Bearing Fundamentals for Energy Efficiency Optimization in Power Transmission Applications: From Systemic Approach to Customized Product Development

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Stronger.
By Design.

Achieving Bearing Efficiency Requires Several Steps

- **M**ake appropriate bearing concept selection based on application needs
- **U**se appropriate tools for bearing validation
- **E**stimate the true power loss at each bearing location
- **O**ptimize macro and micro geometry

➡ Case study: Standard vs. energy-efficient tapered roller bearings

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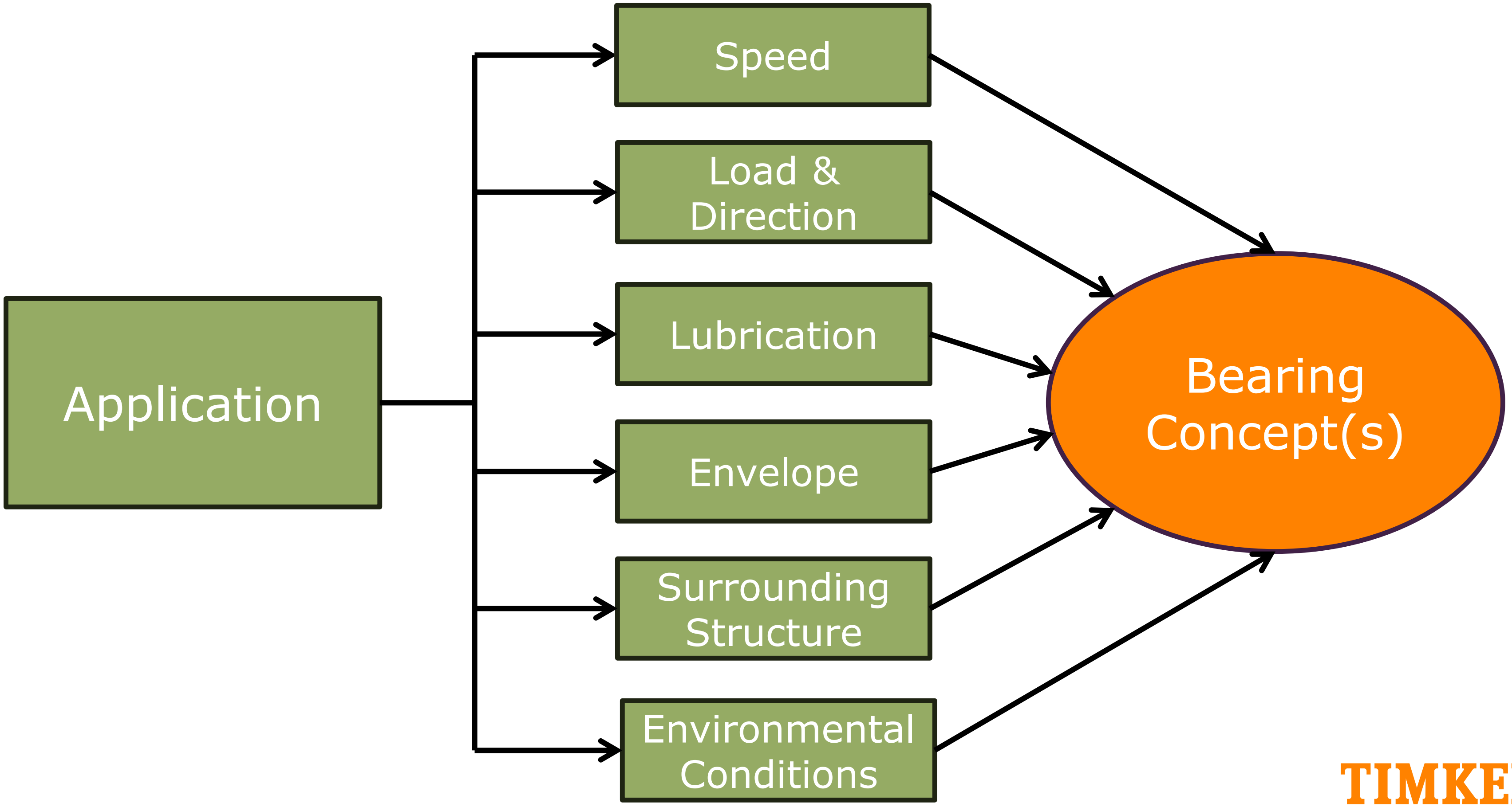
Make Appropriate Bearing Selection Based on Application Needs

- Application describes operating conditions
- At initial stage, bearing concept(s) will be chosen based on the bearing types advantages and according to most demanding conditions



