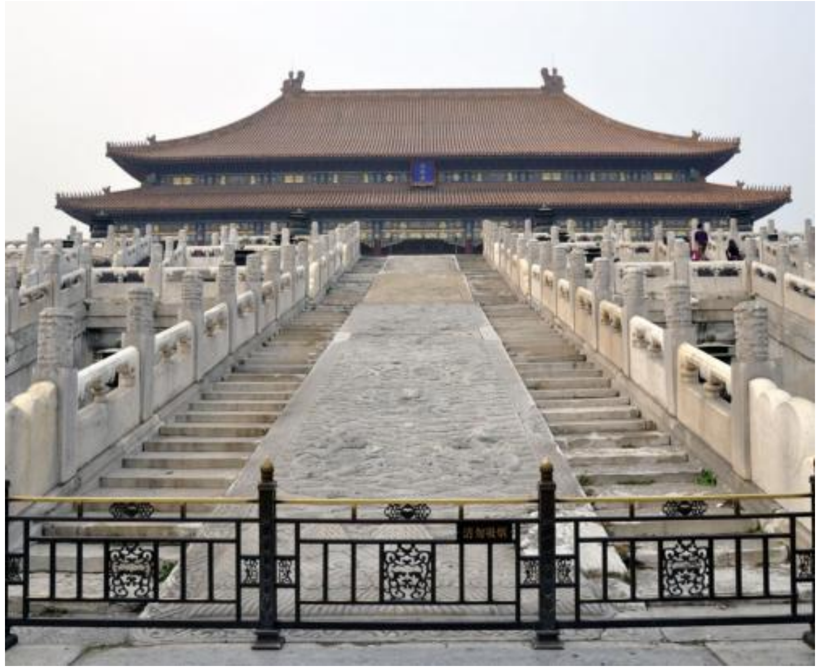
Therefore, Tribology is the study of rubbing
or… "the study of things that rub"

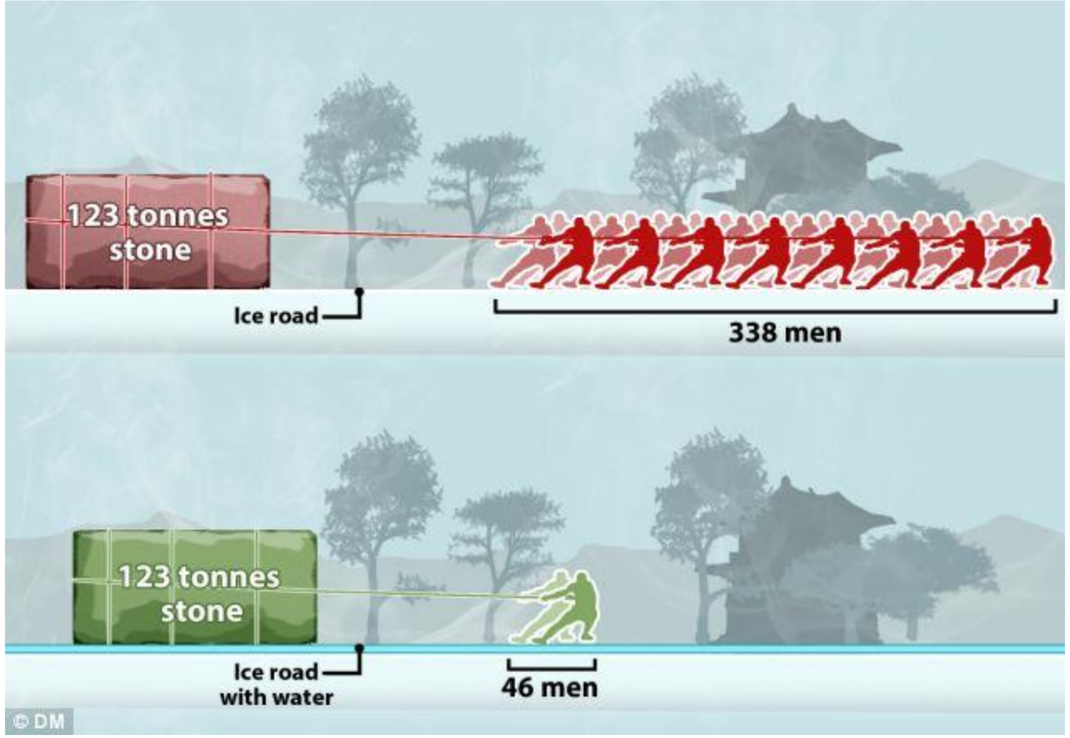
Coined by Dr. H. Peter Jost 1966

1st recorded Tribologist?

Pouring lubricant (water?) in front of the sledge in the transport of the statue of Ti - Egypt, c.2400 BC

Early beginnings





Tribo-engineering in cold weather

An artificial ice road was created, enabling a 123-ton stone to be moved in the Forbidden City in 1557

- Simple road of ice blocks -> 338 men needed to pull the stone
- When warm water added to lubricate the icy road -> just 46 men needed to move it

Ref : https://www.tribonet.org/news/ice-lubrication-and-forbidden-city/

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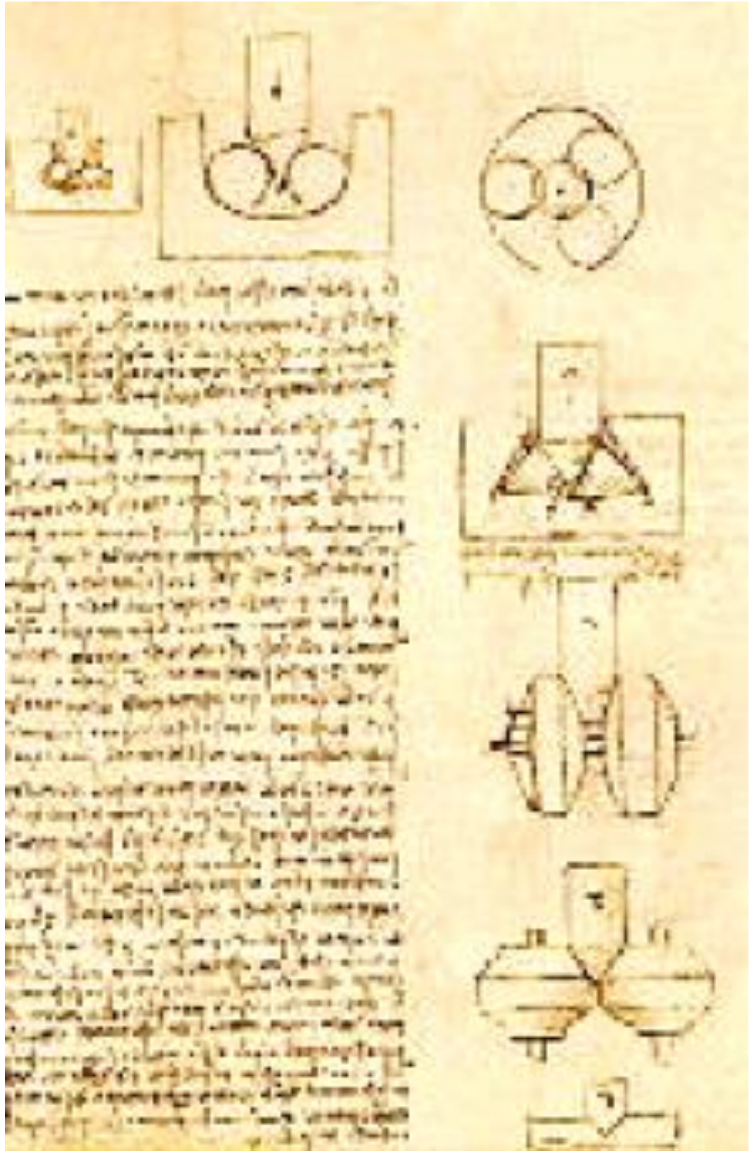
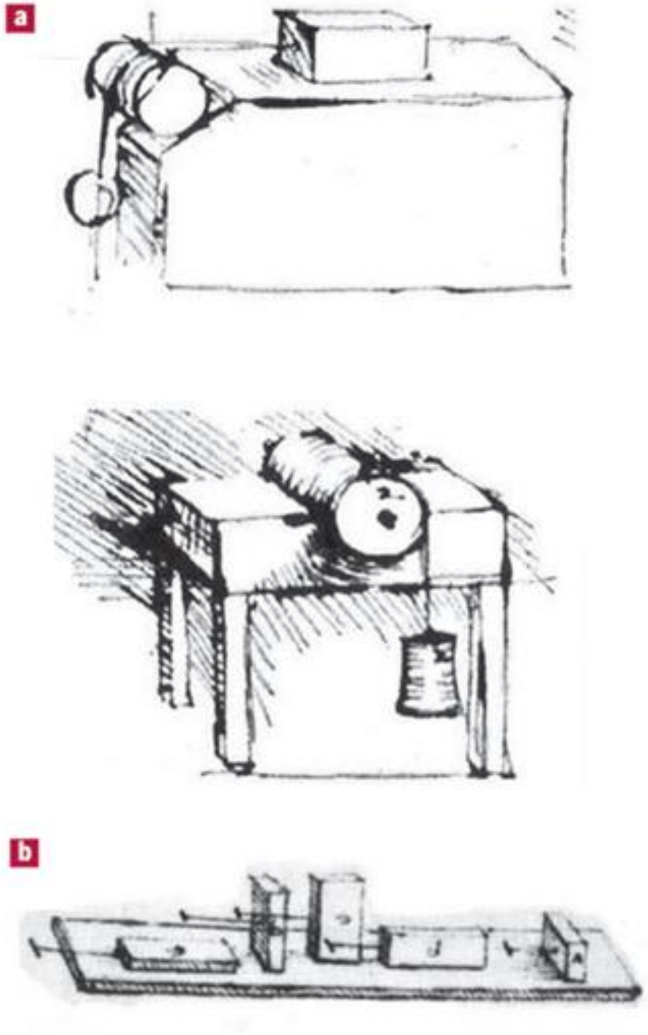
Renaissance and Enlightenment – Da Vinci (1452-1519)

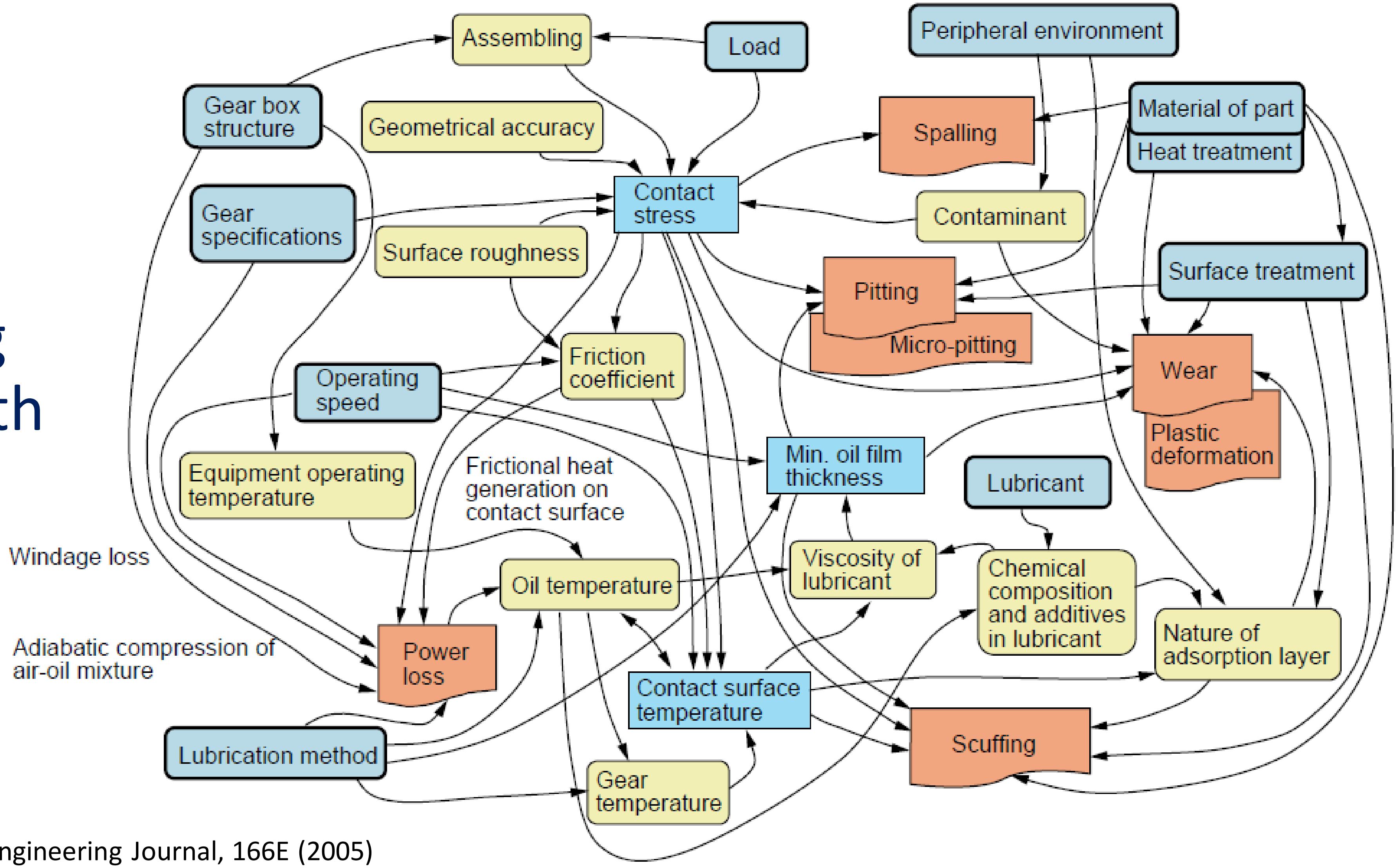




Ref - https://theconversation.com/leonardo-da-vincis-early-work-on-friction-founded-the-modern-science-of-tribology-116225

Tribology - Not usually very simple

Factors influencing damage of gear teeth



Ref - Scope of Tribology by Prof. Aizo Kubo, Koyo Engineering Journal, 166E (2005)

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Before moving on to EV lubricants - ICE Lubricant Requirements

- Important to keep an eye on ICE lubricants – they are going to be around for a while still!
- How can we improve fuel economy through lubricants?
- What are the current pressures on ICE's – and how can additives help improve this?

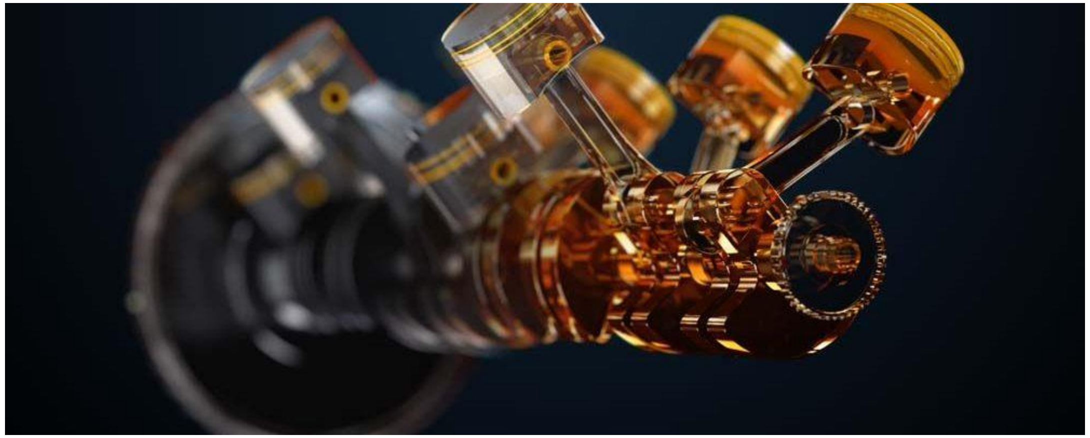

Image - https://www.q8oils.com/automotive/critical-engine-parts-lubrication/

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Fuel Economy – 1970's and 1980's

- 1975 – CAFE (Corporate Average Fuel Economy) set up in the US in wake of the Arab Oil Embargo
- Previously no target for fuel economy
- Called for doubling of fuel economy to 27.5 mpg within 10 years
- 1975-85 vehicle mileage doubled from 13.5 mpg to 27.5 mpg
- Mid 80's Ford and GM successfully lobbied the US government to bring the standard to 26 mpg, where it stayed until 1989

https://www.macrotrends.net/1369/crude-oil-price-history-chart

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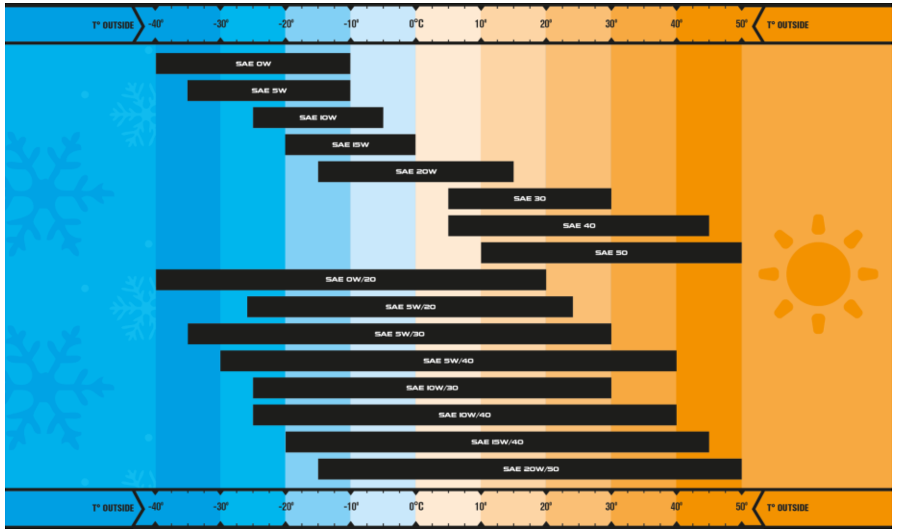
Fuel Economy – 1990's and 2000's

- 1990 – 2 senators sponsored legislation to raise fuel economy by 40% over a decade
- Passed by commerce committee but lost in the Senate – if passed, would be saving the US more than 1 million barrels of oil a day today
- 2009 Obama accelerated increase in CAFE standards
- Requires fleet-wide average of 35.5 mpg by 2016
- Increasing at an average of 5% annually, most passenger cars must achieve 39 mpg, and light trucks 30 mpg, by 2016

Current and Future Requirements for Lubricant Manufacturers

- Current engine requirements are met by SAE 5W-30
- Future engine oils will have to deliver
  - Better fuel economy
  - Long drain intervals (at least 20-30,000 km)
  - Excellent wear protection
  - Engine cleanliness
  - Compatibility with exhaust after-treatment devices
  - Environmental concerns – reducing CO_2



