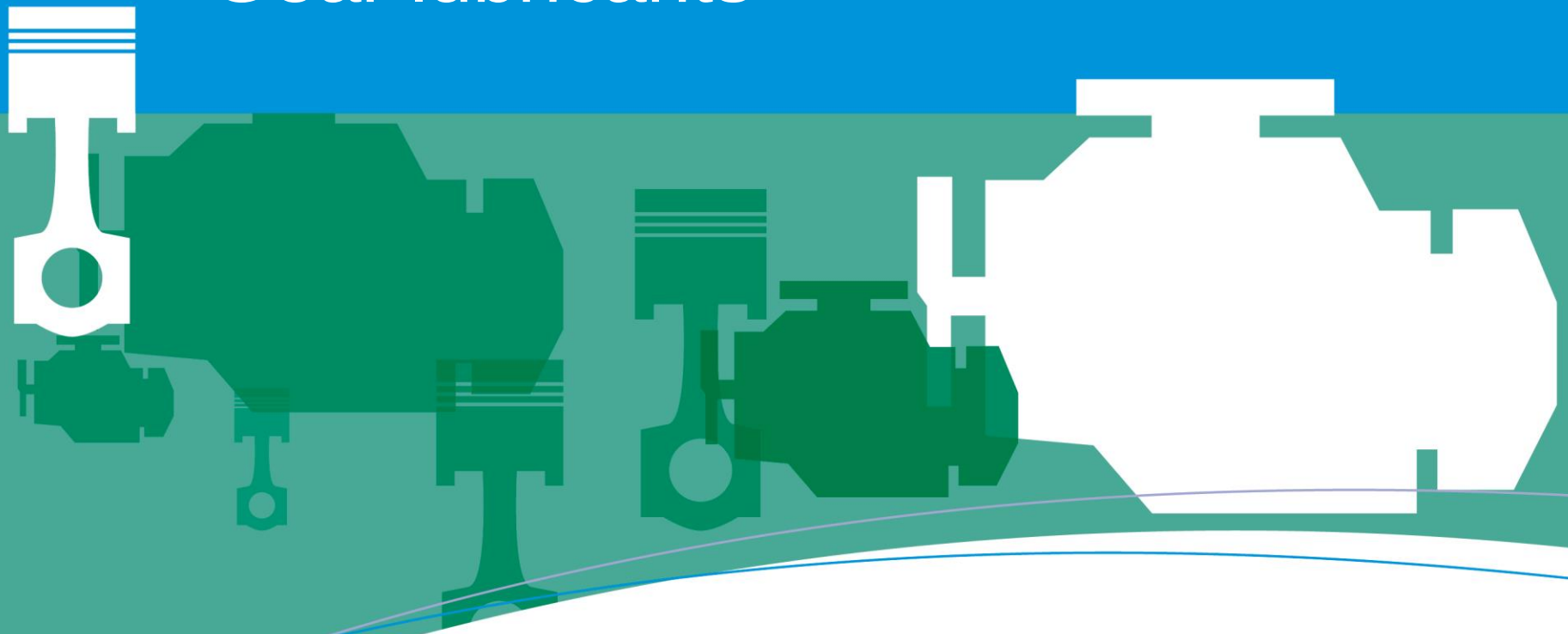
Performance you can rely on.

Gear lubricants



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Gear lubricants outline

Gear types and lube requirements

- Gear Functions, Common Types and Applications
- Gear Oil Requirements and Typical Formulations
- Gear Oil Market Overview

Automotive gear oil [AGO]

- Applications and Lubricant Requirements
- Classifications, Specifications and Testing
- Market and Trends

Industrial gear oil [IGO]

- Applications and Lubricant Requirements
- Classifications, Specifications and Testing
- Market and Trends

Summary

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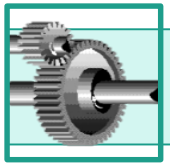
Gears – function and design

- **Gears perform multiple functions:**

Transmit power from one shaft to another
e.g. Industrial motor shaft to mixer shaft

Split power
e.g. Vehicle driveshaft to two driven wheels



Change shaft speed and torque
e.g. Vehicle transmission to driveshaft

➢ **Gear Ratio** $= \frac{\text{TEETH}_{\text{OUT}}}{\text{TEETH}_{\text{IN}}} \approx \frac{\text{RPM}_{\text{IN}}}{\text{RPM}_{\text{OUT}}} \approx \frac{\text{TORQUE}_{\text{OUT}}}{\text{TORQUE}_{\text{IN}}}$

- **Gear applications are extremely diverse**
  - Various gear types are used in both automotive and industrial applications
  - Automotive applications include: manual transmissions, differentials, transfer cases
  - Industrial applications are countless, including: steel mills and wind turbines

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Common gear types - comparison

SHAFT	Parallel	Parallel
TEETH	Straight	Spiral
GEAR TYPE	**SPUR** 	**HELICAL** 
TYPICAL AUTO SERVICE	Manual Transmission Reverse Gear	Manual Transmission Forward Gears
PROS	• Cost • Alignment	• Quiet/smooth • Efficiency • **Load capacity**
CONS	• Noise/vibration • **High friction**	• Thrust loads • Cost • Alignment

- **Gear oils must provide extra anti-wear protection**
  - Required for high loading and sliding contact

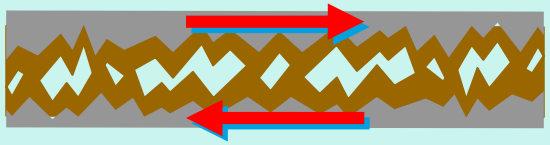
Anti-wear agents

- **Function**
  - Reduce metal-to-metal wear
- **Types**
  - Zinc-containing (ZDDP) ➔ Engines [PCMO]
  - **Ashless phosphorus ➔ moderately loaded gears [ATF, Gear Oil]**
  - Ashless non-phosphorus➔ special cases [Railroad oils]
  - **Extreme Pressure [EP] ➔ highly loaded gears [Gear Oil]**
    - Chlorine-containing molecules and/or highly reactive sulfur or sulfur-phosphorus compounds
    - Work similar to ZDDP, but more active and more corrosive
      - Must balance EP protection with corrosion protection
    - Also known as *Anti-Scuff additives*