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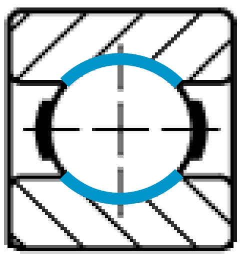
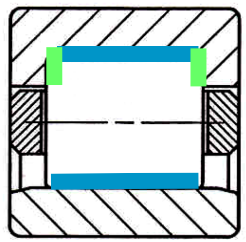
Bearing Type Selection

Ball



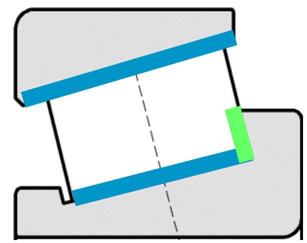
- Point contact
- Low friction (low heat generation)
- **High speed capabilities**
- Radial and axial load carrying capability
- Smallest radial load carrying capability in envelope
- Low stiffness

Cylindrical roller



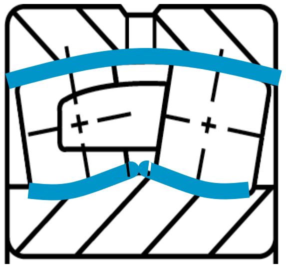
- Line contact
- Medium to high speed capabilities
- High radial load carrying
- Axial load carrying only a fraction of radial load
- **High floating capability**
- Separable inner and outer ring (depending on style)
- Limited acceptance for misalignment

Tapered roller



- Line contact
- Rib contact
- **Capability to carry high radial and axial loads**
- Medium to high speed capabilities
- High system stiffness possible
- Clearance can be adjusted to application needs
- Separable inner and outer ring
- Limited acceptance for misalignment

Symmetrical barrel roller



- Point contact
- High radial load carrying capability
- Limited axial load carrying capability
- **High acceptance for misalignment**
- Medium speed capabilities
- High inherent sliding due to curvature
- No stiffness against overturning moments

Raceways

Rib surface contact zone

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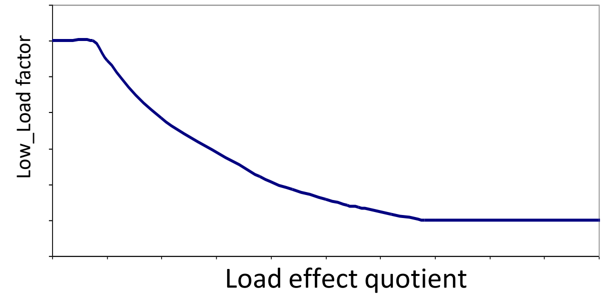
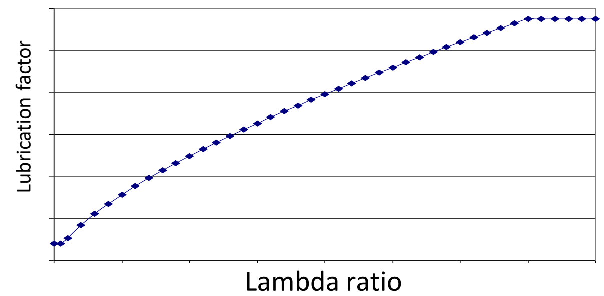
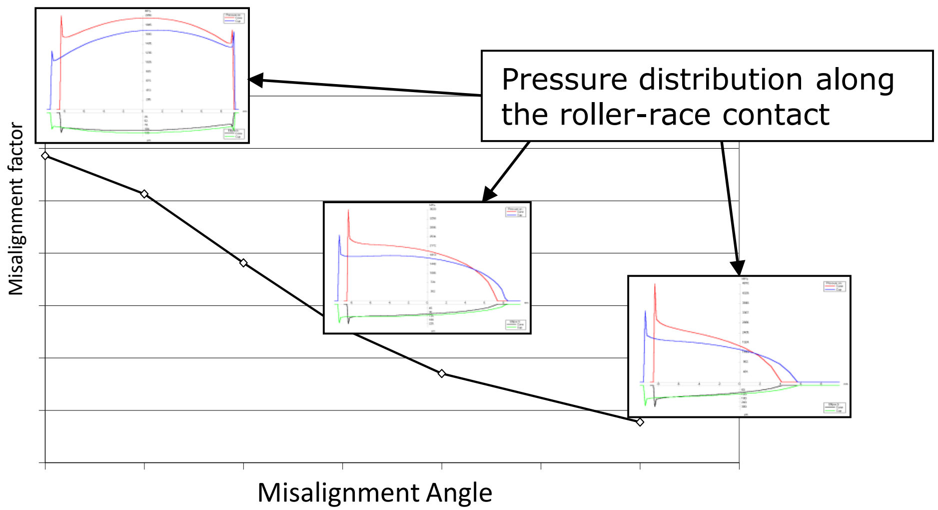
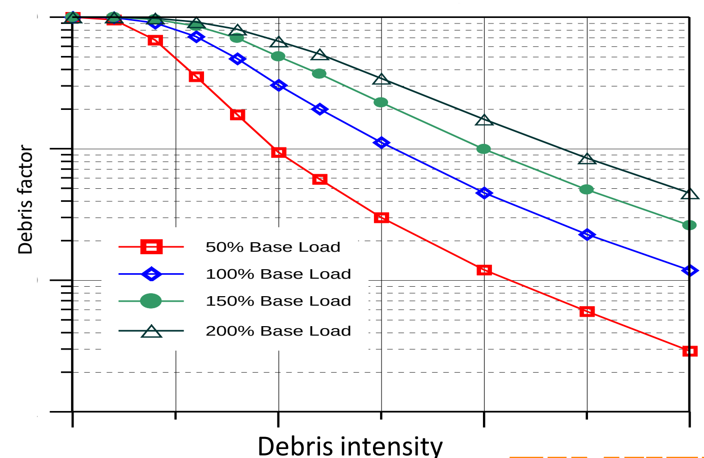
Concept Validation — Life Factor-Based Approach