Ref - https://www.rymax-lubricants.com/updates/what-does-5w-30-actually-mean/

Future Engine Oils

- Fill for life?
  - Unlikely, currently 15,000 miles or 1 year (whichever comes first) is longest drain period
  - Unlike transmissions, engines don’t work in an enclosed system, so has to deal with outside elements (water, dust, pollen, dirt etc..)
  - Engine oils do a lot more than just lubricate. Also helps to control engine temp and clean the engine. Cleaning engine components every time the engine fires is an extremely important function of engine oil
  - Synthetics work better with prolonged higher temps, but the chemistry still breaks down eventually

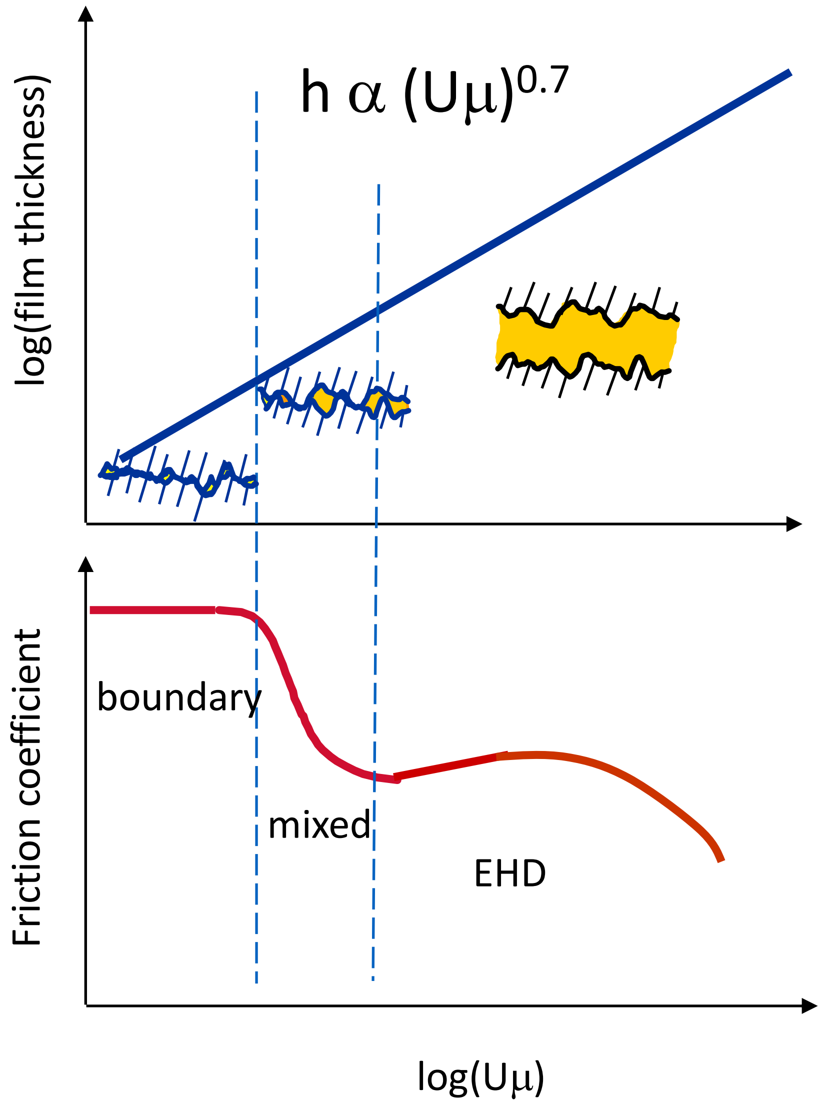
Fluid Film Regimes

Boundary Regime

- Any fluid within the contact is unpressurized so that effectively all of the contact load is borne at asperity conjunctions
- Very thin film (less than composite surface roughness)
- Surface active additives control the friction

Mixed Regime

- Many practical machine components operate within it
- Performance-limiting phenomena such as wear and seizure occur



Mixed Regime

- Thin film (lower than composite surface roughness), resulting in occasional asperity interaction

Full Fluid Film

- Full separation of contacting surfaces
- No metal to metal contact –> no wear
- Bulk viscosity of the lubricant controls the film thickness
- Friction becomes a fundamental property of the lubricant

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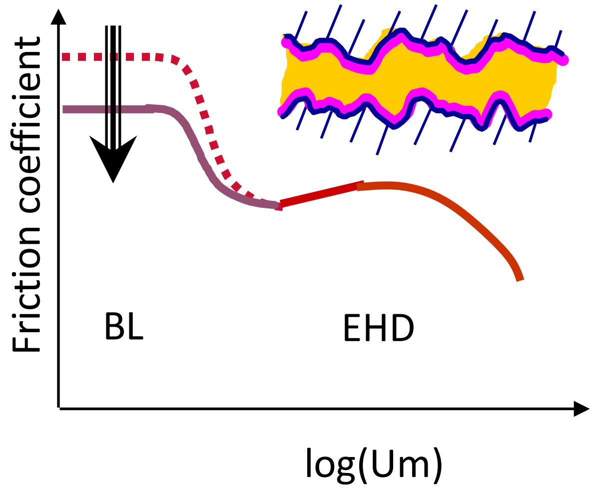
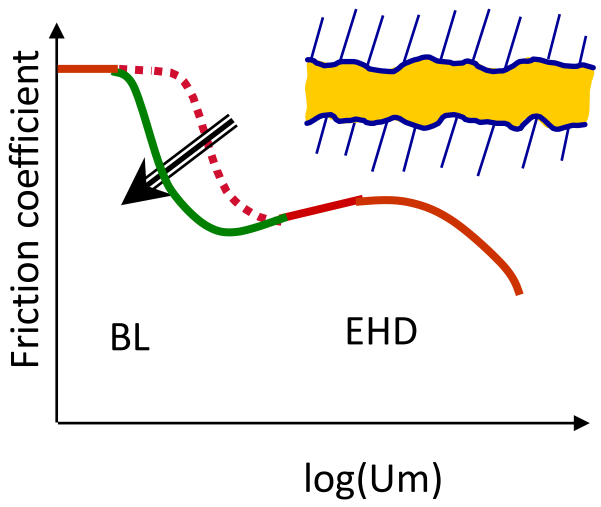
How Might Additives Reduce Friction?

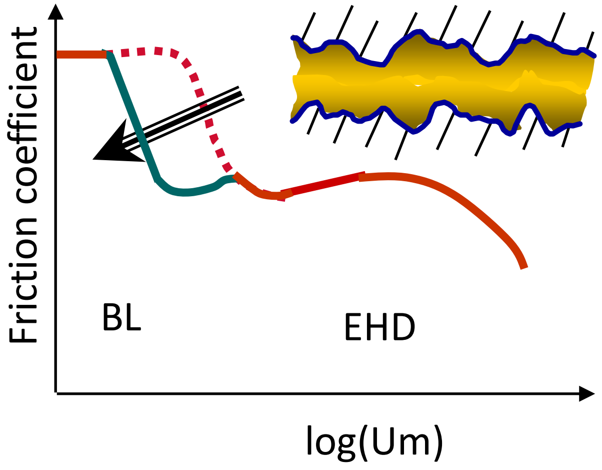
Form thin, solid-like film with low shear strength

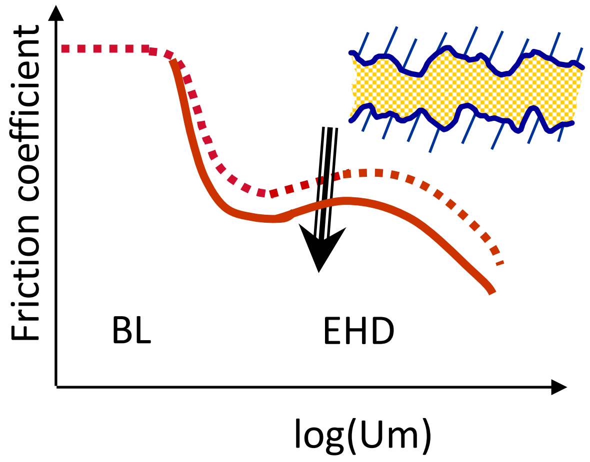




Smooth the solid surfaces

Form a viscous film on surfaces





Reduce EHD traction coefficient of the base fluid

Ref – Professor H.A. Spikes – Imperial College, London

How do Additives work in Practice

- Mineral Oils
- Fully formulated oils

+

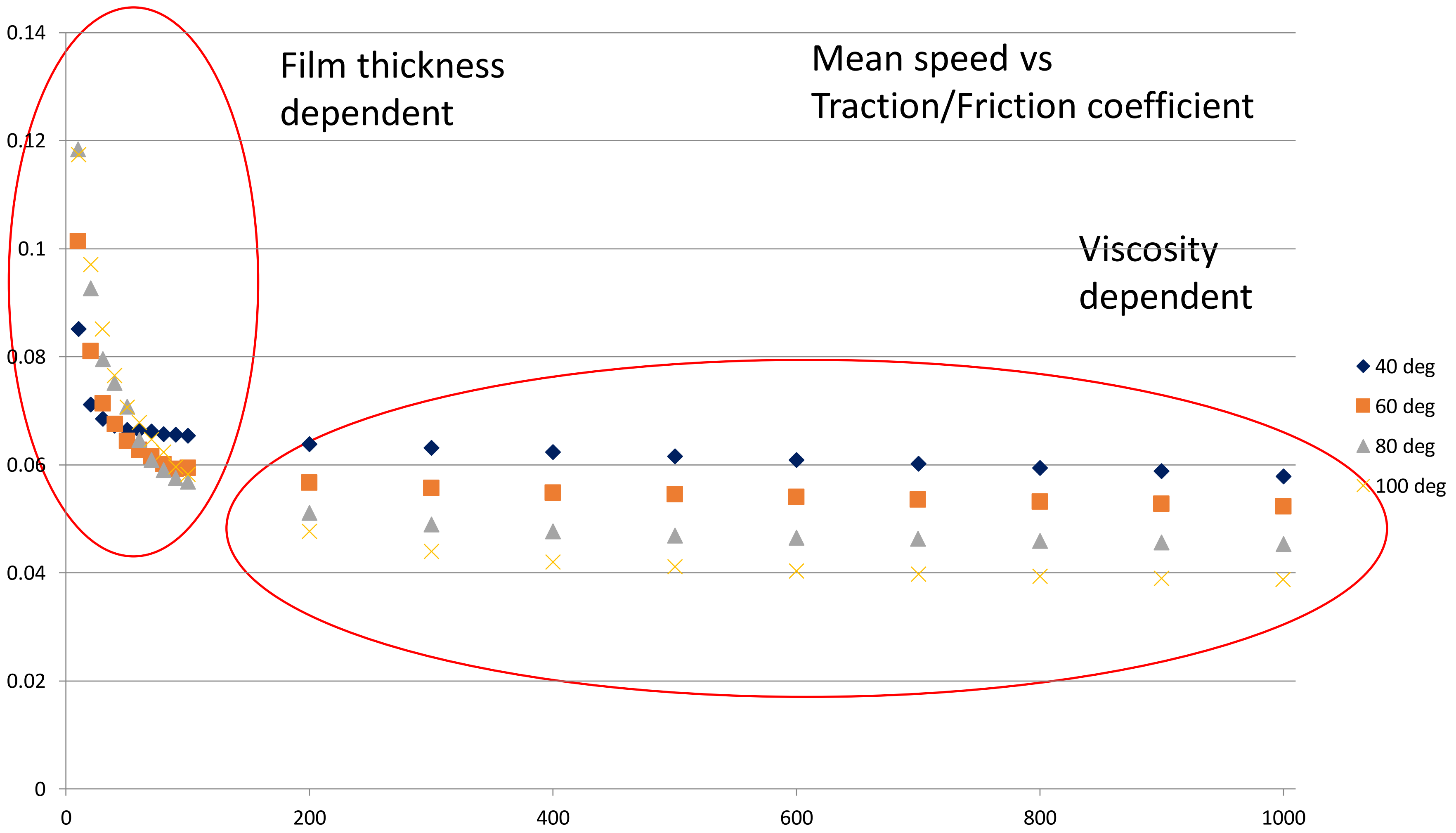
Some (or all of):

- Viscosity Index (VI) Improvers,
- Detergents
- Dispersants
- Anti-wear (AW) agents
- Friction modifiers (FM)
- Anti-oxidants
- Foam inhibitors
- Corrosion inhibitors (CI)
- Maybe more. . .

=

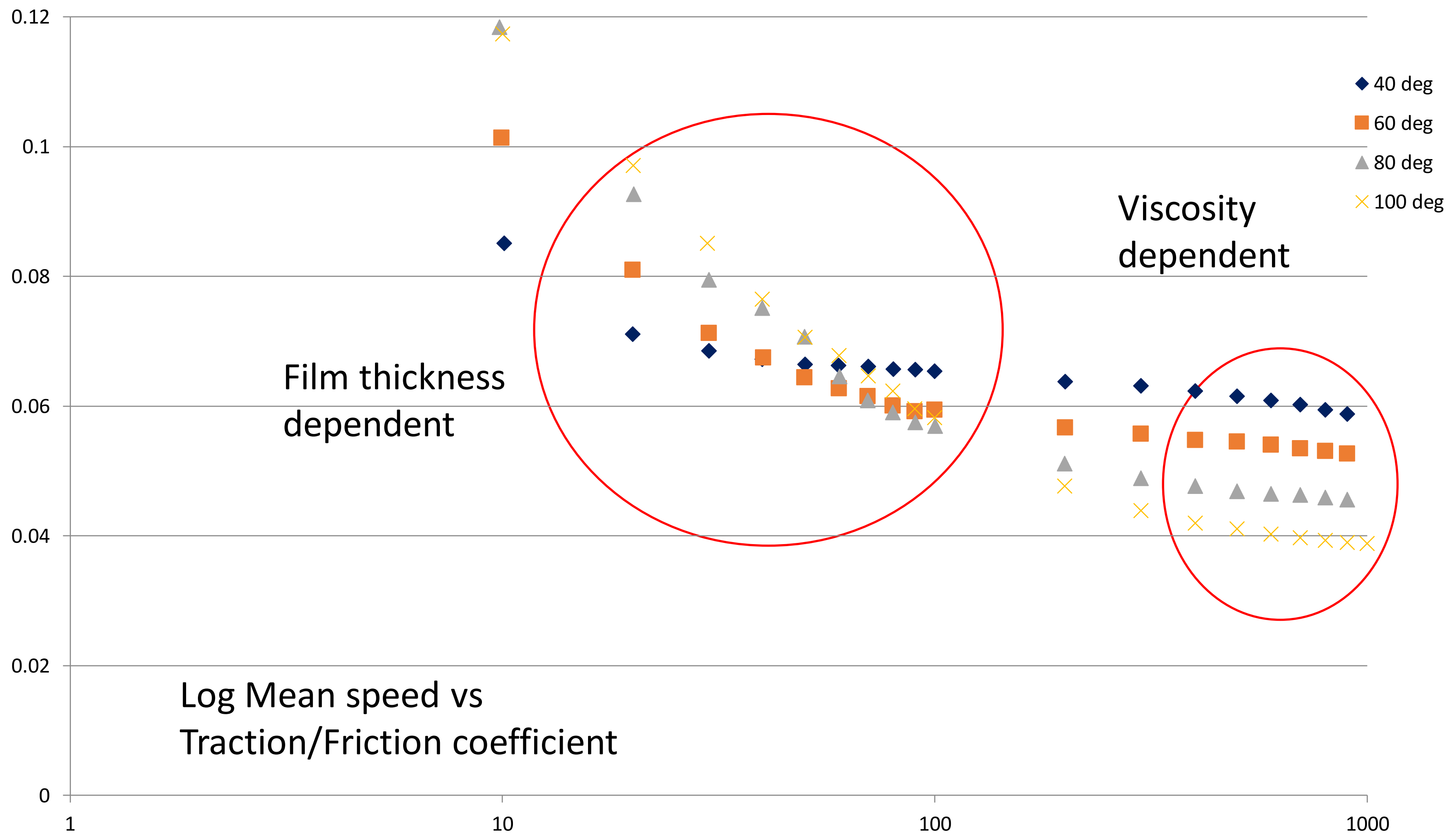
Fully Formulated Oil

Mineral Oil



Film thickness dependent
Mean speed vs Traction/Friction coefficient
Viscosity dependent
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
200
400
600
800
1000
40 deg
60 deg
80 deg
100 deg

Mineral Oil – Log-Log



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Mineral Oil vs Formulated Oils

Lubricants

- Mineral Oil
- SAE90 Gear Oil (~SAE50 Engine Oil)
- 15W 40
- 0W 40
- 5W 30
- 0W 30