Mechanisms of anti-wear and EP protection

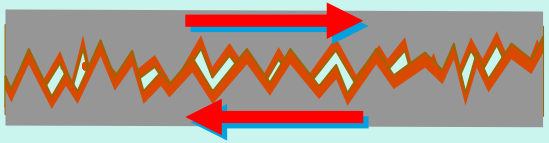
Anti-wear

- Decompose at local hot spots in a mixed lubrication regime
  - ➢ Friction at moderate loads
- Zinc, phosphorus, and sulfur compounds released by thermal decomposition form a solid film
  - ➢ Acts as a protective layer
- Film has lower shear strength than metal surface
  - ➢ Prevents contact and welding



Extreme pressure [EP]

- Decompose at local hotter spots in a boundary lubrication regime
  - ➢ Friction at heavy loads
- Sulfur compounds released by thermal decomposition reaction with metal to form an iron-sulfide layer
  - ➢ Acts as a sacrificial layer
- Reaction layer has lower shear strength than metal surface
  - ➢ Prevents contact and welding



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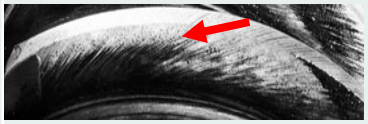
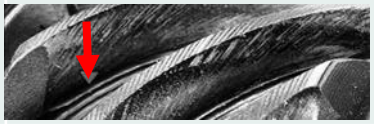
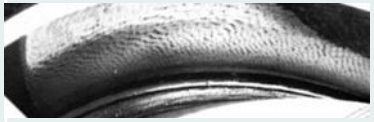
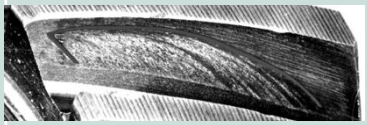
Gear distress and lubrication cures

Type	Distress	
New	None – smooth contact surface area.	
Pitting	Many small irregular cavities from surface metal breaking off.	
Spalling	As pits grow, larger flakes or chunks break off. Tooth breakage can result.	
Wear	Removal of metal, without pitting or scoring. May result in a shoulder ridge.	
Ridging	Parallel ridges in direction of sliding, from heavy loads when oil film ruptures.	
Rippling	Alteration of tooth surface to a pattern resembling water ripples or fish scales.	
Scuffing [Scoring]	Matte surface from metal transfer between teeth by momentary welding.	

LUBE REQUIREMENT

VISCOSITY

ANTI-WEAR

ANTI-SCUFF

EP AGENT

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Typical gear oil additives

70 - 80%

Components	Primary function	Typical chemistry
ANTI-SCUFF [EP AGENT]*	Enhances load-carrying capacity and controls scuffing	Sulphurized hydrocarbon and/or sulphurized ester
ANTI-WEAR	Provides anti-wear performance and rust protection	Phosphates, amine-phosphates and amines

*Anti-scuff additives are aggressive and often require additional component to minimize copper corrosion, oxidative/thermal instability, seal incompatibility, etc.

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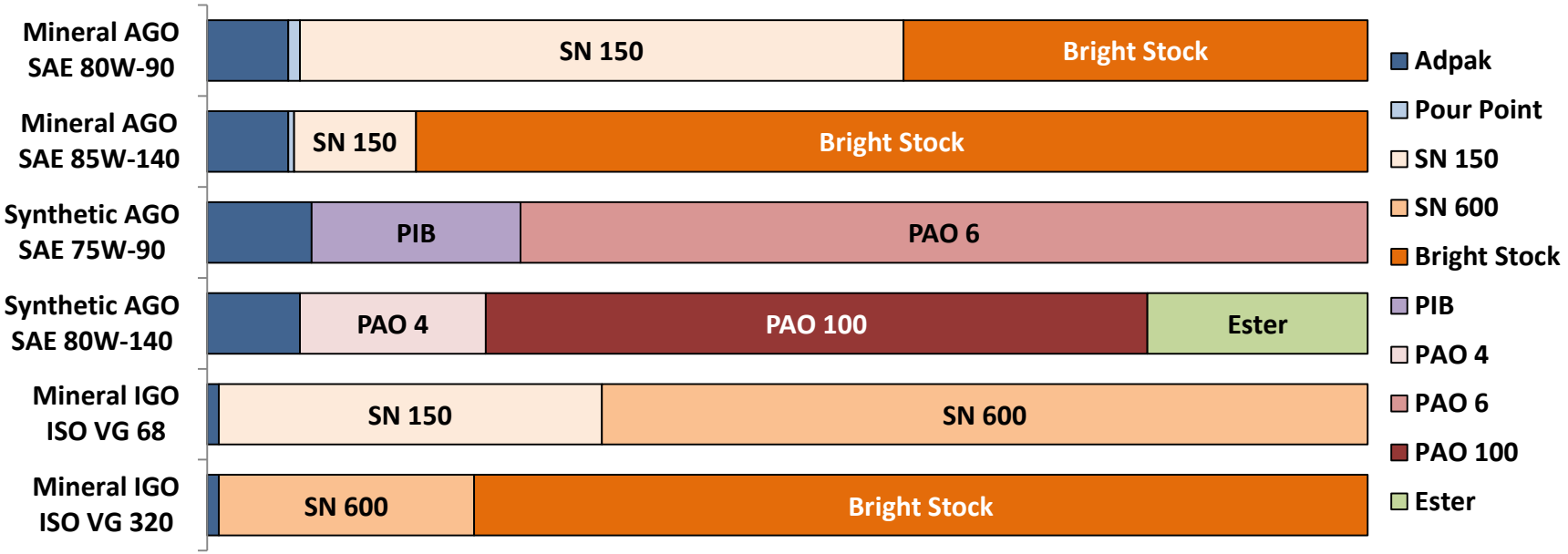
Typical gear oil formulations