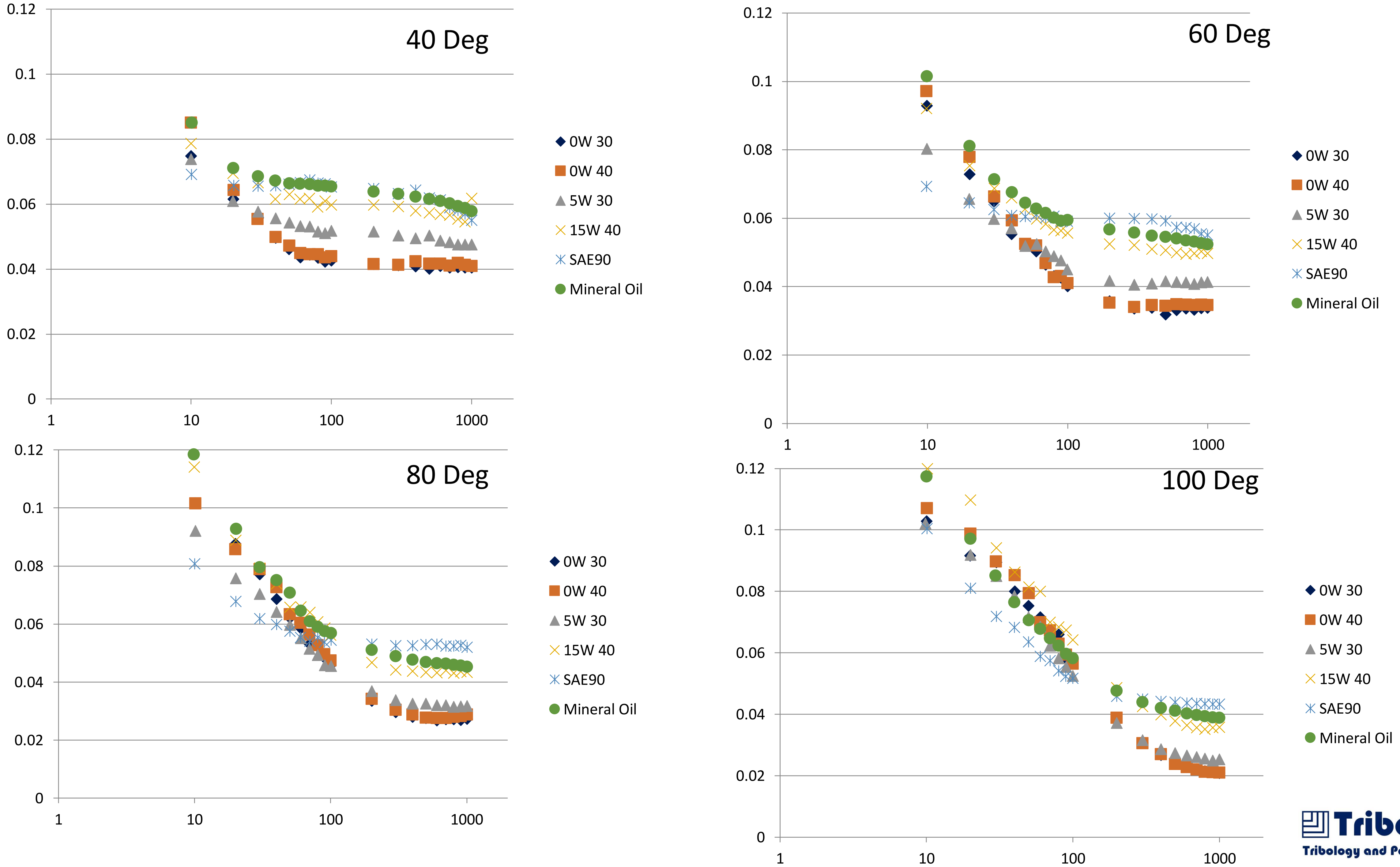
Test Conditions

- Load 30N (0.94 GPa)
- Speeds 0.01m/s – 1m/s
- SRR 50%
- Temperatures
  - 40 °C
  - 60 °C
  - 80 °C
  - 100 °C

Specimens

52100 ¾" Ball against a 45mm dia smooth disc

https://pcs-instruments.com/product/mtm/



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Future - Affecting Additives

• Trends for Autos, Engine Oils

- Additives R&D investment rising
- Efforts to reduce R&D Costs
- Rising Oil Demand in Asia and Middle East
- Pressure to Reduce Fuel Economy
- Rising Performance Demands
- Pressure to use less metals in engine oil
- Increase in Exhaust gas recirculation
- Increase in Exhaust after-treatment
- Growing use of bio-fuel

Effect on Additive Companies

- More than 5% of sales goes to R&D
- Focus on mol engineering, simulation
- Additive manufacturing follows to reduce costs
- Reduce viscosity; use of friction modifiers
- Need for customized additives in harsh environments
- New generation of detergents, antiwear agents
- Need for better oxidation control, more dispersancy, better soot-handling capability
- Need for additive technologies low SAPS
- Need better control of viscosity, oxidation and sludge, better corrosion inhibition

Lubricant Efficiency Today

- Fuel economy has improved significantly over past 40 years, driven by
  - Legislation (initial main driver, but ongoing pressures)
  - Engine Design – better components
  - Consumer – both cost and environmental issues
- The best passenger car engine lubricants are currently about 4-5% more efficient than their early 1990s counterparts as a result of lubricant development
- This increase in efficiency corresponds to an annual reduction of nearly 4×10^{10} kg (about 0.1%) of global man-made CO_2 emissions*

* Based on 600M cars, 10k km/yr, 150 g/km CO_2, 4% reduction, 2010 total 30.6 Gtonnes.

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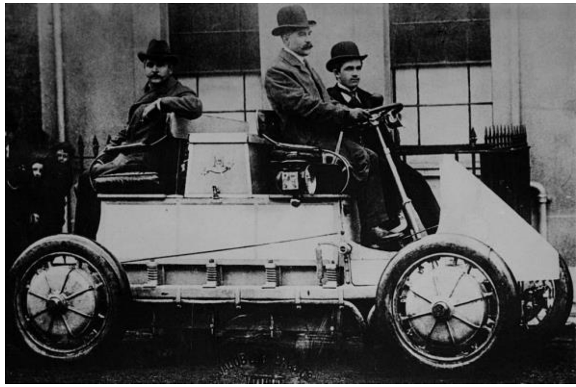
Brief history of EV's

- 1828-35 1st Small-Scale Electric Cars created
- 1870's become more practical - main transport horse & carriage
- 1899 – Gain popularity, quiet, easy to drive and no *smelly* polutants
- 1900-12 – Electric Cars Reach their Heyday
  - 1901 – Edison works to build a better battery
  - 1901 – Ferdinand Porche created first Hybrid Electic Car



Courtesy of Departement of Energy website - https://www.energy.gov/articles/history-electric-car

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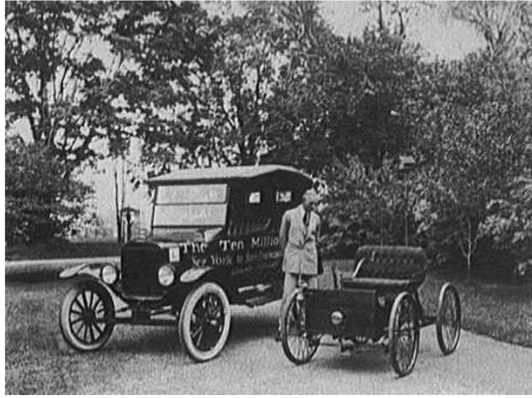
Brief history of EV's

- 1908-1912 – Mass produced Model T makes cars widely available – and starts decline in EV's
- 1920-1935 - Better Roads and discovery of cheap Texas Crude further led to decline in EV's
- 1968-1973 – Cheap, plentiful gasoline and ICE improvements meant no changes. But in 1960's and 1970's gas prices soared
- 1973 – Next Generation of EV's – GM produce a prototype



Courtesy of Departement of Energy website - https://www.energy.gov/articles/history-electric-car

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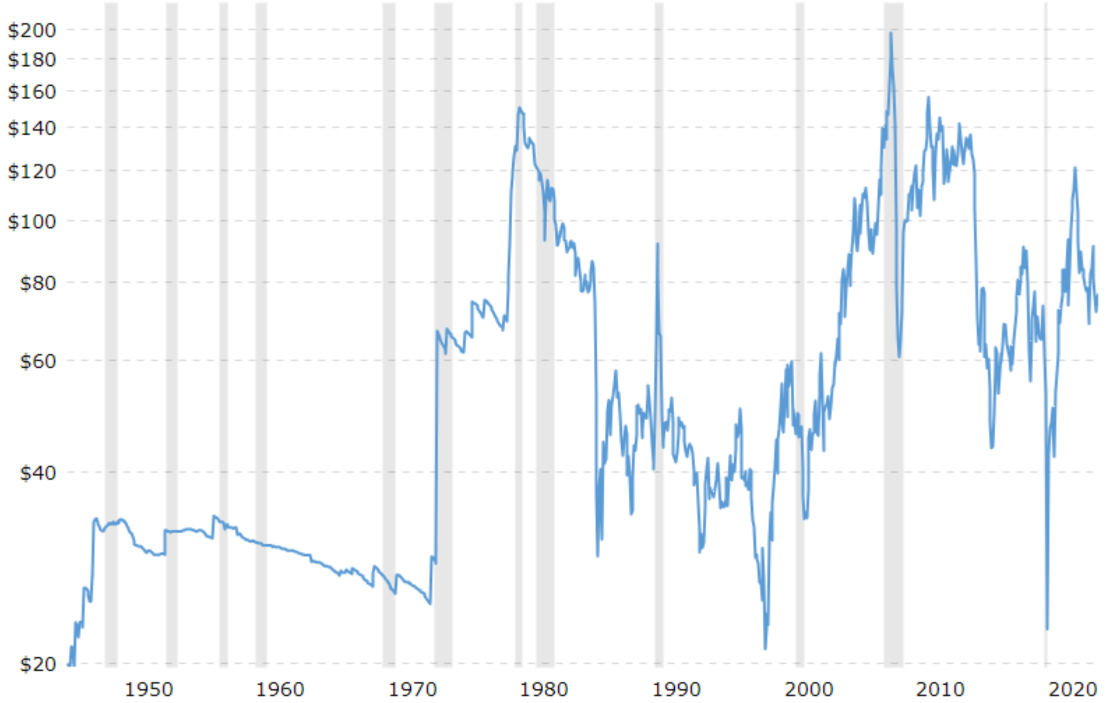
Brief history of EV‘s

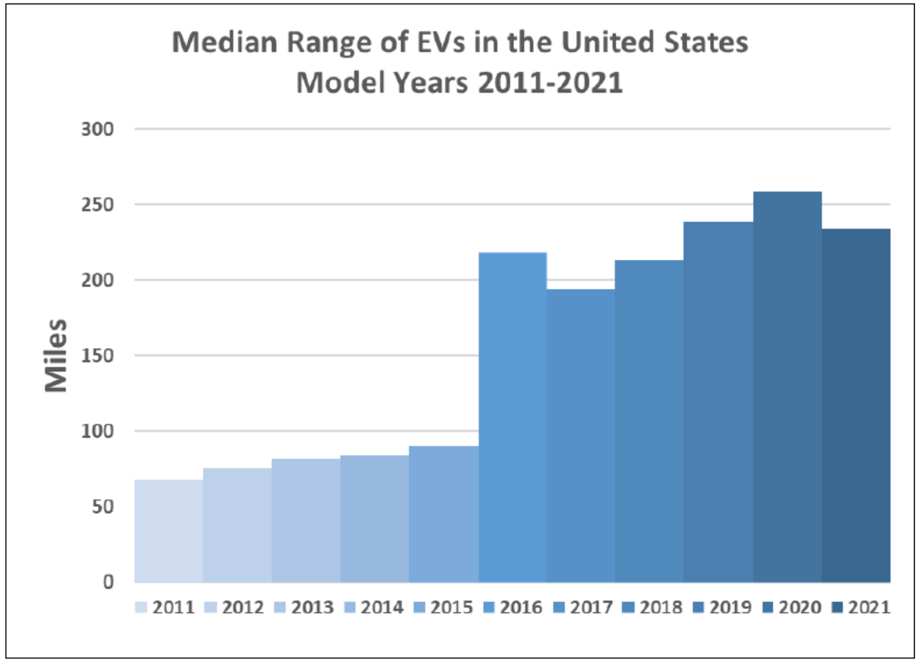
- 1974-1977 – Sebring-Vanguard made over 2,000 CitiCars – range 50-60 miles
- 1980’s – Interest faded as petrol prices stabilized
- 1997 – Toyota introduced the Prius
- 2006 – Tesla announces it will make luxury electric sports cars with a range of 200+ miles
- 2010 – Nissan Leaf released



Ref - https://en.wikipedia.org/wiki/History_of_the_electric_vehicle

EV Concerns

- Resistance to change
- Range anxiety
- Charging times
- Infrastructure
- Battery production and life
- Buzz, squeak and rattle (BSR) noise more noticeable in EV’s than in ICE’s
- Limited choice –improving – now over 200 models of EV available
- Where is the energy coming from to create the electricity?

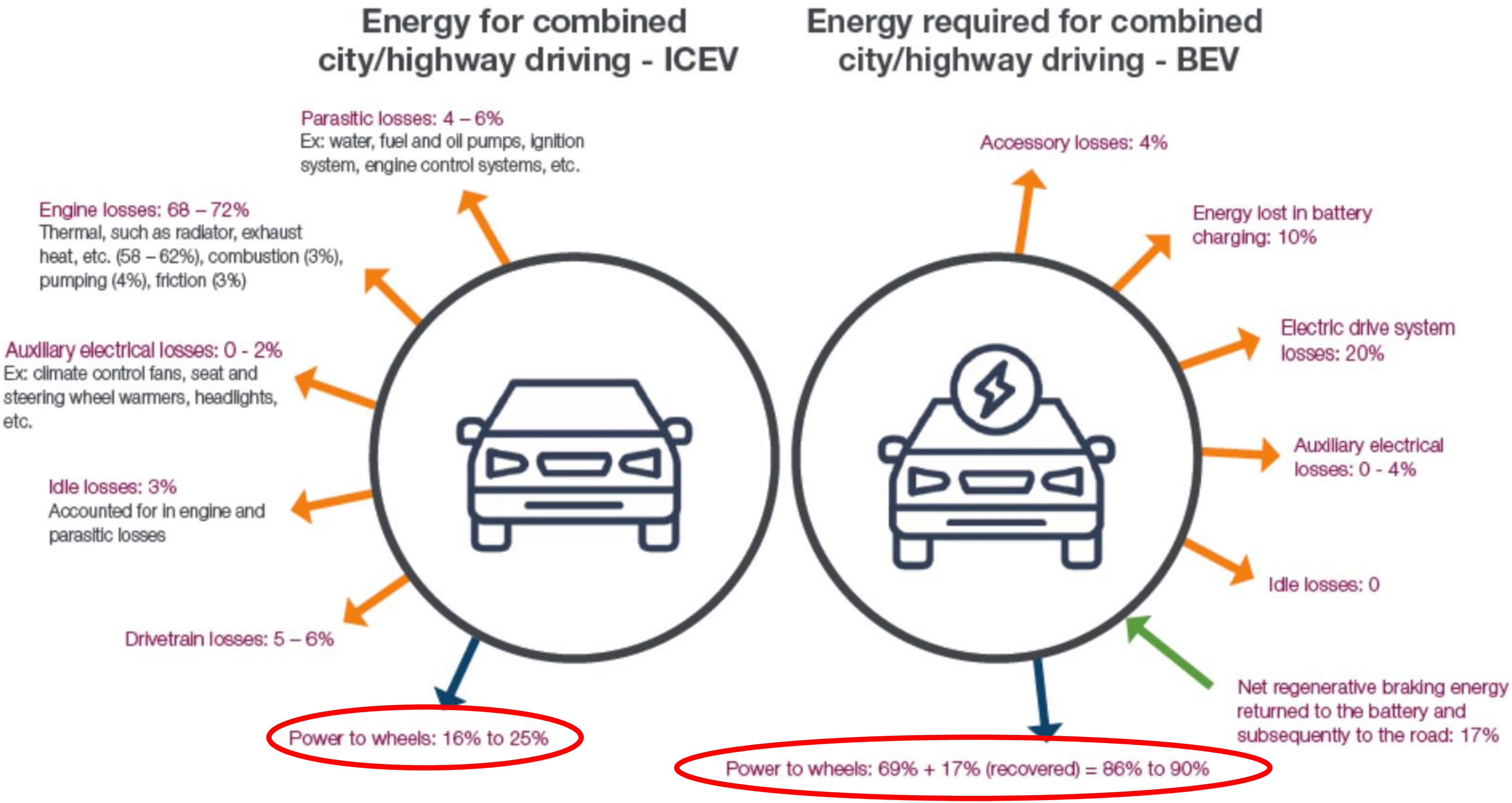


Rimac Nevera
0-60 – 1.74 sec
Top Speed 258 mph

Ref : Edelstein, S. EPA finds median range of EVs dropped in 2021
https://www.greencarreports.com/news/1134758_epa-finds-median-range-of-evs-dropped-in-2021
(accessed Feb 9, 2022).

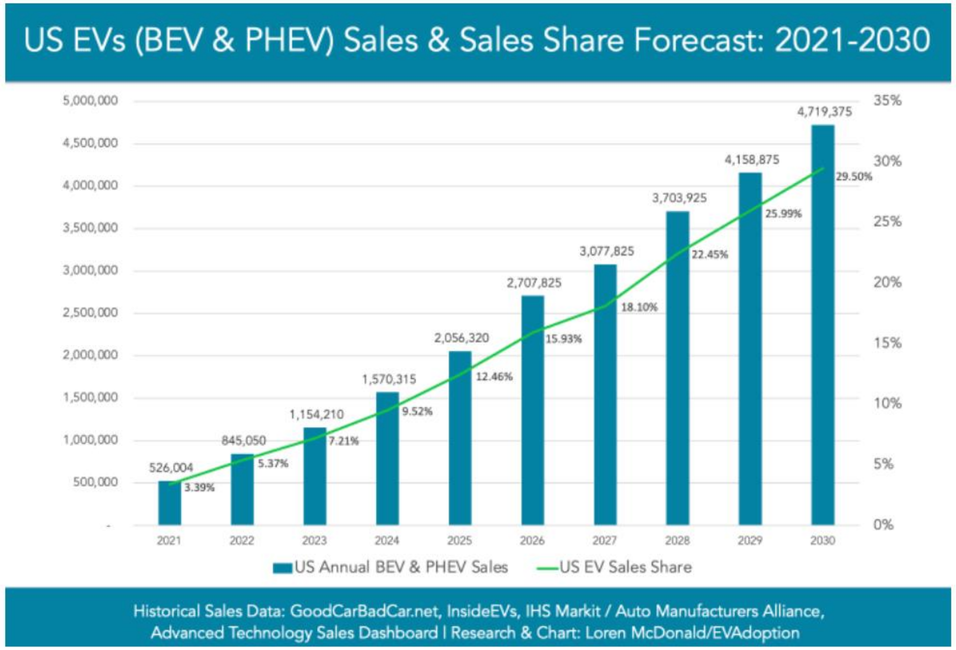
ICE vs EV - Efficiency

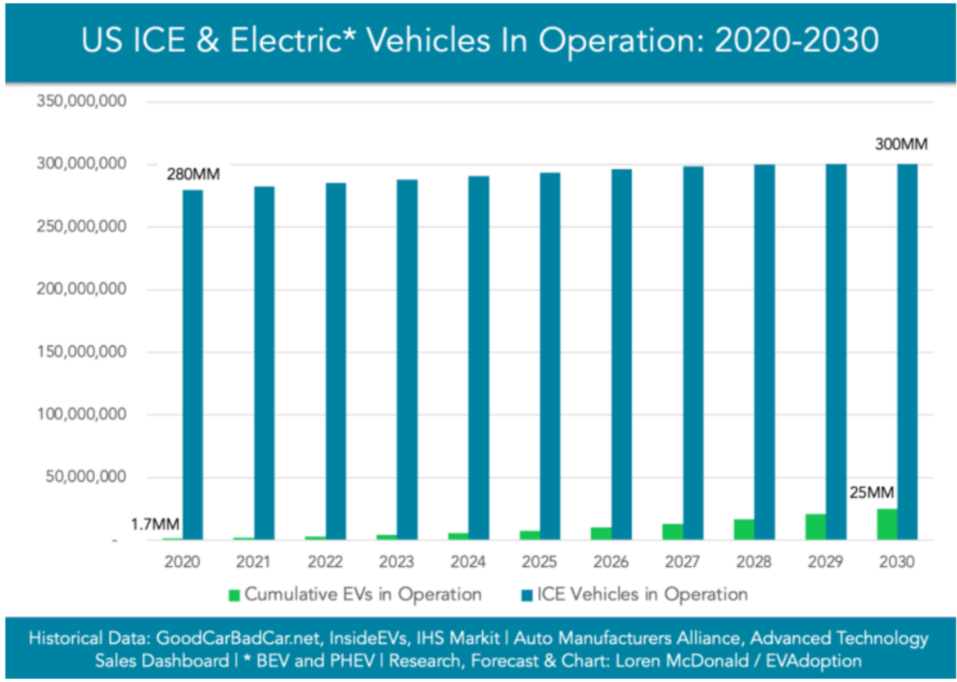
Source: U.S. Department of Energy – Office of Energy Efficiency and Renewable Energy – Where the Energy Goes: Electric Cars, Gasoline Vehicles



US vs Europe

- US sales of EV's expected to increase significantly this decade. But by end of 2030 EVs will still only be a small % and ICE's will actually increase by 20 million
- Despite big plans and promises, 27 of 37 major automakers do not offer a single BEV for sale in the US
- EV sales growth reaching ~30% of new vehicle sales. **Bigger picture** - by 2030 only 8 out of 100 vehicles in operation will be electric
- In Europe the prediction of >50% EV's by 2030 should actually be achieved earlier than this





Source : https://evadoption.com/2030-20-million-more-ice-vehicles-will-be-on-the-roads-in-the-us-than-in-2021/

The turning tide?