- **AGO additive treat rates range from 7 to 10 mass%**
  - IGO additive rate rates are considerably less, generally only ~1-2 mass%
- **Mineral gear oils use heavier basestock cuts**
  - Most notably, bright stock
- **Synthetic gear oils are typically PAO based**
  - With polyisobutylene [PIB] and/or esters

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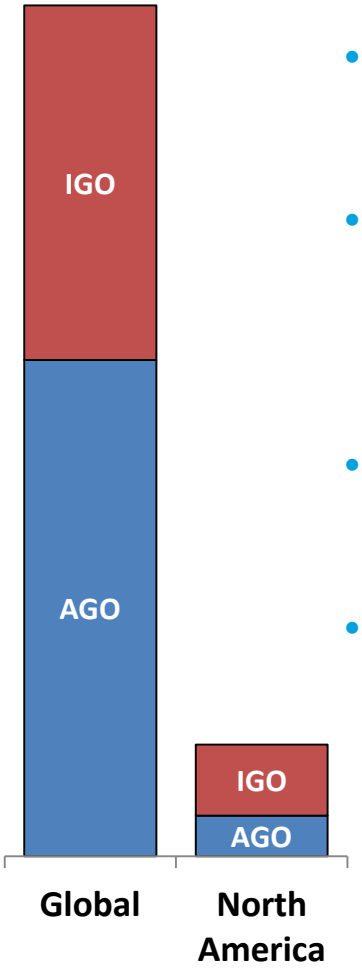
Gear oil demand



Data Source: Kline

- **Global market demand for gear lubricants is ~2400 kT/yr**
  - AGO demand is ~40% more than IGO
- **N. American demand is ~15% of global market**
  - due to relatively low population of manual transmissions
  - AGO demand is ~40% less than IGO
- **About half of AGO demand is for SAE 80W-90 viscosity**
  - followed by SAE 85W-140 and monogrades
- **Synthetic gear oils used in specialty applications**
  - Primarily for extended drain, ~10-20% of the market.
  - Increasing use for fuel efficiency, with lower viscosity

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Summary

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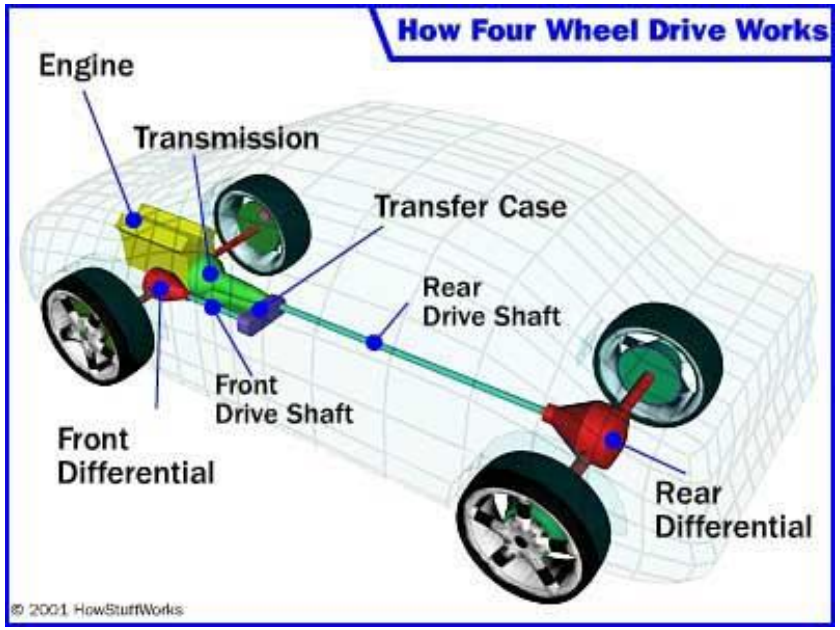
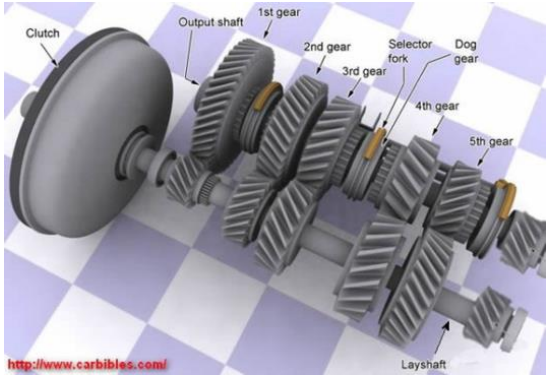
Automotive gear oil [AGO]

- **Gears are used throughout drivetrain:**
  - **Manual transmission** – to adjust drive shaft torque and speed.
  - **Differential** – to increase and split drive shaft torque to the axles, while allowing different wheel speeds.
  - **Transfer Case** – to adjust and split 4WD torque to front and rear drive shafts while allowing different shaft speeds.
- **Each application presents unique lubrication challenges**
  - Different fluids are often specified:
    - Manual Transmission Fluid [MTF]
    - Differential Fluid
    - Transfer Case Fluid
  - With different fluids within an application:
    - e.g., $MTF_a \neq MTF_b \neq MTF_c$



Manual transmission

- **Manual transmission operation**
  - Driver selects gear ratio via shift lever and rails
  - Two primary gear box mechanisms:
    - Constant Mesh helical gears – used for forward speeds.
      - Output gears freely rotate on the output shaft until locked to the shaft by a dog clutch on the shift rails.
      - Gears shift while in motion, output gear speed must be brought to drive shaft speed prior to engaging
    - Sliding [Crash] Mesh spur gears – used for reverse.
      - An Idler gear is engaged between countershaft and drive shafts. Must stop before shifting.
- **Manual transmission lubrication**
  - Heavily loaded power transfer between a single set of helical or spur gears [vs. planetary gear set], requires extreme pressure [EP] additives, in addition to anti-wear additives