- Push by governments to move away from ICEs to EV’s
- Automotive companies - By 2025
  - Audi and GM both plan to have 30 EV’s each, Hyundai will have 23
  - BMW expects EV’s to account for 15-25% of global sales
  - Jaguar plans to be ALL electric
  - Toyota will launch 60 hybrid, electric or fuel-cell vehicles – expects annual sales of 5.5 million etc. . .
- Countries –phasing out ICE cars
  - 2025 – Norway
  - 2030-35 Denmark, Iceland, Japan,

  Ireland, Netherlands, Sweden, UK

Organization / State	2025	2030	2035	2040	Goal / Notes
General Motors			X		GM aspires to exclusively offer electric vehicles by 2035, ending production of its cars, trucks and SUVs with diesel- and gasoline-powered engines.
Volvo		X			Volvo announced that its entire car line-up will be fully electric by 2030.
Jaguar	X				Jaguar to become an electric-only luxury brand from 2025 onwards.
FedEx				X	By 2040, the entire FedEx parcel pickup and delivery (PUD) fleet will be zero–emission electric vehicles
ZEV2030		X			California non-profit. All new vehicles purchased in California will be zero emission vehicles by 2030.
Zero Emission Transportation Assoc.		X			ZETA is the first industry-backed coalition of its kind advocating for 100% of vehicles sold by 2030 to be electric vehicles (EVs)
California			X		100% of new light-duty vehicles sold in the California are zero emission vehicles (ZEVs)
Washington state		X			Clean Cars 2030 bill (HB 1204/SB 5256), would require all 2030-model-year passenger cars and light-duty trucks to be electric in order to be registered in Washington. (Status: Bill was introduced in state House.)
Massachusetts		X			100% of new light-duty vehicles sold in the Commonwealth are zero emission vehicles (ZEVs)
New Jersey			X		Recommendations from state’s Global Warming Response Act Report: All new sales of light-duty cars, SUVs, and trucks are electric by 2035.
New York			X		Senate Bill S9008A (currently in committee): Provides that 100% of in-state sales of new passenger cars and trucks shall be zero-emissions by 2035

References:STLE October 2021 – ‚Plans for electrification‘ – Page 78
Table - https://evadoption.com/2030-20-million-more-ice-vehicles-will-be-on-the-roads-in-the-us-than-in-2021/

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The turning tide - lubrication

- EV lubes run under different operating conditions, loads and temps – require purely synthetic lubricants that can run at higher operating temps and resist oxidation from hot running electric motors
- Unlike ICE's, electric motors release no combustion by-products, so oils don't degrade as quickly -> fill for life more attainable
- Electric motors running at 15,000 RPM or more and gear reducer in EV's functions as its transmission
- EV Transmission fluids specifically formulated for thermal management of electric motor(s) integrated in the same gearbox

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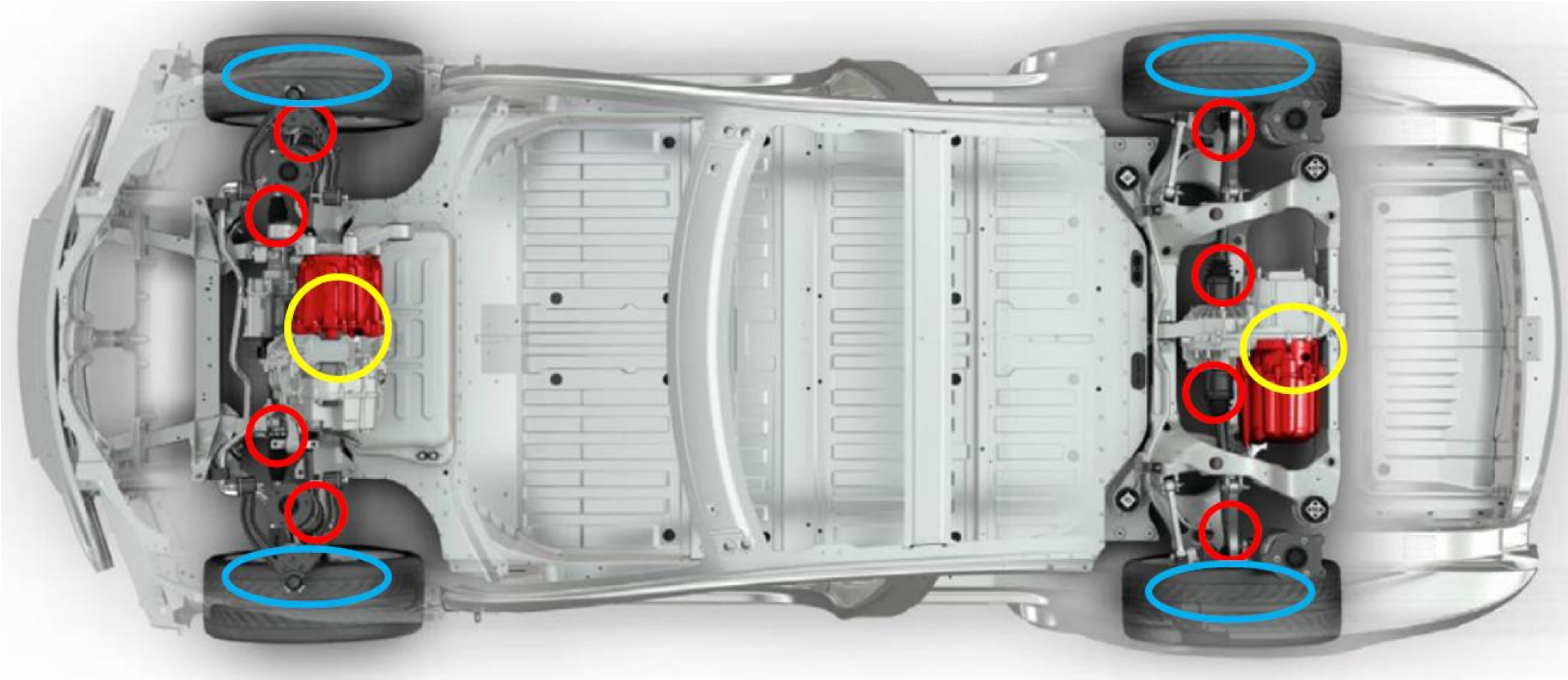
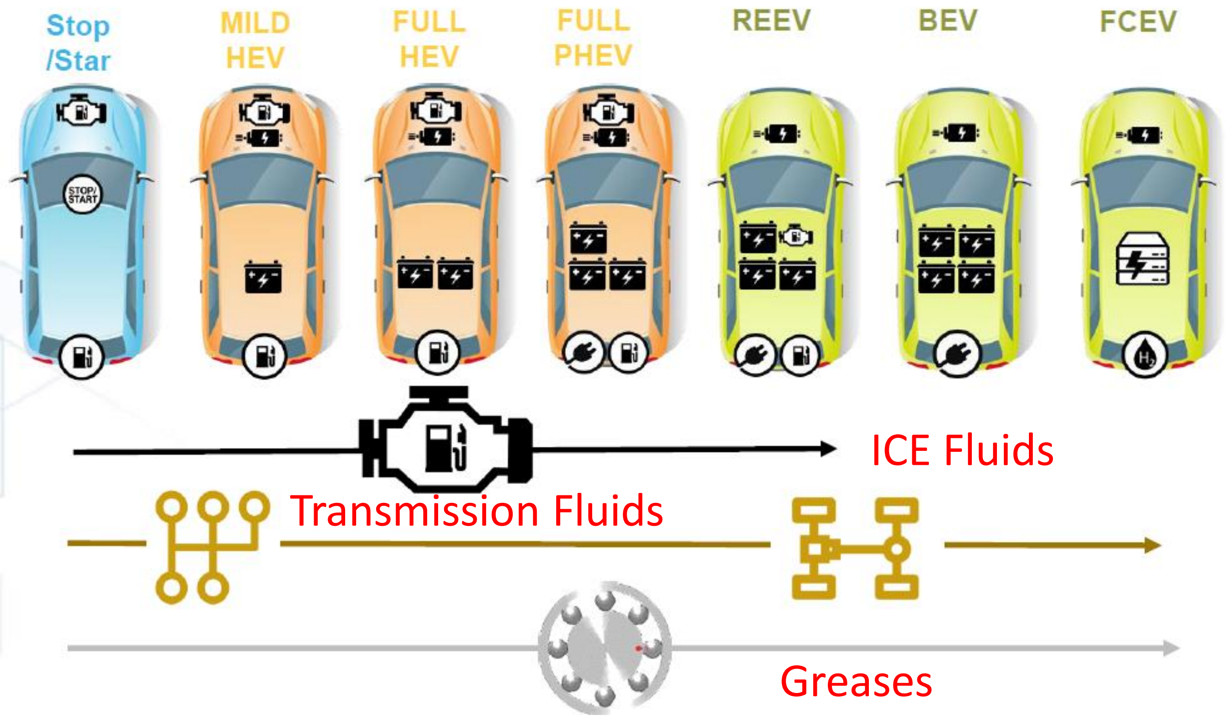
Greases



Ref: Bakker, B. S. Tesla Model 3 powertrain fun. from carburetors to carborundum. you've come a long way, baby! https://cleantechnica.com/2018/05/28/more-tesla-model-3-powertrain-fun-from-carburetors-to-carborundum-youve-come-a-long-way-baby/ (accessed Apr 1, 2022).

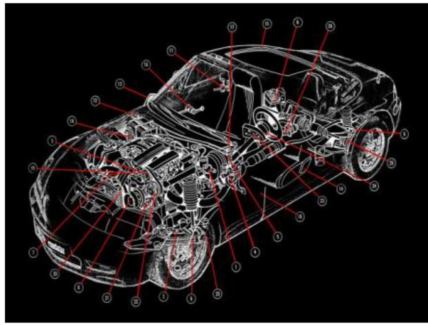
EV's and Grease Lubrication

- Grease formulation changing – but volume to remain stable
- Types of Greases
  - Corrosion protective
  - Lubricating
  - Water resistant
  - Anti-squeak
- Combinations of one or more
  - Can be up to 50 greases on a typical passenger car or light truck
- Constant – GREASE



ICE – Internal Combustion engine, HEV – Hybrid EV, PHEV – plug-in HEV, REEV – range extended EV, BEV – battery EV, FCEV – fuel cell EV

Grease - EV’s vs ICE



- Obsolete Greases
- Driveshafts
  - Center bearings
  - High speed CV joints
  - Hooke’s joints
  - Sliding splines
- Accessory drive bearings
  - Water pump
  - Engine cooling fan bearings
  - Alternator
  - Belt tensioner pulley bearing
- Starter motors

- Modified Greases
- CV Joints
  - could be smaller
  - No risk of shock loads or “idiot” starts
  - Hard acceleration may need wide angle plunging joints to prevent shudder
- Greases for coolant pumps and motor bearings
  - Thermal fluid rather than anti-freeze
  - Cooling circuits for the E-drive motors
  - Temperature control circuits for battery
- All greases optimized for energy efficiency and longer life
  - To reduce drain on batteries
  - Driving in the rain will reduce range

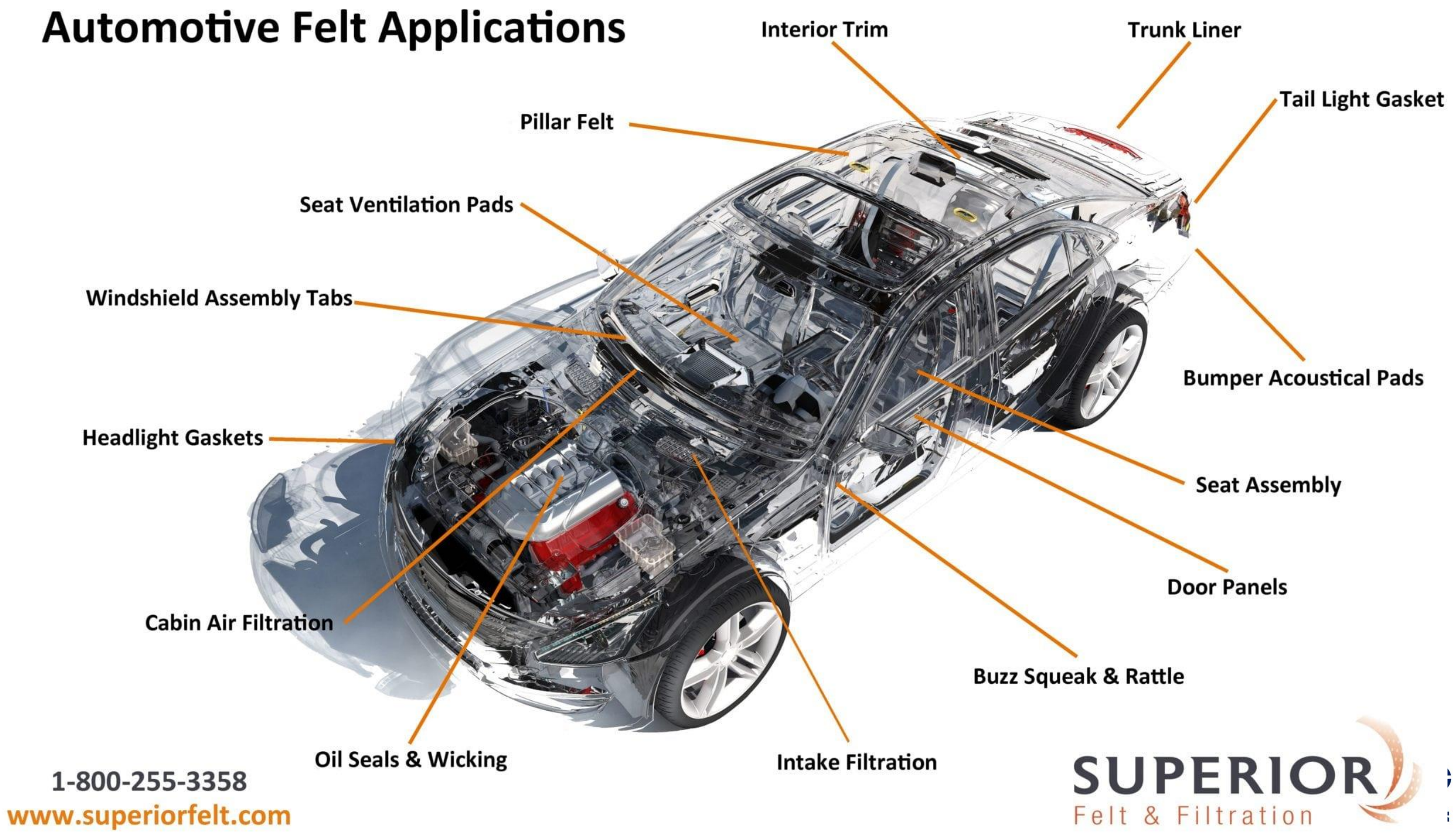
- New Greases
- Transmission electric motor bearings may be grease lubricated or oil lubricated when incorporated within the gearbox or differential
- Electric motor bearing greases
  - Long life
  - Low noise
  - Conducting or insulating
  - Energy efficient
- EVs have motor and coolant pump to control the battery temperature to within its optimum range

Pressure on Greases

- Demand for lithium batteries leading to alternatives to lithium-based thickeners due to price increases or shortages
- Battery weight a concern in all EV's due to the extra load batteries place on wheel bearings (~1600kg v 1300kg ICE)
  - More viscous base oils and higher amounts of EP+AW additives increase a grease's load-carrying capacity. Bearings under heavier loading run hotter, so extra antioxidants are needed to extend the grease's life
- Shifting the balance from greases with a longer life to greases with greater energy efficiency
- Conductivity - assumption grease was insulating. EVs run on 12V electronics, and 24 or 48V systems may come soon
- EV motors generate instantaneous torque. So, no gradual running-in time, in which grease has time to work its way into gears or bearings
- Components experience a great deal of force, at low speeds, before a fluid film can form. Solid coatings may be needed to protect surfaces at low speeds

NVH – Squeak and Rattle (S&R)

- Due to lower engine noises, increase in noticeable S&R – but there is no agreed industry test (limit) for it – in an ICE it is run at 30km/h with a noise limit.