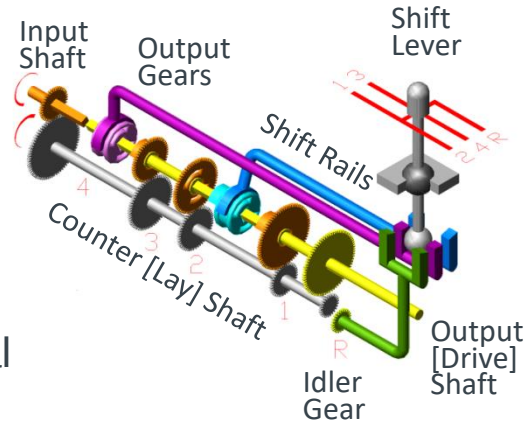
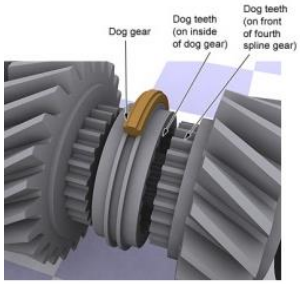
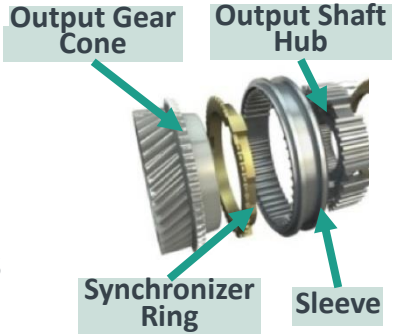


IMAGE SOURCE: WIKIPEDIA

Manual transmission synchronization





- –Wide range of friction materials are used; including carbon composites, bronze, brass and molybdenum

- **Synchronizer lubrication**
  - Precise friction control is required for a diverse range of materials and geometries.
  - Low temperature fluidity is critical at synchronizer/cone interface.

Automotive gears - differential

- **Differential operation**
  - Power from the drive shaft [1] axis is transmitted by a hypoid pinion gear [2] to a ring gear [3] on the wheel axis, while increasing torque via a high gear ratio.
  - The ring gear has a carrier [4] for planetary bevel (spider) gears [5] that transfer equal torque to sun bevel (side) gears [6] on the drive wheel axles [7].
  - By rotating on their own axis, spider gears allow the outer drive wheel to rotate faster during a turn.

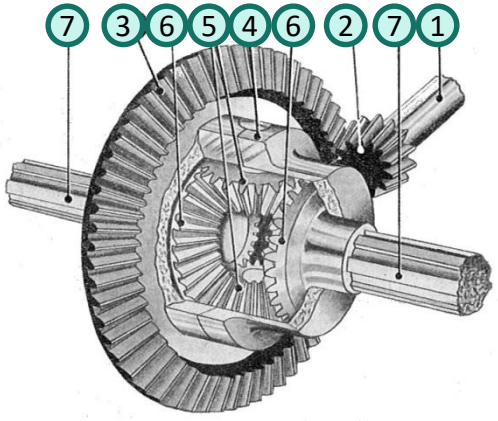


IMAGE SOURCE: WIKIPEDIA

- **Differential lubrication**
  - With high loading and a rolling/sliding motion that can rupture the lubricating film, a high viscosity oil with extreme pressure [EP] additives are used.
    - EP additives can generate deposits and be aggressive to seals and yellow metals

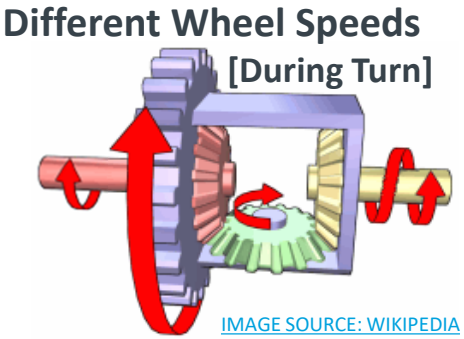


IMAGE SOURCE: WIKIPEDIA

Automotive gears – limited slip differential

- **Standard [open] differentials** – unlimited slip
  - With equal torque sent to each wheel, a tire with less traction can spin with not enough torque for the wheel with more traction to move the vehicle.

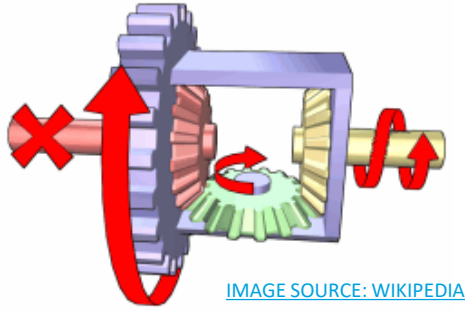


IMAGE SOURCE: WIKIPEDIA

- **Limited-slip differentials** don't get stuck in the mud

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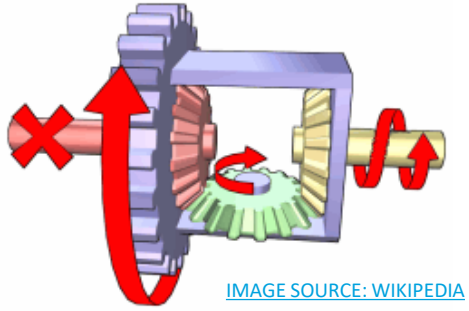


IMAGE SOURCE: WIKIPEDIA

- **Limited-slip differentials** don't get stuck in the mud
  - The spin on the wheel with less traction is limited via clutch packs, gears or a viscous coupling to increase torque for the wheel with more traction.

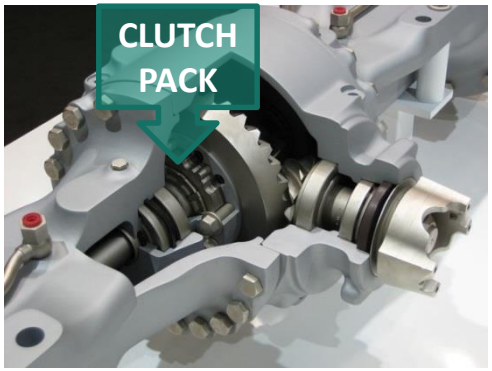
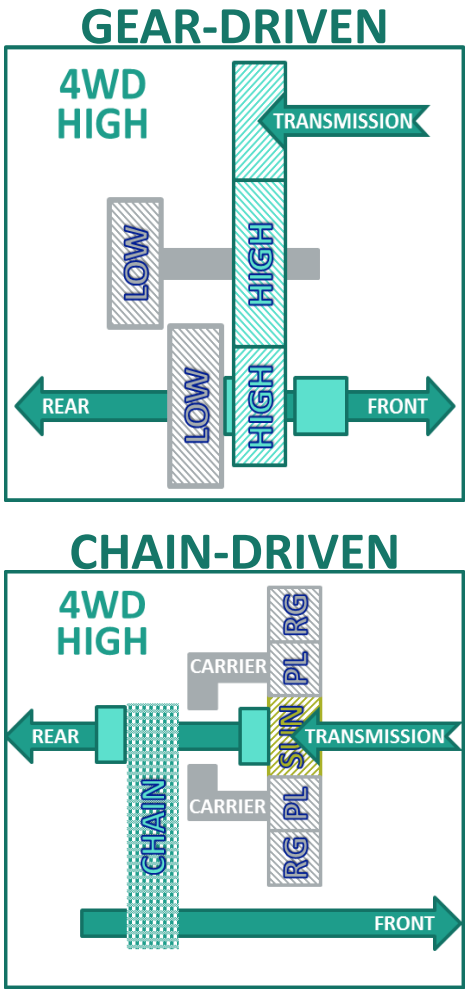


IMAGE SOURCE: WIKIPEDIA

- **Limited slip differential lubrication**
  - In addition to EP additives, designs with clutch packs require friction-modifiers, while those with a viscous coupling often use silicone-based oils.

Automotive gears – transfer case

- **Transfer case operation**
  - Splits power to front and rear axles in 4WD vehicles
  - Two primary mechanisms:
    - Gear-driven – used in off-road utility vehicles
      - Strong, but heavy and noisy
      - 4LOW, sliding mesh gears; stop before shifting
    - Chain-driven – used in light duty & passenger cars
      - Quieter and lighter, but not as strong
      - 4HIGH, can be automatic with clutches
      - 4LOW, planetary gear; stop before shifting
- **Transfer case lubrication**
  - Gear Driven – similar to differentials, with EP additives
  - Chain Driven – similar to planetary gear transmissions, may require friction control
    - AWD uses a center differential to send power to both front and rear differentials, with similar lube requirements.



AGO viscosity classification

- **SAE J306 viscosity standard**
  - Defines automotive gear, axle and manual transmission oil viscosities
  - Standard revised in 2005 to add SAE 110 and SAE 190
  - Demanding 70W and 75W Brookfield viscosity limits
    - Requires synthetic basestock and or pour point depressants
  - Demanding shear stability requirement for multi-grade oils
    - Conventional engine oil VMs generally aren't sufficient for AGO applications

SAE J306 Viscosity Grade	Max Temp for 150,000 cP Brookfield Vis, °C	Kinematic Viscosity @ 100 °C	
		Min(1)	Max
70W	-55	4.1	--
75W	-40	4.1	--
80W	-26	7.0	--
85W	-12	11.0	--
80	--	7.0	<11.0
85	--	11.0	<13.5
90	--	13.5	<18.5
110	--	18.5	<24.0
140	--	24.0	<32.5
190	--	32.5	<41.0
250	--	41.0	--

(1) Must remain in grade after 20 hr tapered roller bearing shear test (CEC-L-45-A-99)

API performance designations

- **API Publication 1560 -** Lubricant Service Designations for Automotive Manual Transmissions, Manual Transaxles, and Axles

API	APPLICATIONS	NOTES
GL-4	• Axles with spiral bevel gears in moderate to severe conditions and hypoid gears in moderate conditions. • May be specified in select manual transmissions, where API MT-1 lubricants are unsuitable.	• Test equipment no longer available. • OEMs normally add frictional specs for limited-slip differentials.
GL-5	• Axle gears, particularly hypoid, in high-speed/shock load and low-speed/high-torque conditions.	• OEMs normally add frictional specs for limited-slip differentials.
MT-1	• Non-synchronized manual transmissions used in buses and heavy-duty trucks.	• Extra protection against wear, thermal degradation and seal deterioration. • Not for synchronized transmissions.
GL-1	*NO LONGER IN USE. Was for manual transmissions operating under mild conditions.*	
GL-2	*NO LONGER IN USE. Was for worm-gear axles where API GL-1 service would not suffice.*	
GL-3	*NO LONGER IN USE. Was for manual transmissions in moderate to severe conditions.*	
GL-6	*NO LONGER IN USE. Was for gears with very high pinion offset, with extra scoring protection.*	

Key AGO performance tests

- **SAE J2360** – the global AGO standard.
  - combines most GL-5 and MT-1 tests, plus field tests and LRI review