Agenda

- Brief Introduction to Tribology
- Lubricants and Additives in ICE's
- EV History
- Lubricants in EV's
- Testing of Greases for EV's
  - Existing vs future testing/methods
- Conclusions/Discussion

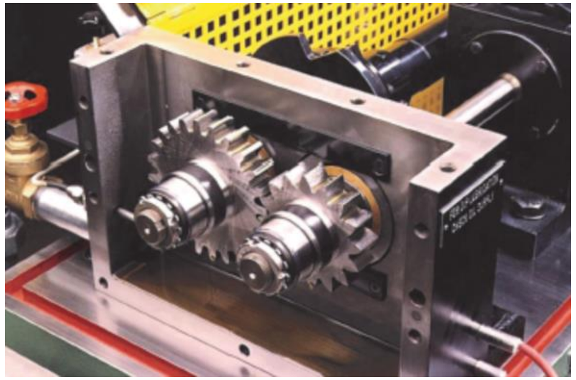
Traditional Grease Testing

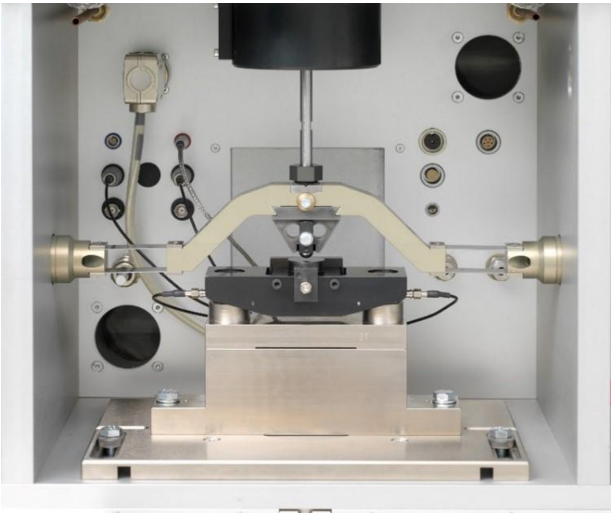
- The ASTM def of lube grease is:
  - "A solid or semi-solid lubricant consisting of a thickener agent in a liquid lubricant. Other ingredients imparting special properties may be included"
- Most common lubricating grease tests

Characteristics	Test	Designation
Apparent Viscosity	ASTM D1092	Apparent Viscosity of Lubricating Greases
Bleed Resistance	ASTM D6184	Oil Separation from Lubricating Grease by Conical Sieve Method
	ASTM D1742	Oil Separation from Greases During Storage
Corrosion	ASTM D1743	Corrosion Preventive Properties of Lubricating Greases
	ASTM D6138	Corrosive Preventive Properties of Greases by Emcor Test
	ASTM D4048	Copper Corrosion from Lubricating Grease
Antiwear	ASTM D2266	Wear Preventing Characteristics of Lubricating Grease (Four-Ball Method)
	ASTM D5707	Friction and Wear Properties of Lubricating Grease Using a High-Frequency, Linear-Oscillation (SRV) Test Machine
Extreme Pressure	ASTM D2596	Extreme Pressure Properties by Four Ball Method
	ASTM D2509	Load Carrying Capacity of Grease by Timken Method
	ASTM D5706	Extreme Pressure Properties of Lubricating Greases Using a High-Frequency Linear Oscillation (SRV) Test Machine
Oxidation Resistance	ASTM D942	Oxidation Stability
	ASTM D5483	Oxidation Induction Time of Lubricating Greases by Pressure Differential Scanning Calorimetry
Dropping Point	ASTM D2265	Dropping Point
	ASTM D566	Dropping Point
Grease Life	ASTM D3336	Life of Lubricating Greases in Ball Bearings at Elevated Temperatures
	ASTM D3527	Life Performance of Automotive Wheel Bearing Grease
Shear Stability	ASTM D217	Cone Penetration
	ASTM D1831	Roll Stability of Lubricating Grease
Water Resistance	ASTM D1264	Water Washout Characteristics of Lubricating Greases
	ASTM D4049	Resistance of Lubricating Grease to Water Spray
Low Temperature	ASTM D4693	Low-Temperature Torque of Grease Lubricated Wheel Bearings
	ASTM D1478	Low-Temperature Torque of Ball Bearing Grease

Figure from STLE TLT Magazine September 2021, ‚New and in-service grease testing', Page 39

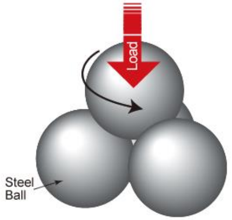
Some examples ofTribology Standard Grease Testers

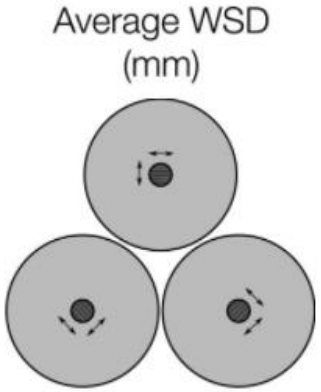


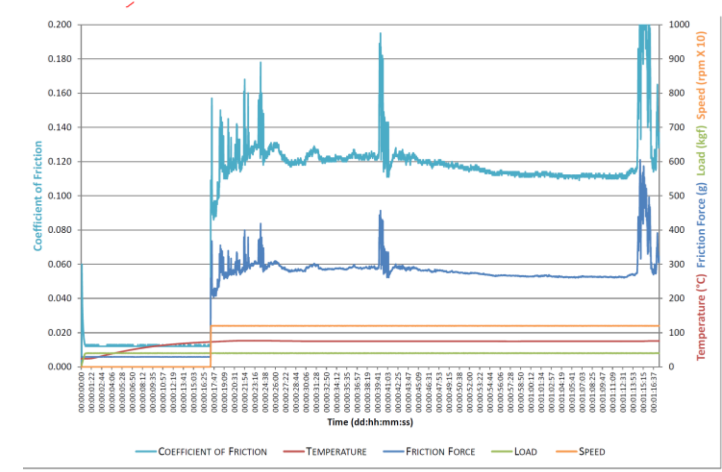


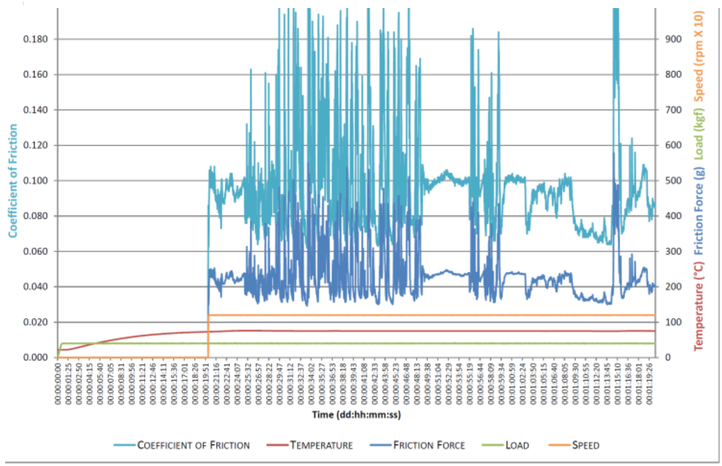
ASTM Standard Grease Testing

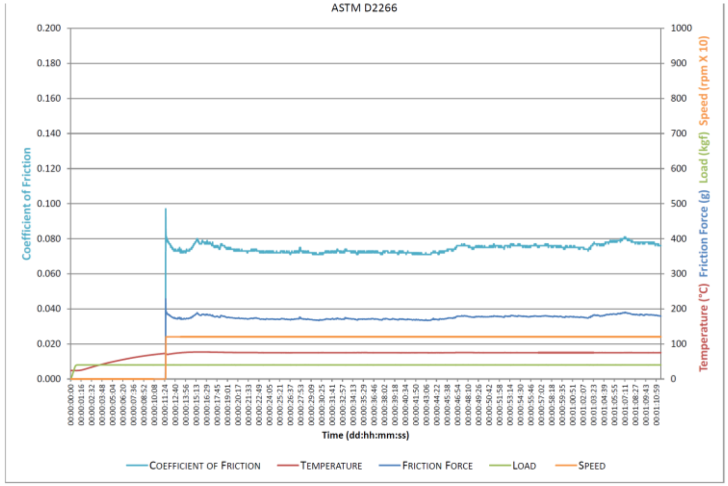
- Anti-Wear Properties
  - ASTM D2266 - Wear Preventive Characteristics of Lubricating Greases
- EP Properties
  - ASTM D2596 - Measurement of Extreme Pressure Properties of Lubricating Greases



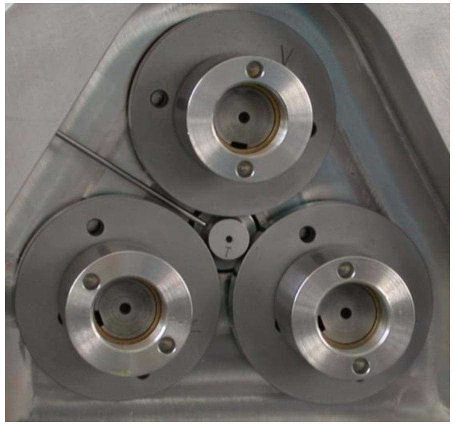


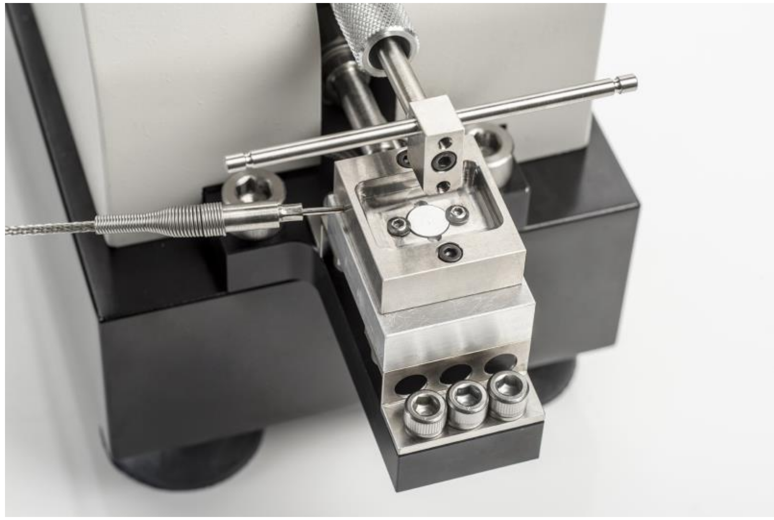






Non-standards based Grease Testers





https://pcs-instruments.com/instruments/

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Standards Testing

- Speeds, temperatures,loads (stresses) all increased in EV's – so standard testing needs to be modified and/or extended
- While there are plenty of 'EV' Greases on the market – there are no specific standards for EV greases at this time – some internal OEM tests appearing – but industry needs to coordinate this better
    - E.g. No standard for measuring the conductivity of grease – varying claims in the literature
- OEM's have their own unique electric motor design, thus requiring a specific lubricant for their electric motors to fit their needs for performance
- Lack of testing standards has led to a lack of data on repeatability or reproducibility

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EV Grease Testing

- Example new Tribology test to look at greases in EV's
  - Electrically Induced Bearing Damage (EIDB) Testing
- New Tribology test equipment developed to look at greases in EV's
  - High Speed Bearing Tester
  - Modified Four-Ball Machine
  - Ball-on-Disc Tribometer

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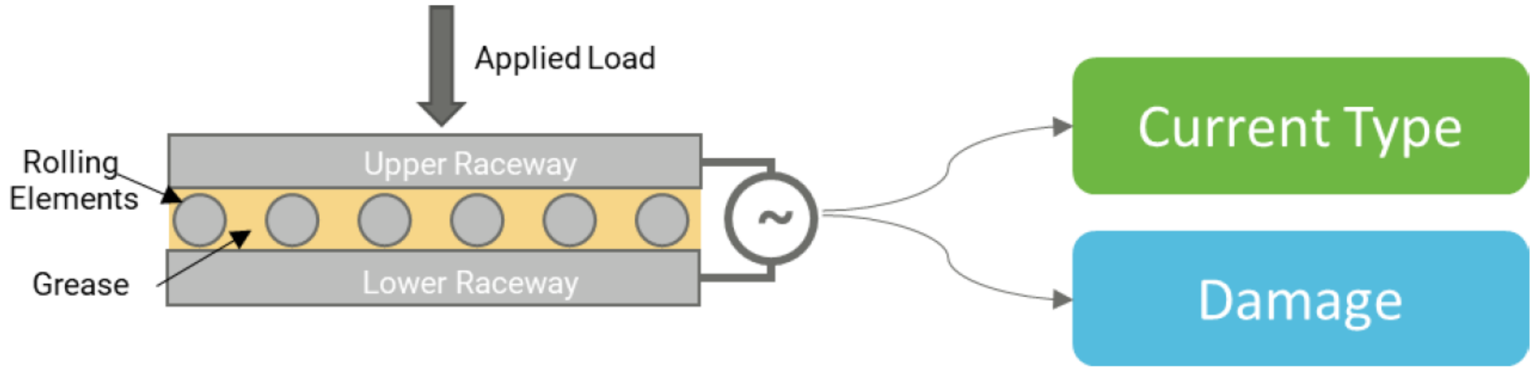
Electrically Induced Bearing Damage (EIDB) Testing



- Dynamic bearing test - provides specific data on the types of measurable current through the bearing (capacitive, EDM or Ohmic). Used to evaluate how these effects link to observable damage to bearing component's surfaces.
- Use thrust type ball bearing. Run at 2000 N, 1000 RPM with testing temp from 30 °C to 80 °C in 10 °C increments
- Breakdown voltages are taken at each interval with common mode applied voltages of 5 V, 10 V, and 20 V (peak to peak)

Source – Compositional Effects on the Electrical Properties of Lubricating Greases, ELGI May 2022, Dr Gareth Fish et al, Lubrizol Corp.

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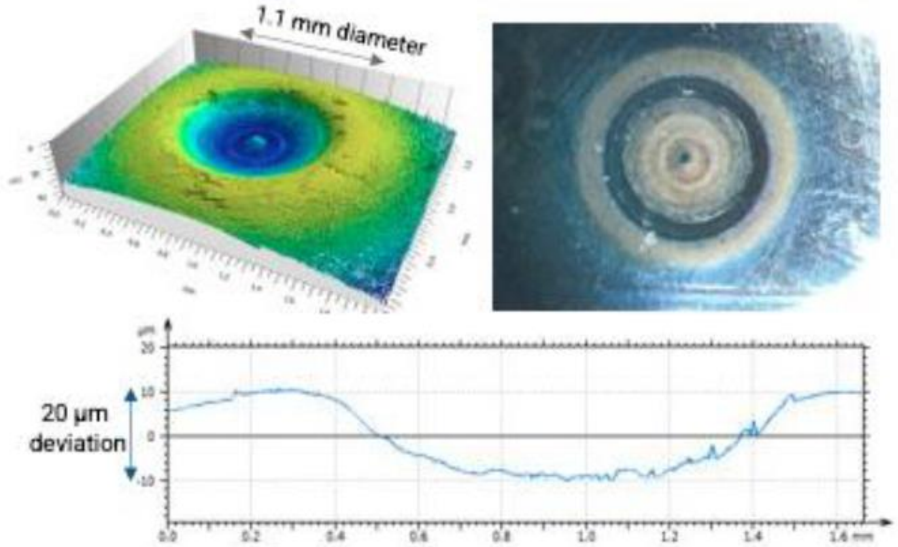
Results

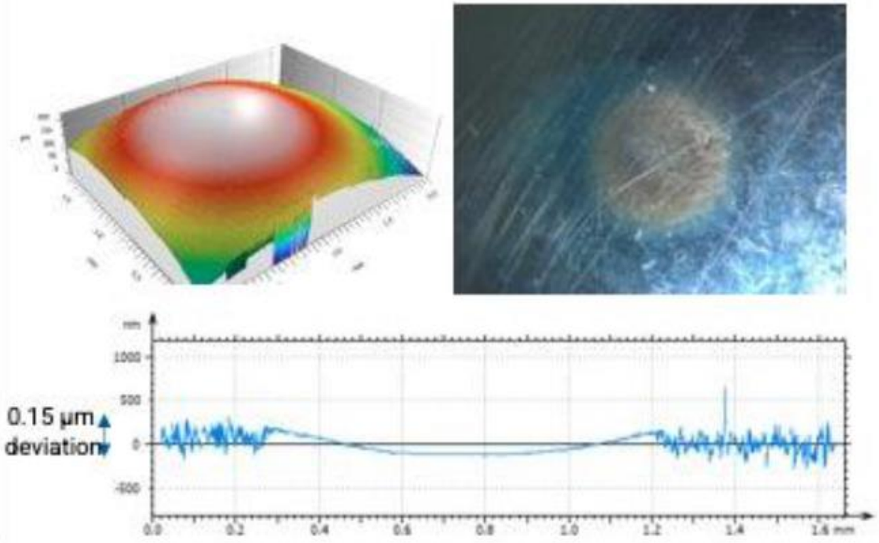
Formulated grease displays no high voltage Electric Discharge Machining (EDM) currents but the highest number of low voltage EDM currents.