ASTM [CRC]	KEY TEST MEASURES	API GL-5	API MT-1	SAE J2360	BASIC PROCEDURE
D6121 [L-37]	Gear distress	☑	-	☑	Complete axle assembly on dynamometer; - low-speed, high torque for 24 hours
D7452 [L-42]	Gear scoring	☑	-	☑	Complete axle assembly on dynamometer; - high-speed, shock loading for 2 hours
D7038 [L-33-1]	Corrosion	☑	-	☑	Differential in humidity oven; motored for 7 days
D5704 [L-60-1]	Oxidation stability	☑*	☑	☑	Spur gear set with copper catalyst; motored for 50 hours
D5579	Thermal stability	-	☑	☑	Heavy duty synchronized transmission; in a ~10 day cyclic durability test
D5662	Seal compatibility	-	☑	☑	Static seal bench test, for 240 hours
D5182	Scuffing wear	-	☑	-	FZG spur gear test
D892	Foaming tendency	☑	☑	☑	Bench test
D130	Copper corrosion	☑	☑**	☑**	Bench test
Field Tests and LRI Committee Review				☑	

* Does not include performance requirements for deposits ** Increased Severity

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OEM specifications and approvals

- **OEM gear oils and specifications**
  - OEMs often specify API service categories for some of their equipment
    - API GL-5 is frequently specified for light vehicles, in all applications
  - OEMs also have unique gear oil specifications and part numbers
    - Required for more demanding and unique performance needs
    - Some offer service fill approvals:
      - Light duty: e.g., DEXRON® gear oils
      - Heavy duty, extended drain, e.g.:
        - » Dana Shaes 256
        - » Eaton PS-386
        - » Mack GO-J Plus, and TO-A Plus

Sampling of GM Gear Oils in Use	MANUAL TRANS.	TRANSFER CASE	DIFFER-ENTIAL
API Service GL-3	X		
API Service GL-4	X		
API Service GL-5	X	X	X
API GL-5 Limited-Slip			X

Table based on: Motor 2005-16
"Lubrication Recommendations Guide"

U.S. Heavy-duty OEM specifications

Key U.S. drive axle and manual transmission lubricant specifications:

Dana SHAES 256 Differential Oil **500,000 mile ODI***	**Eaton PS-386**** Transmission Oil **500,000 mile ODI***
SAE J2360, plus: • 200 hours D5704 • Dynamic seal tests • Gear spalling test • High temp. D6121 • Wet D6121 • Field test	**API MT-1, plus:** • Mack TO-A Plus • Navistar MPAPS B-6816 Type II • Full Synthetic

*ODI = maximum Oil Drain Interval
**Replaced Eaton PS-164 rev7

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AGO trends

- **Gear boxes are being designed to be smaller and more efficient**
  - **Increased torque capacity**, with larger engines and smaller gears
  - **Higher operating temperature**, with lower profile for less wind resistance
  - **New synchronizer designs** and materials
  - **New friction materials** in transfer cases and differentials
  - **Oil sump capacity reduction** and extended ODI
- **Move from multi-purpose to specialized AGOs**
  - Global trend away from the use of API GL-4 and engine oils
- **Recent AGO performance improvements include:**
  - **Protection**: anti-scuffing, bearing wear and micro-pitting resistance
  - **Performance:** precise frictional characteristics for synchronizers and clutches
  - **Lubrication**: low temperature fluidity, antifoam performance with smaller sumps
  - **Synthetics**: equipment cleanliness, viscometric properties and extended ODI
  - **Energy conserving**; lower viscosity

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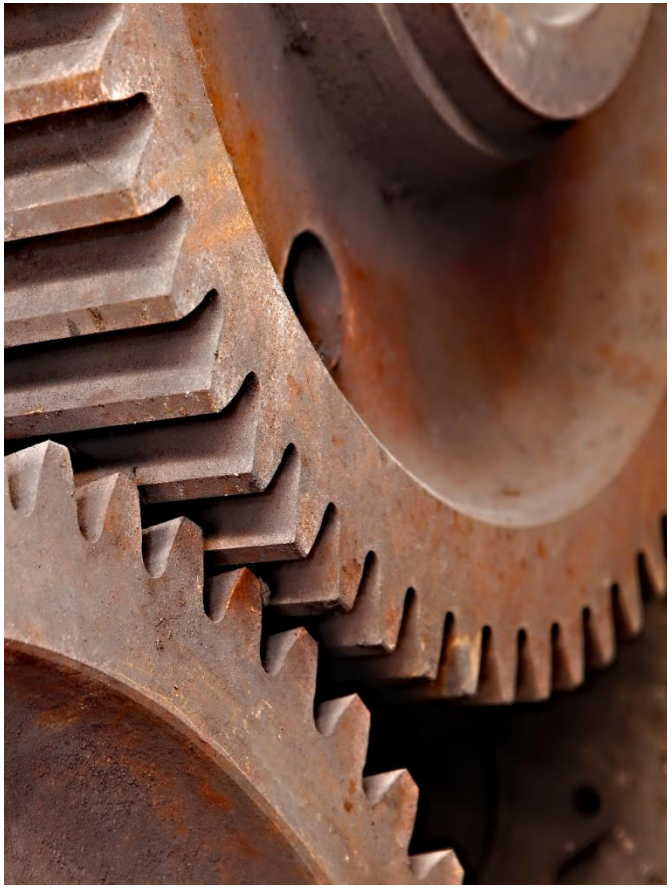

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IGO Applications and oil requirements

- **Enormous diversity in applications and operating conditions, e.g.:**
  - General industrial: open [exposed] or enclosed gear boxes
  - Mining: surface/subsurface; contaminants
  - Steel Mills: high heat; lots of water
- **A wide array of factors must be considered for IGO formulation:**

IGO Operating Factor	IGO Requirement
Gear Type	Anti-scuff and/or lubricity agents for high sliding contact
Open Gears	Surface adherence; via viscosity, tackifiers and/or solids
Gear Speed	Lower viscosity for higher speed, with anti-foamant
Temperatures	Oxidation resistance, pumpability at startup
Material Compatibility	Corrosion inhibition, particularly with yellow metals
Gear Loading	Anti-scuff protection with high loading
Water / Humidity	Demulsibility, to shed water
Gearbox Components	e.g., bearing lubrication, seal and paint compatibility, etc.