Market Available Grease Volume Resistivity = 2.6 10^{8} Ω cm						
Voltage	30°C	40°C	50°C	60°C	70°C	80°C
5V	2847	9333	3417			
10V	3722	958				
20V	83					



Market available grease targeted at high-speed bearings in EV applications

PU Base Grease + 5% wt Additive C1 Volume Resistivity = 2.9 10^{13} Ω cm						
Voltage	30°C	40°C	50°C	60°C	70°C	80°C
5V					19361	19250
10V	7819	3292	4611	4458	3014	3736
20V						



Formulated grease

Capacitive Currents

EDM Currents

Ohmic Currents

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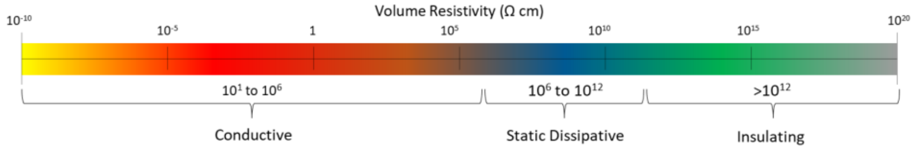
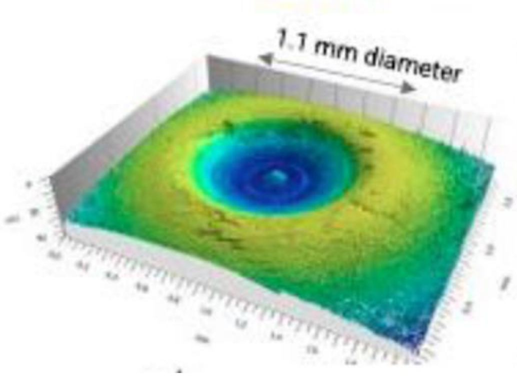
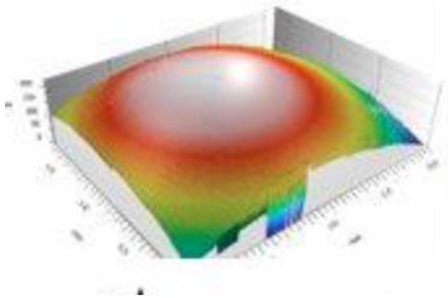
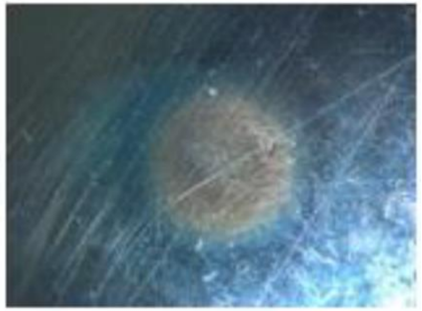
Conclusions



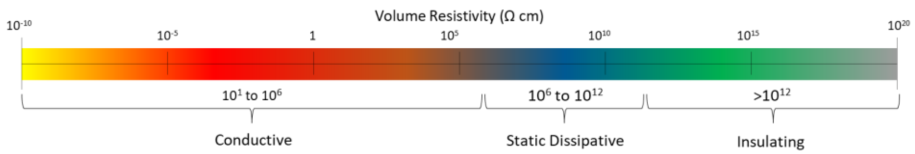
- High voltage EDM events lead to significant and large (> 1 mm diameter, > 20 µm depth) craters with a characteristic “electro-pitting”
- However - lower voltage EDM events display no high impact/damage craters but some smaller, less distressing surface events
- Important as market available grease is far more conductive and specifically used in E-Motor bearings but still experiences significant bearing surface damage



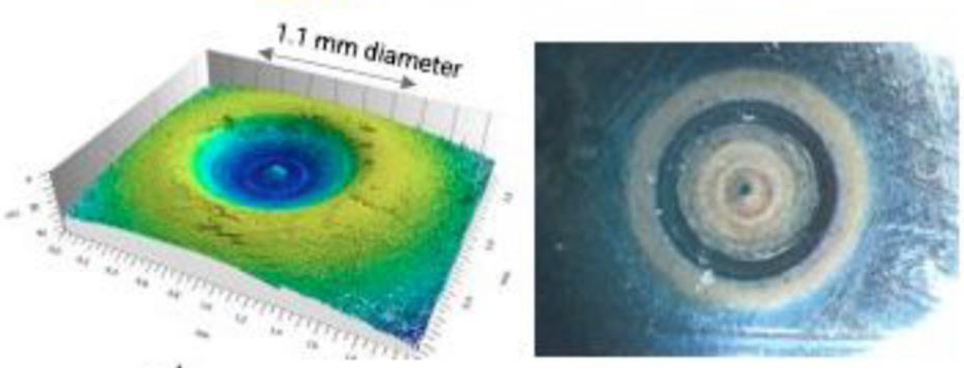




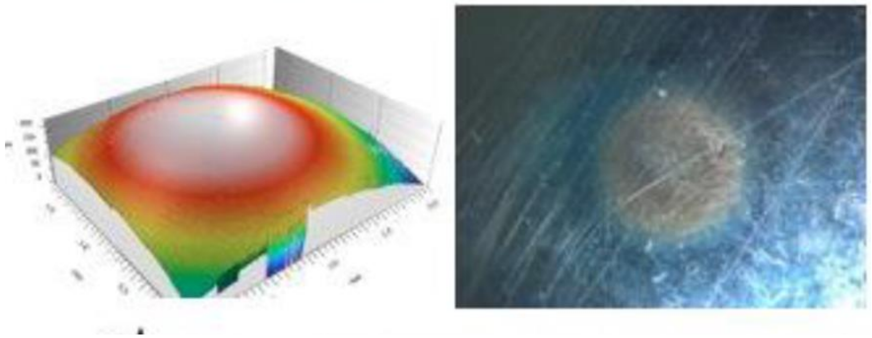
Source – Compositional Effects on the Electrical Properties of Lubricating Greases, ELGI May 2022, Dr Gareth Fish et al, Lubrizol Corp.

Conclusions



- Suggests electrical resistivity of the grease plays important role in durability of the grease and in decreasing EDM events, but other electrical properties and electrically induced damage modes must be considered for future component and grease design
- Results suggest that the perceived wisdom that a conducting grease will reduce bearing damage may not be correct and the optimum position is likely to be that the grease needs to be static dissipative

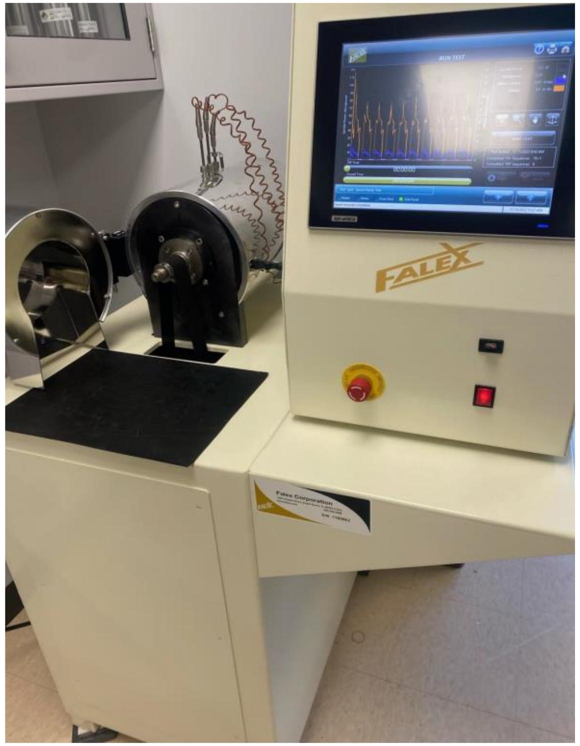


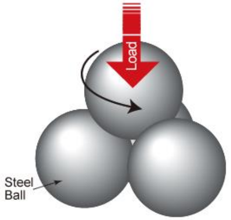


Source – Compositional Effects on the Electrical Properties of Lubricating Greases, ELGI May 2022, Dr Gareth Fish et al, Lubrizol Corp.

3 example Grease tests

1) High Speed, High Temperature Bearing Test Rig
2) Electric Motor Grease Testing – using the Four-ball
3) Ball-On-Disk versus Bearing Tests – benchtop comparison





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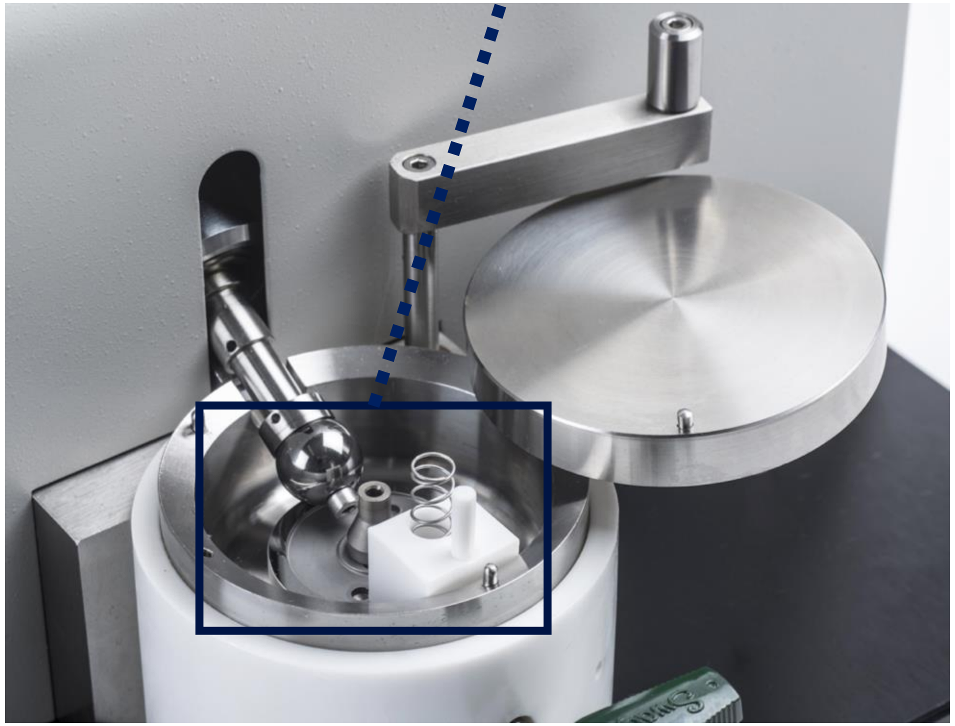

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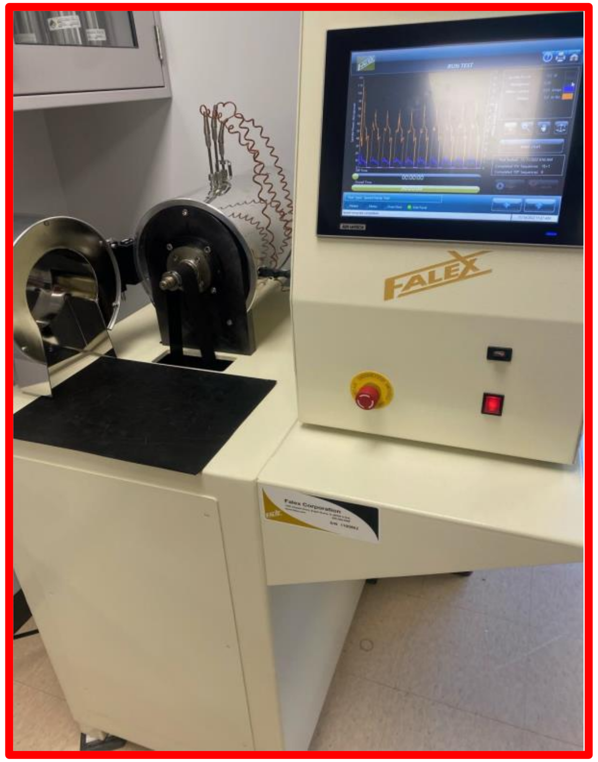

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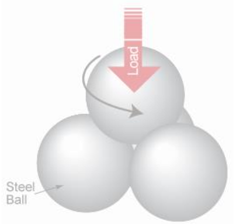
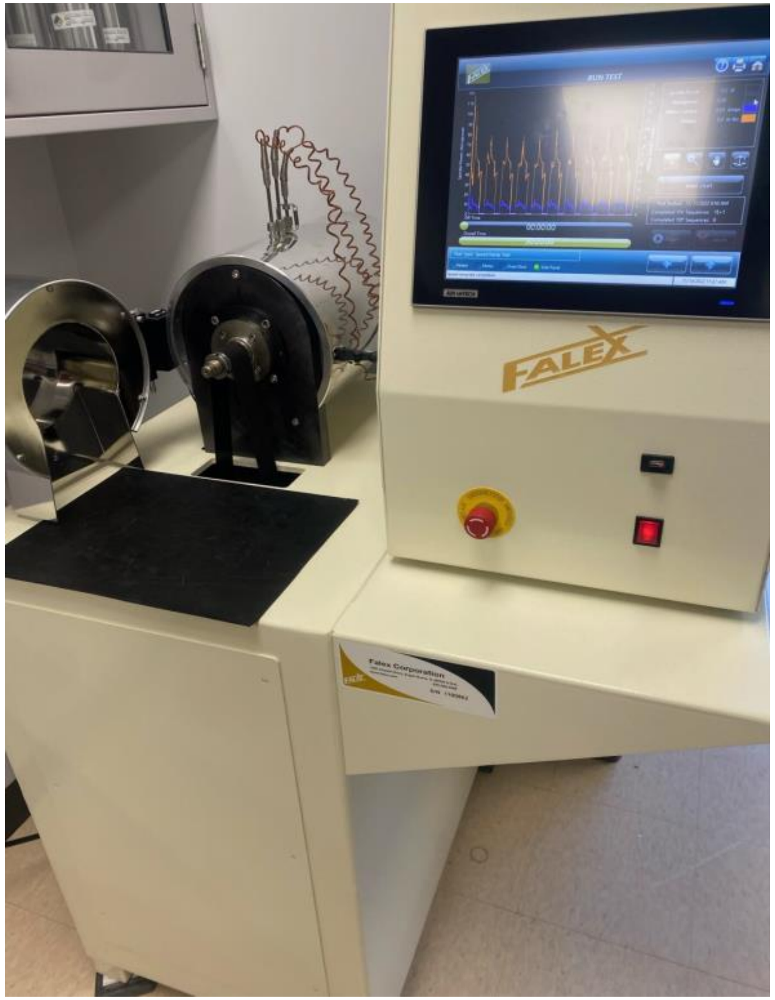


PCS Instruments

High Speed, High Temperature Bearing Test Rig

- Not new equipment
- Standard Test Methods ASTM D3336 - Standard Test Method for Performance Characteristics of Lubricating Grease in Ball Bearings at Elevated Temperature
- But due to max speed of 10,000 RPM becoming of interest in the industry – proven design and production



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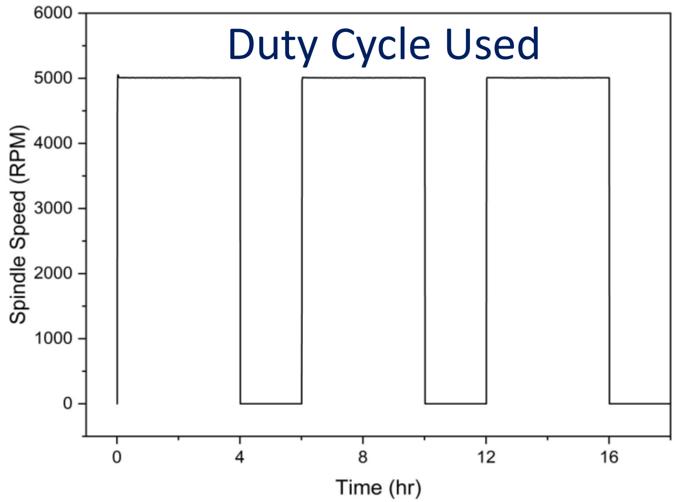
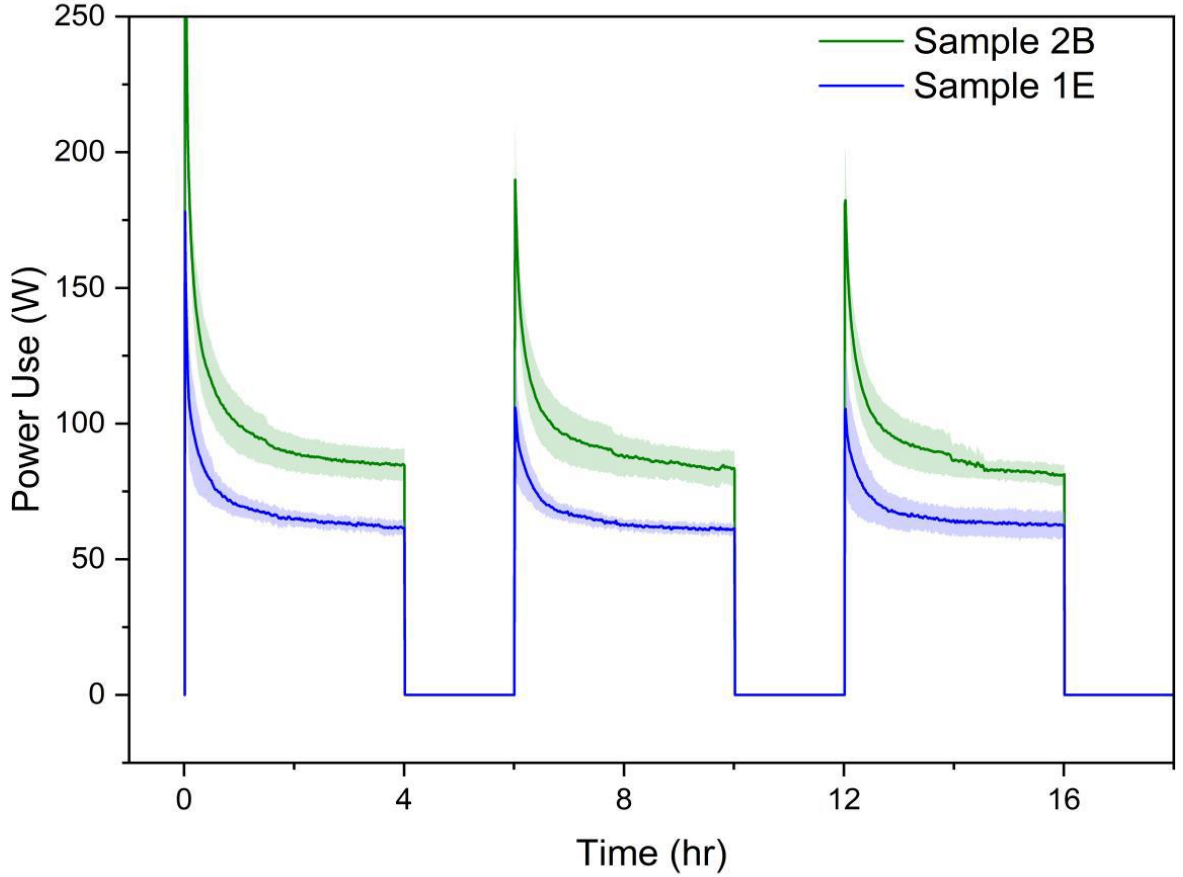
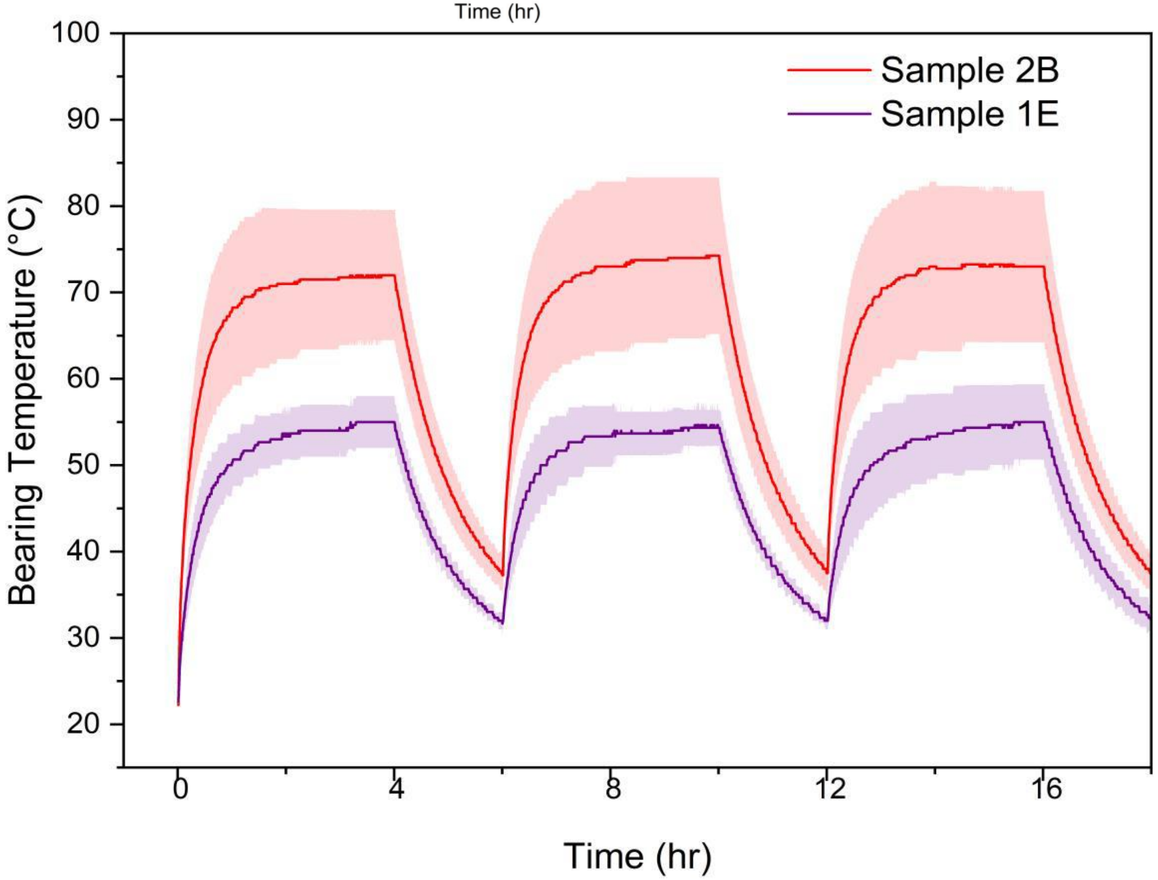
Shift from Performance to Efficiency