IGO – viscosity

- **Viscosity is most important in IGO selection**
  - Industrial gear oils use the ISO 3446 viscosity classification
    - expressed as “ISO VG 220”; indicates mid-point viscosity

GRADE		VISCOSITY @ 40°C, cP			GRADE		VISCOSITY @ 40°C, cP		
ISO VG	AGMA*	MIN	MID	MAX	ISO VG	AGMA*	MIN	MID	MAX
2	--	1.98	2.2	2.42	**100**	3	90	100	110
3	--	2.88	3.2	3.52	**150**	4	135	150	165
5	--	4.14	4.6	5.06	**220**	5	198	220	242
7	--	6.12	6.8	7.48	**320**	6	288	320	352
10	--	9.0	10.0	11.0	**460**	7	414	460	506
15	--	13.5	15.0	16.5	**680**	8	612	680	748
22	--	19.8	22.0	24.2	**1000**	8A	900	1000	1100
32	--	28.8	32.0	35.2	**1500**	9	1350	1500	1650
46	1	41.4	46.0	50.6	**2200**	10	1980	2200	2420
68	2	61.2	68.0	74.8	**3200**	11	2880	3200	3520

  - **The American Gear Manufacturers Association [AGMA]** provides minimum guidelines for viscosity grade selection [in AGMA 9005]
    - For use in the absence of specific gearbox OEM recommendations
    - *Note: AGMA viscosity grades have been retired

IGO – performance

- **AGMA groups IGOs for closed gear drives into three classifications,** each with minimum performance standards [AGMA 9005 STANDARD]:
  - **INHIBITED**: rust and oxidation [R&O] resistant, with anti-foamant
  - **ANTISCUFF**: also contain EP agents for high loading / sliding
  - **COMPOUNDED**: contain 3 -10% natural or synthetic fatty oils for lubricity
- **AGMA IGO classifications are typically used according to gear type:**

IGO Class	Spur	Helical	Bevel	Hypoid	Worm
Inhibited	**normal loads**			not used	light loads
Antiscuff	heavy or shock loading			**required**	OK for most
Compounded	not normally used			light loads	**preferred**

Table based on: "Lubrication Selection for Enclosed Gear Drives" *Machinery Lubrication,* Jan. 2005

- **Gearbox manufactures often add additional requirements**

IGO Specifications - overview

- **Industry associations and OEMs specify performance, including:**
  - ISO (International Organization for Standardization) 12925-1
  - AIST (Association for Iron and Steel Technology) 224 (formerly USS 224)
  - ANSI (American National Standards Institute) / AGMA 9005 [America]
  - DIN 51517-3 Category CLP [Europe]
  - MAG / Cincinnati Machine (e.g., P-74 for ISO VG 220)
  - Other OEMs, e.g., Siemens, Hansen, Renk, Danielli, Eickhoff, SKF, FAG, etc.)

Key Performance Criteria	ASTM Method	Test	ISO 12925-1	AIST 224	AGMA 9005	DIN 51517 Part 3	MAG P -series
Load capacity	D2782	Block on ring (Timken)	ISO 14635-1	☑			☑
Scuffing resistance	D5182	FZG gear test (A/8.3/90)		☑	☑	☑	
Wear resistance	D4172	Four ball Wear test		☑			
Load capacity	D2783	Four ball EP test		☑			
Antiwear	DIN 51819	Bearing wear	☑		☑	☑	
Oxidative thickening	D2893	Oxidation test		☑	☑	☑	
Thermal Stability	D2070	With copper and steel					☑
Water separation	D1401	Demulsibility				☑	
Water separation	D2711	Demulsibility	☑	☑	☑		
Rust prevention	D665A/B	Steel corrosion		☑	☑	☑	☑
Metal compatibility	D130	Copper strip corrosion		☑	☑	☑	
Foam suppression	D892	Foaming characteristics			☑	☑	
Seal compatibility	D471	Weight gain or loss				☑	

  - Significant overlap, many commercial brands meet most, or all, specs

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Product positioning

- **The IGO market has loosely defined tiers:**

IGO TIER	MARKET %	BASIC ATTRIBUTES	ISO 12925-1	AIST 224	AGMA 9005	MAG P-series	DIN 51517 Pt 3	SPECIALIZED	SYNTHETIC
BASIC	~10%	Fit for purpose, low cost	X	X					
MAINLINE	~60%	Meets most standards and specifications	X	X	X	X	X		
PREMIUM	~20%	Specialized mineral based, e.g. “clean gear”	X	X	X	X	X	X	
TOP TIER	~10%	Full Syn. broad application	X	X	X	X	X	X	X

IGO trends

- **Gear boxes are being designed to be smaller and more efficient**
  - **Increased power density**, higher temperature
  - **Oil sump capacity reduction**
  - **New materials** and finishes
  - **Extended ODI** – especially for applications such as wind turbines

- **Recent IGO performance improvements include:**
  - **Protection**: Bearing wear and micro-pitting resistance
  - **Lubrication**: demulsification and antifoam performance
  - **Synthetics**: equipment cleanliness, viscometric properties and low temperature fluidity
  - **Economics**: reduced maintenance and inventory rationalization, as well as ODI
  - **Energy conserving**: lower viscosity
  - **Environmental**: biodegradability, ODI

Gear lubricants outline

Gear types and lube requirements

- Gear Functions, Common Types and Applications
- Gear Oil Requirements and Typical Formulations
- Gear Oil Market Overview

Automotive gear oil [AGO]

- Applications and Lubricant Requirements
- Classifications, Specifications and Testing
- Market and Trends

Industrial gear oil [IGO]

- Applications and Lubricant Requirements
- Classifications, Specifications and Testing
- Market and Trends

Summary

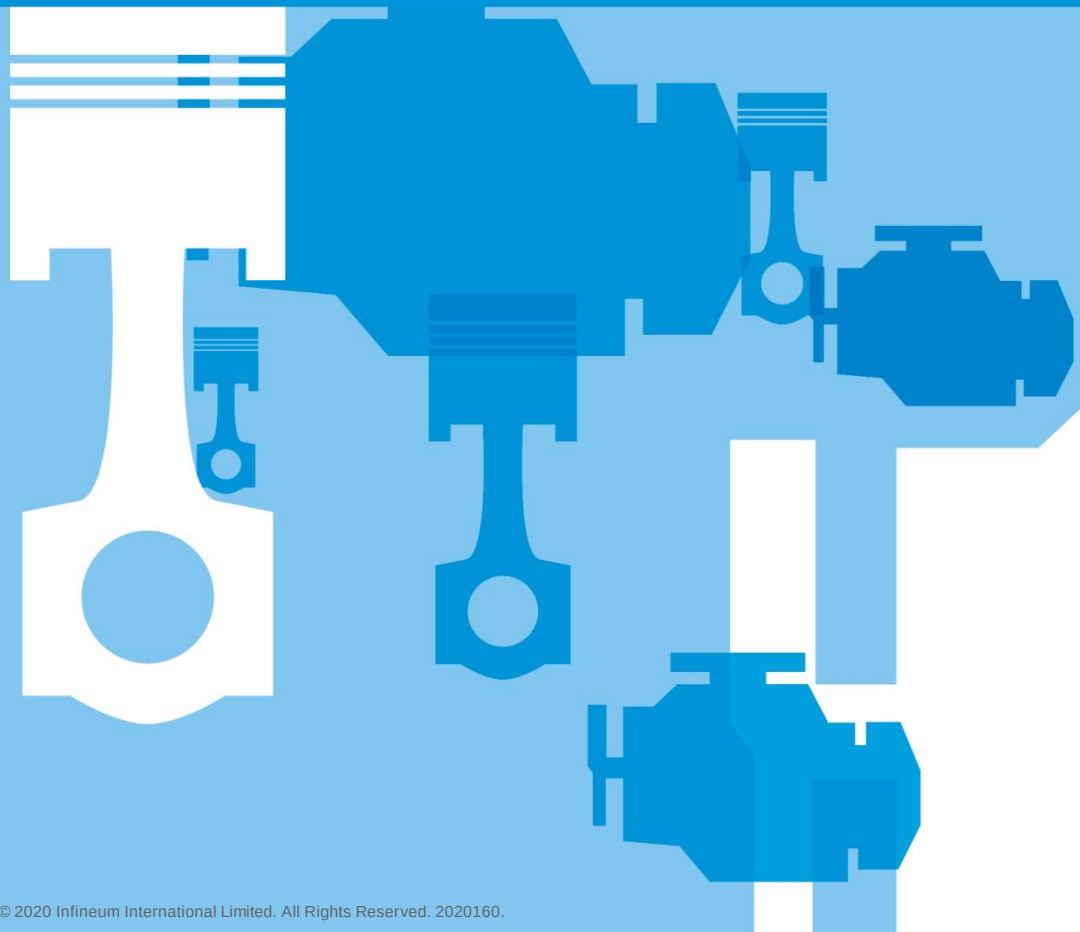
Gear oil requirements - summary

- **Gear Oil Applications are diverse, with unique lubrication requirements**
  - Synchronized MTFs provide proper friction characteristics for synchronizer
  - Non-Synchronized MTF, Axle and Industrial Gear Oils provide EP protection

Lube requirements	ATF	WET DCTF	Sync MTF	Non Sync MTF	AXLE OIL	IGO	Unique gear oil needs
Paper on Steel Friction	✓✓	✓✓	✗	✗	✓	✗	Axle clutch packs
Synchronizer Friction	✗	✓✓	✓✓	✗	✗	✗	Diverse synchro materials
Gear Protection	✓	✓	✓	✓✓	✓✓	✓✓	Heavy load / sliding friction
Wear Protection	✓	✓	✓	✓✓	✓✓	✓✓	Heavy load / rolling friction
Shear Stability	✓	✓	✓	✓✓	✓✓	✓✓	Retain mixed lubrication film
Oxidation Inhibition	✓✓	✓✓	✓	✓	✓	✓	Cooler, with less/no clutches
Corrosion Protection	✓	✓	✓	✓✓	✓✓	✓✓	EP balance / IGO exposure
Demulsibility	✗	✗	✗	✗	✗	✓	IGO exposure

Appendix

Specialty industrial gear oils



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Slideway oils
(IGO related chemistry)

- **Slideway oils lubricate the positioning tracks (horizontal or vertical) of computer controlled machining devices**
  - During service, slideway oils come in contact with metalworking coolants, so excellent demulsibility is a key performance property
  - Other key performance properties include stick-slip friction, extreme pressure (EP), rust and copper corrosion, and tackiness
- **MAG and General motors (GM LS-2) specifications define performance:**
  - Both recognize three viscosity grades:
    ISO VG 32, ISO VG 68, and ISO VG 220
  - MAG uses in-house tests for key properties :
    - Stick-slip friction (static: kinetic ratio)
    - Thermal stability
  - Key properties of GM LS-2 include:
    - Rust and copper corrosion (ASTM D665B, D130)
    - Demulsibility (ASTM D1401, D2711-EP)
    - Load carrying (ASTM D2782)
    - MAG stick-slip friction

Profiler machine - Courtesy MAG IAS, LLC

Pneumatic tool (rock drill) oils

- Pneumatic tool oils lubricate valves and moving parts of compressed air actuated tools with related chemistry

- Shock loading, entrained water and operating environments present unique requirements:
  - High EP
  - Water emulsification
  - Mist suppression

- Like slideway, OEM specifications define performance requirements

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