Ref - Next Generation, High Efficiency Grease for Electric Vehicles Developed in Racing Applications, Jacob Bonta, Valvoline, STLE 2023

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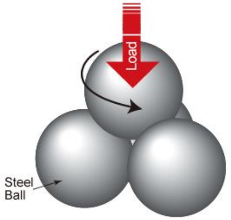

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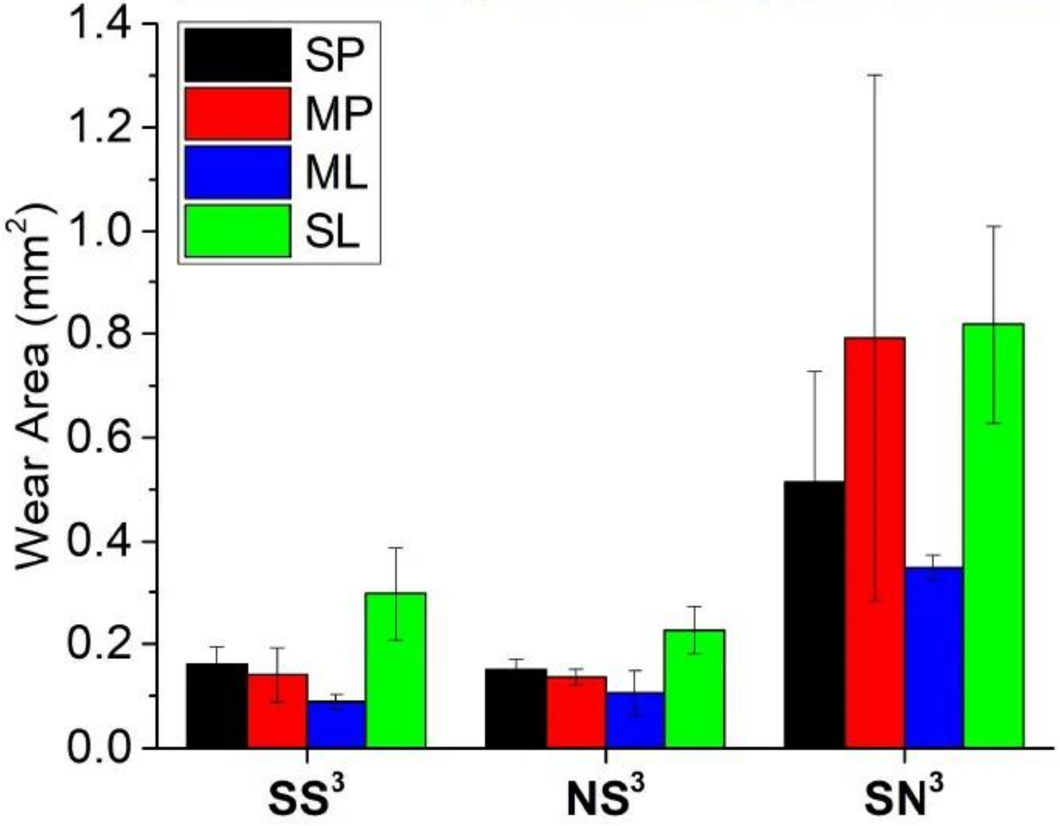
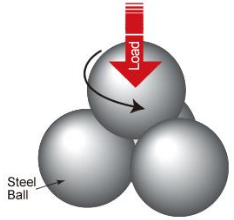
Electric Motor Grease Testing

Four ball tests

- Three different material combinations tested on a four-ball instrument on 4 different greases
- Lowest average wear in order : NS^3 -> SS^3 -> SN^3
- Observed that the wear rate for NS^3 is the lowest



EM Grease	Acronym	Base Oil Viscosity at 40 °C (cSt)	Base Oil Viscosity at 100 °C (cSt)	Base Oil Density at 15 °C (g/cm³)	Dropping Point (ASTM D2265 °C)
Synthetic-polyurea	SP	100	14	0.85	250
Mineral-polyurea	MP	100	12	0.88	260
Mineral-lithium	ML	100	11	0.93	180
Synthetic-lithium complex	SL	100	14	0.85	260



‘S’ 52100 steel,
‘N’ Silicon nitride ceramic

From - Daniel Sanchez Garrido, Samuel Leventini and Ashlie Martini, “Effect of Temperature and Surface Roughness on the Tribological Behavior of Electric Motor Greases for Hybrid Bearing Materials”, https://doi.org/10.3390/lubricants9060059

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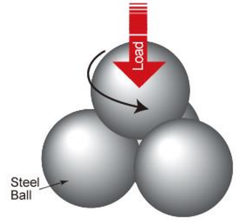
Electric Motor Grease Testing - Conclusions



- Mineral-lithium grease best of 4 commercial greases tested
- Does not say that ML grease is universally the best choice of thickener – depends on base oil for EV bearings
- Many different types of
  - lithium complex thickeners,
  - Synthetic base oils
  - Additive combinations
  - Manufacturing processes
- Leads to every grease being unique!

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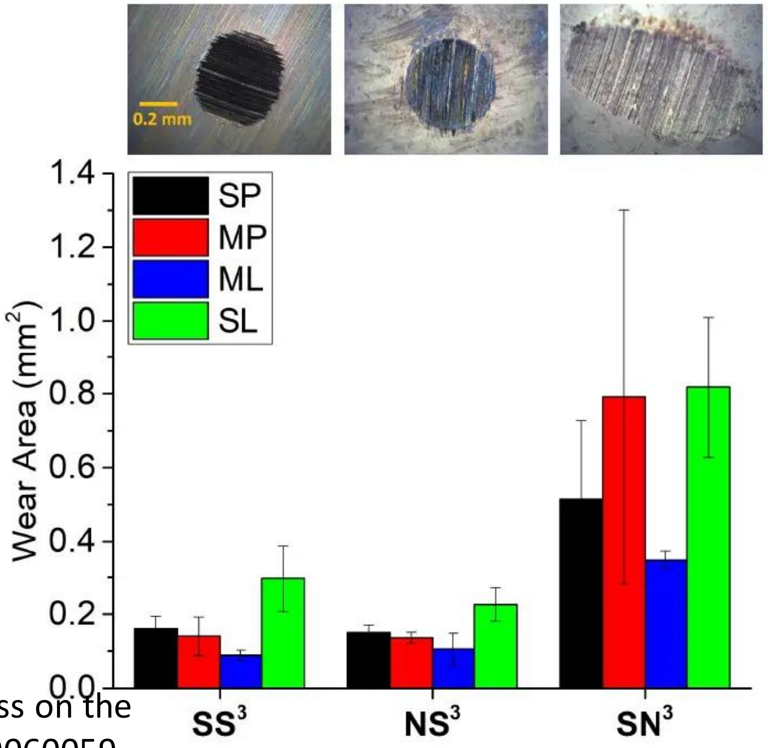

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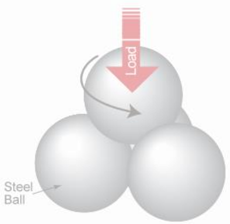

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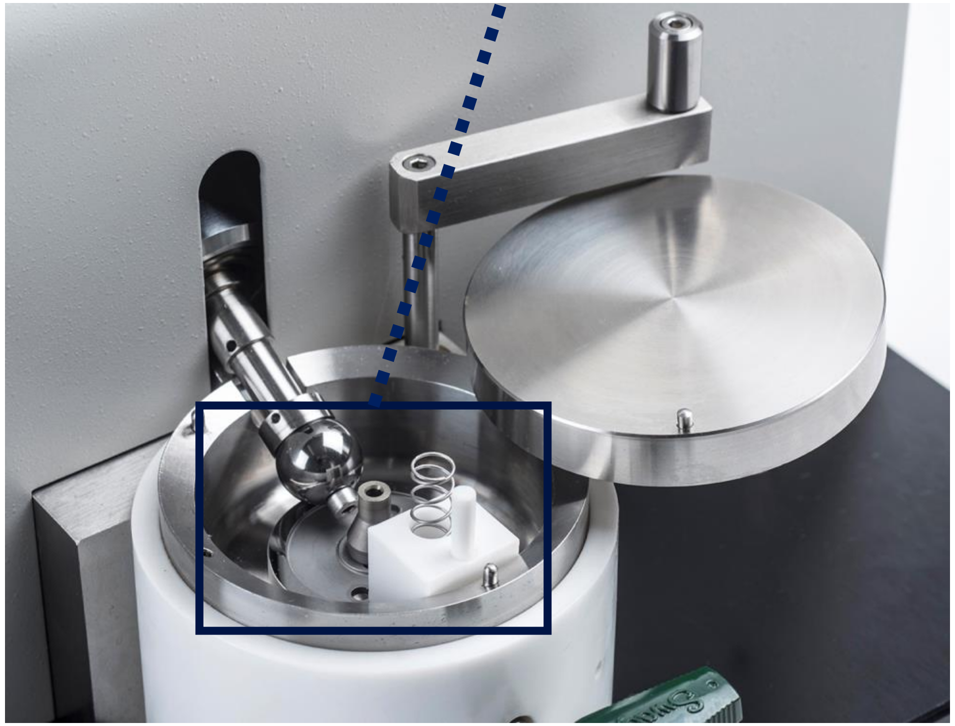
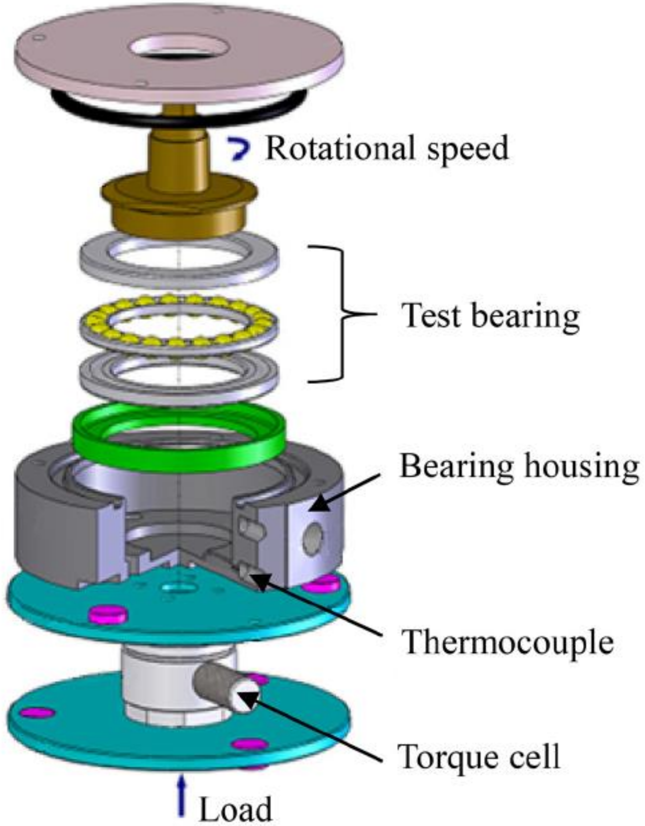


Ball-On-Disc v Full Bearing Tests

- 5 different formulations tested on both Thrust rolling bearing tests and ball-on-disc (MTM) instrument
- Effective λ ratio reported based on measured grease film thicknesses

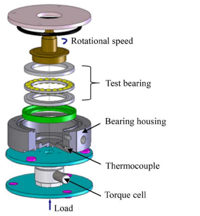
V



Lubricant name	Thickener type	Base oil type	Viscosity at 40 °C (mm²/s)	Viscosity at 100 °C (mm²/s)
Base oil L	—	PAO	48	8
Grease UL	Aliphatic diurea	PAO	48	8
Grease LL	Lithium complex	PAO	48	8
Base oil H	—	PAO	395	40
Grease LH	Lithium complex	PAO	395	40

Reference - Studies of Friction in Grease-Lubricated Rolling Bearings Using Ball-on-Disc and Full Bearing Tests, Kanazawa, De Laurentis, Kadiric - https://doi.org/10.1080/10402004.2019.1662147

Ball-On-Disc v Full Bearing Tests



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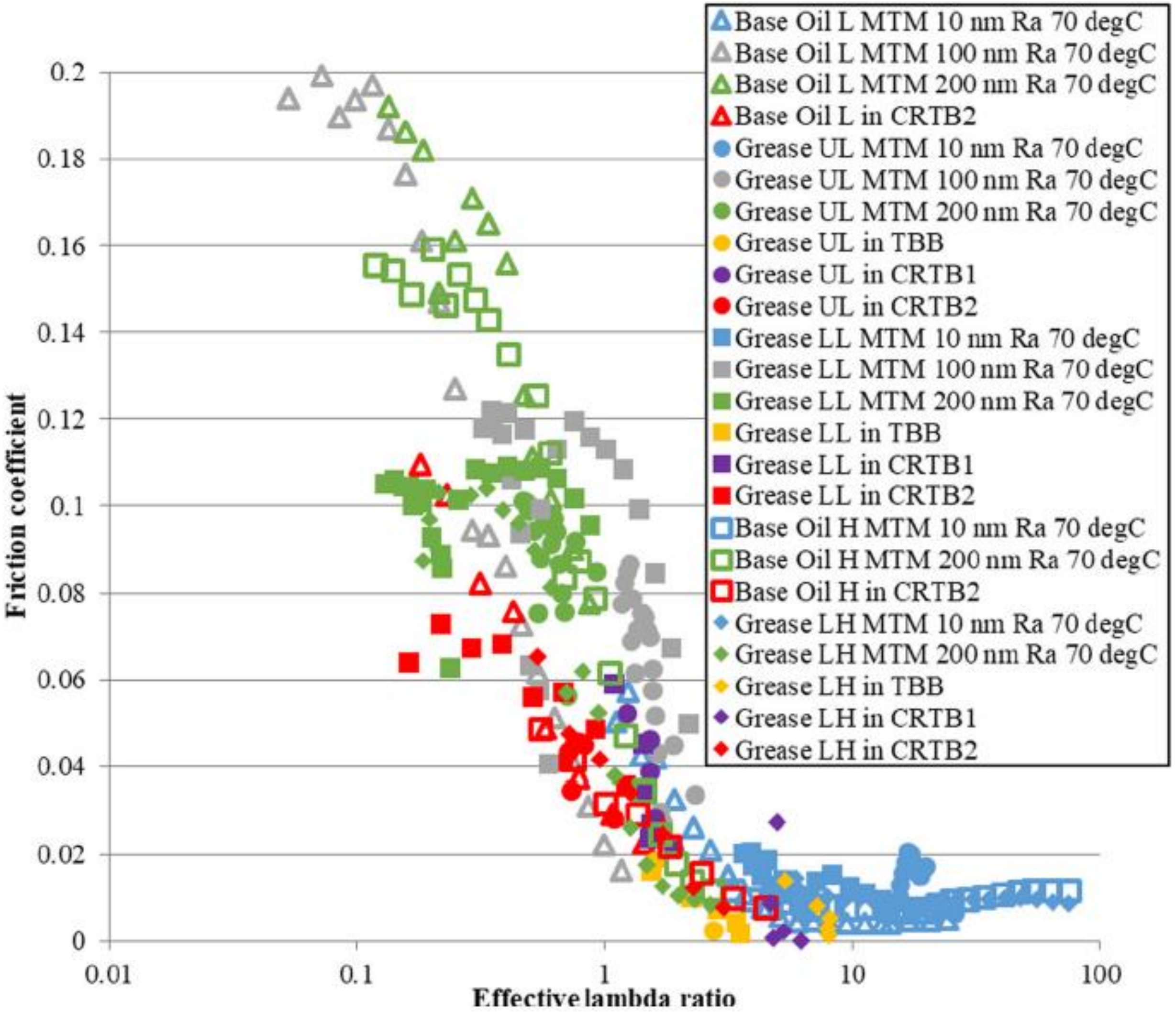

Conclusions

- Frictional behavior diurea & lithium complex greases deviates from their base oils at low nominal λ ratios (lower friction than base oils)
- At higher λ values, greases and oils have similar friction behavior and follow the trend of a classical Stribeck curve for an oil

Same Trends in full bearing & single-contact ball-on-disc tests

Reference - Studies of Friction in Grease-Lubricated Rolling Bearings Using Ball-on-Disc and Full Bearing Tests, Kanazawa, De Laurentis, Kadiric - https://doi.org/10.1080/10402004.2019.1662147

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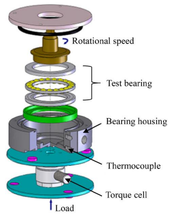
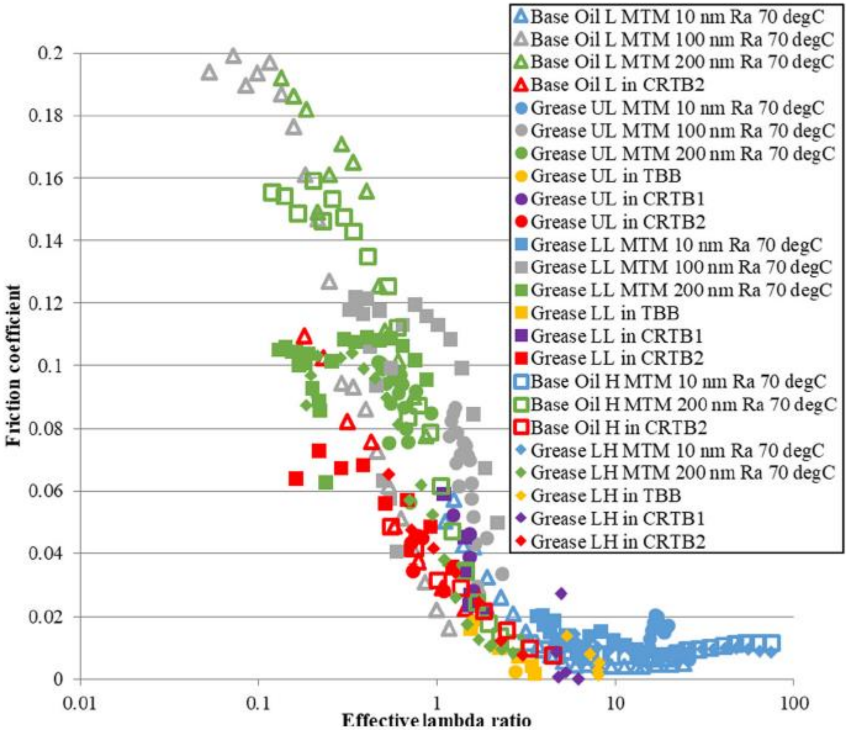
Conclusions



v

- Sliding μ values in all bearing + MTM tests fall onto a 'Master Stribeck' curve
  - Suggests single-contact ball-on-disc tests can be used to assess the frictional perf. of greases in full bearings
- True for both ranking of grease compositions and actual quantitative estimates of bearing friction torque
- **Overall** - Ball-on-disc tests provide a fast and economical means for early development of low-friction bearing grease formulations



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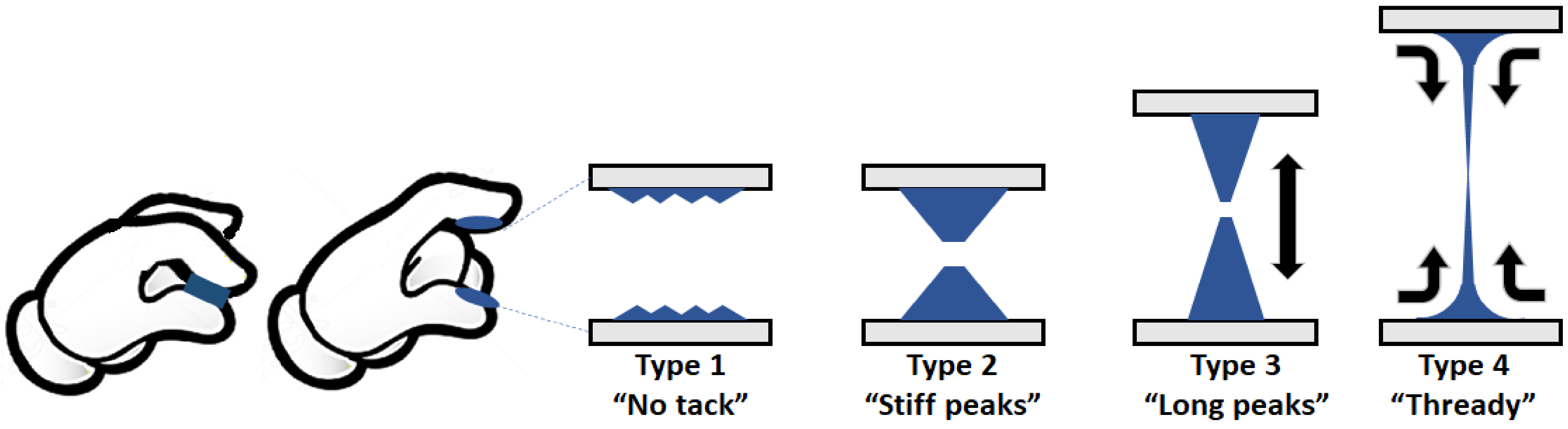
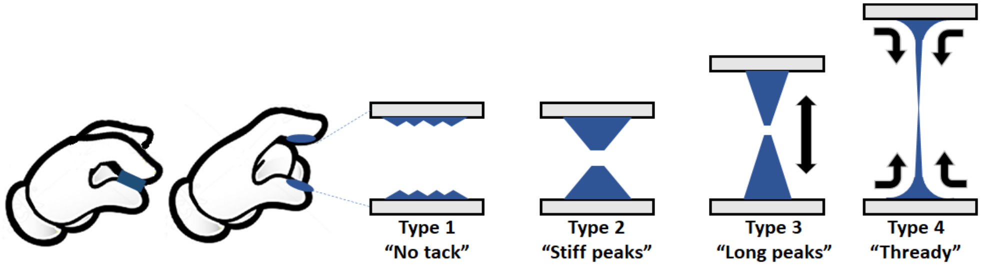
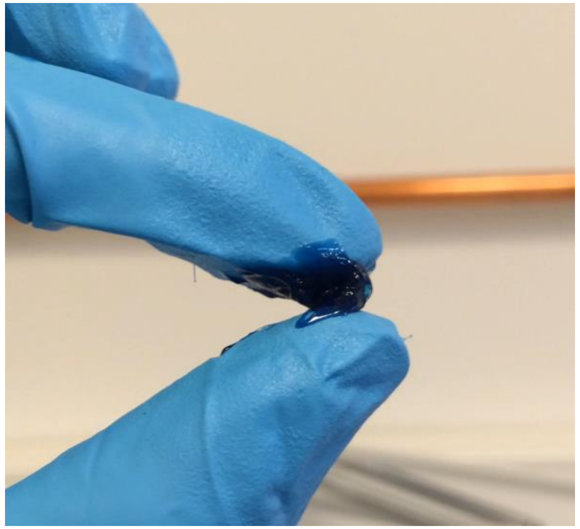
New Standards coming soon

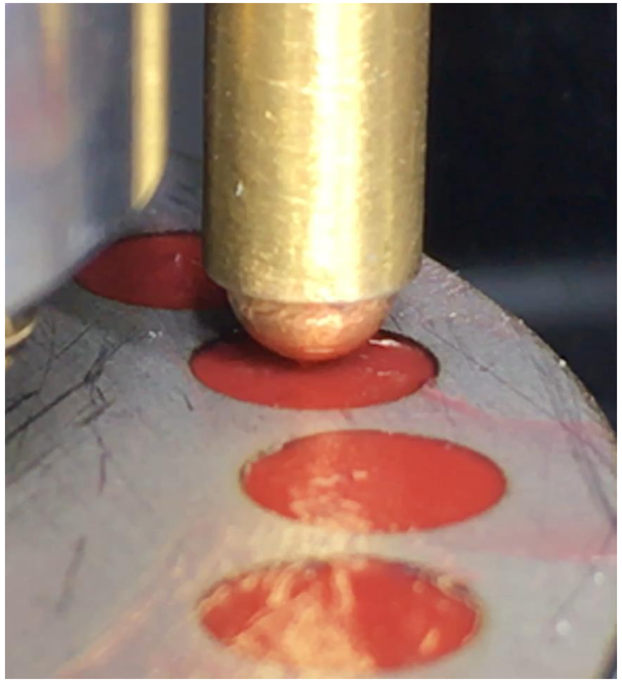
- Grease Tackiness Testing

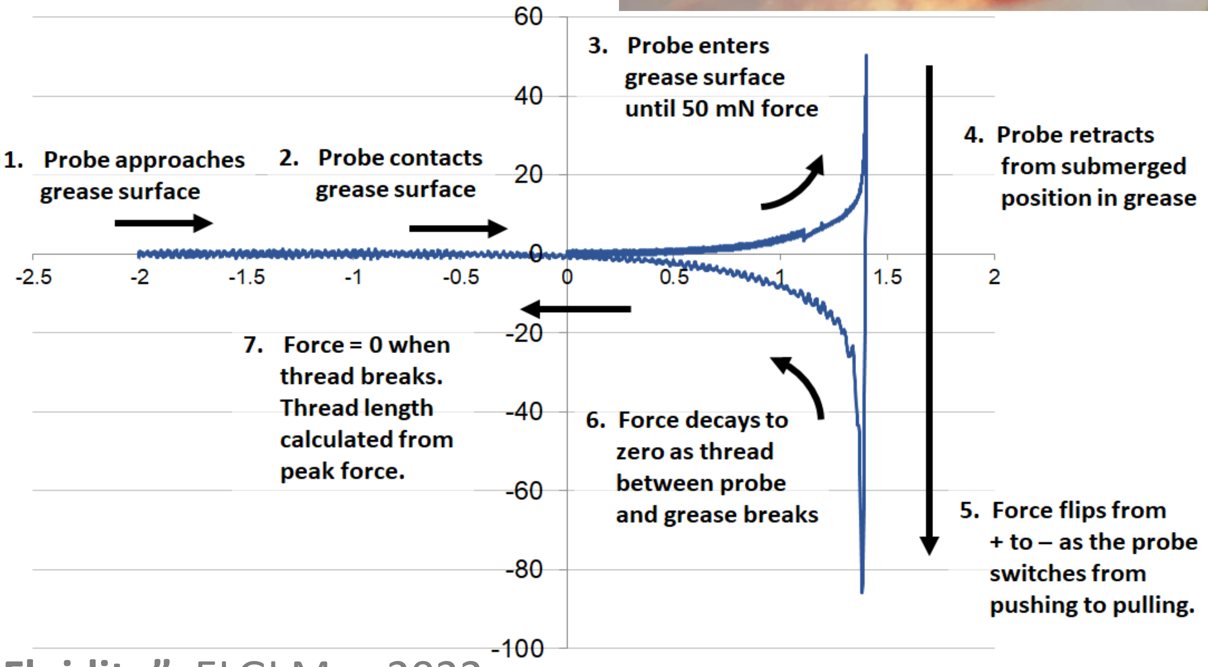


Proposed Standards are coming - grease tackiness









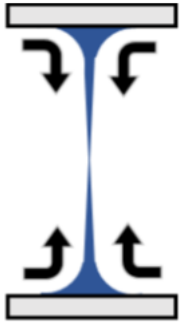
"**Tacky Polymer-Modified H1 Greases and Their Low Temperature Fluidity**", ELGI May 2022,
Erik Willett, Functional Products

Tackiness Results – ASTM method – at final ballot

Type 1
“No tack”

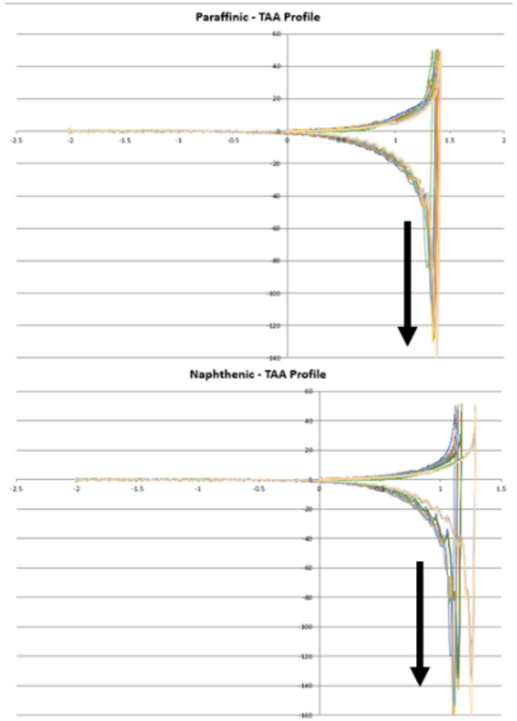
Type 2
“Stiff peaks”

Type 3
“Long peaks”

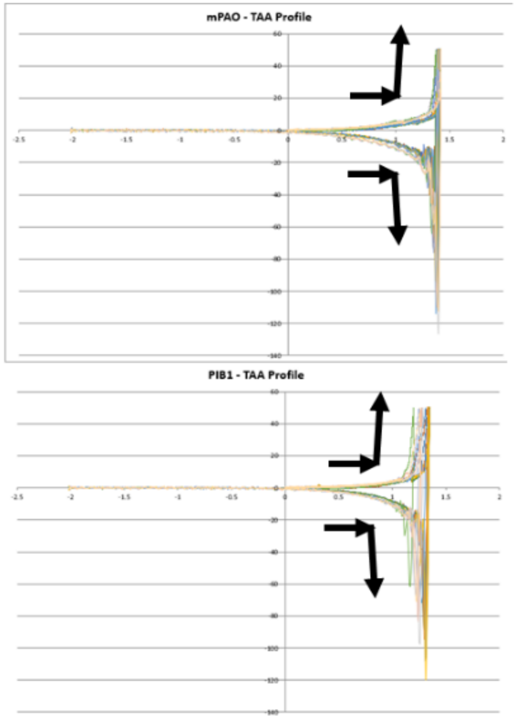


Type 4
“Thready”

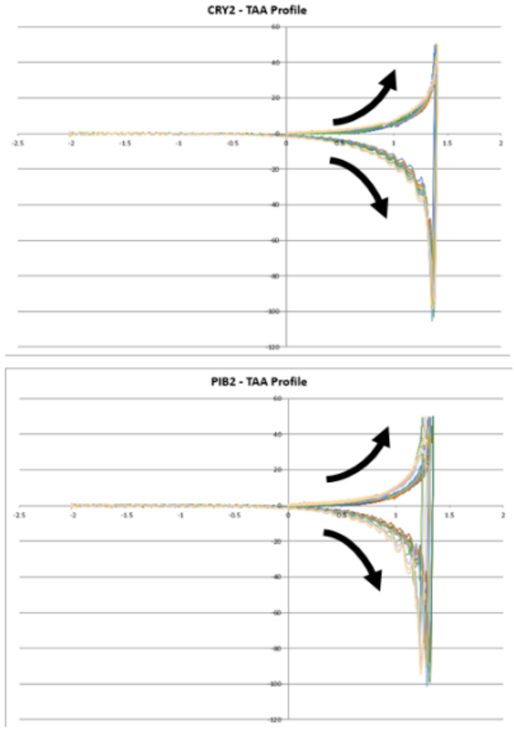
Type 1 – “No Tack”
Very high pull-off force



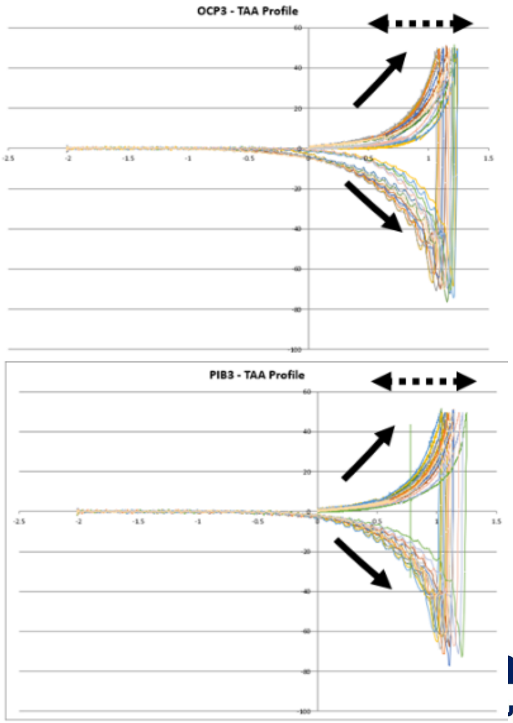
Type 2 – “Stiff peaks”
Sharp corners where force changes



Type 3 – “Stretch and break”
Soft corners where force increases
Looks similar to Type 1 otherwise



Type 4 – “Thready”
Broader, more linear force vs. distance
High cycle-to-cycle variability



Agenda

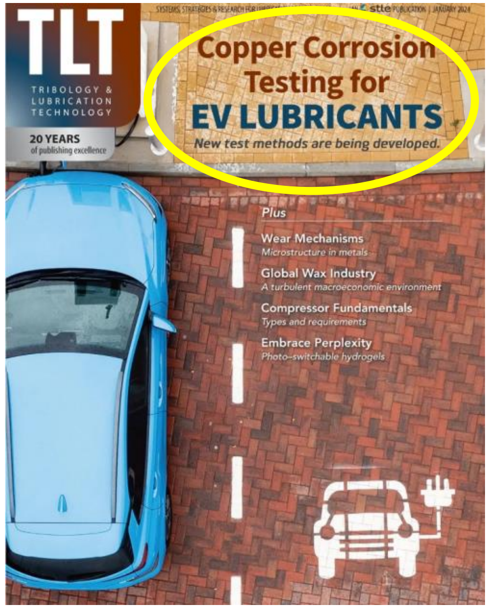
- Brief Introduction to Tribology
- Lubricants and Additives in ICE's
- EV History
- Lubricants in EV's
- Testing of Greases for EV's
  - Existing vs future testing/methods
- Conclusions/Discussion

EV – THE hot Topic in the Lubricant industry

March 2024

Feb 2024

Jan 2024



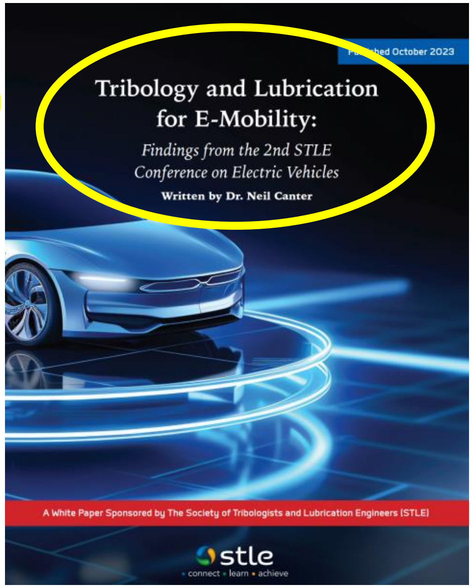
Nov 2023

Oct 2023

Aug 2023

July 2023

Oct 2023



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Conclusion from Kline STLE Article

- Making mechanical and electrical components function together “is where tribology meets electronics,”
- Thermal management, friction reduction, wear protection and electrical conductivity all come into play in EVs
- Advances in the EV market are happening so rapidly that “we’re having to publish [reports] by the semester rather than annually.”

Reference TLT Magazine Nov 2021, „The electric vehicle grease industry finds its bearings”

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Summary and Conclusions

- EV’s are here to stay and will be growing year on year
- Demand for a wide variety of greases expected to remain strong in the future, as electric, fuel cell, hybrid and internal combustion engine vehicles share the road
- EV lubricants must reduce friction and wear under high speeds, temperatures and voltages—as well as resisting oxidation and shear thinning and reducing noise
- OEMs currently develop their own specs and test methods for grease formulations, but they also collaborate with industry groups and academic researchers around the world
- New grease standards will be required, and tribology instrument manufacturers will have to work with the grease industry to support their requirements – higher electrical contacts, faster motor speeds, higher vehicle loads etc. . .
- Greases for EV’s will need to be upgraded to become more
  - Energy efficient
  - Increased durability and life

Thank You

Questions?

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