- Base life calculation based on dynamic equivalent loads
- Factors used to adjust bearing life based on fundamental modeling and test results calibration
  - Misalignment
  - Load zone
  - Lambda ratio
  - Low load
  - Oscillating movements
  - Debris









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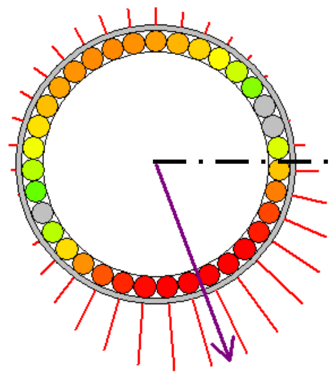
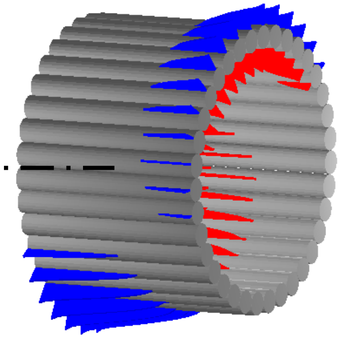
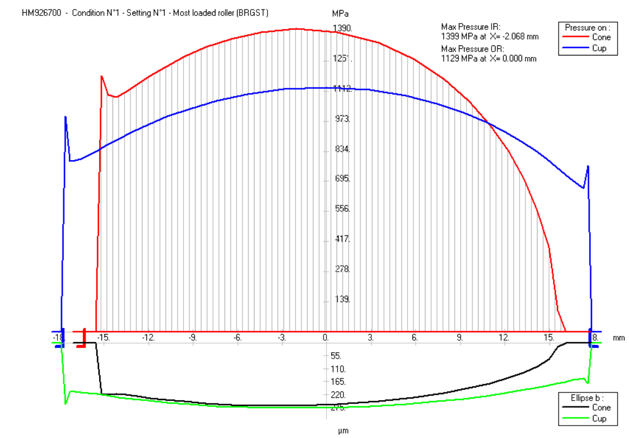
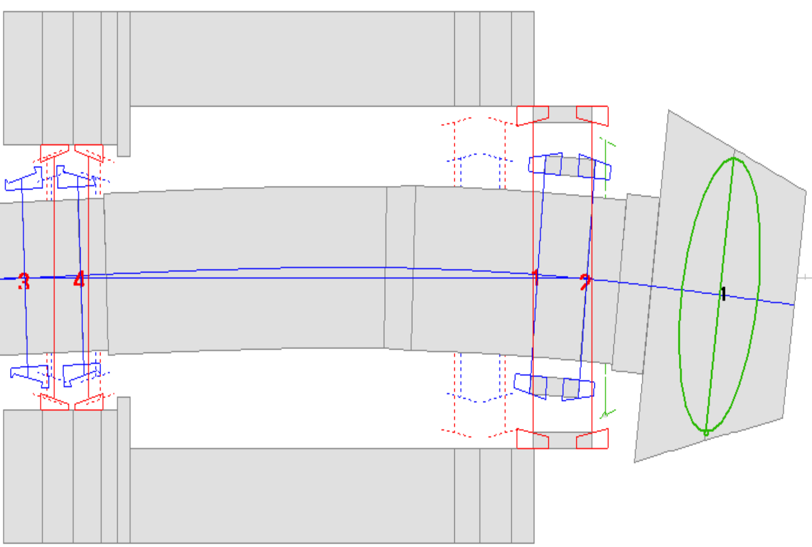
Concept Validation — System Analysis

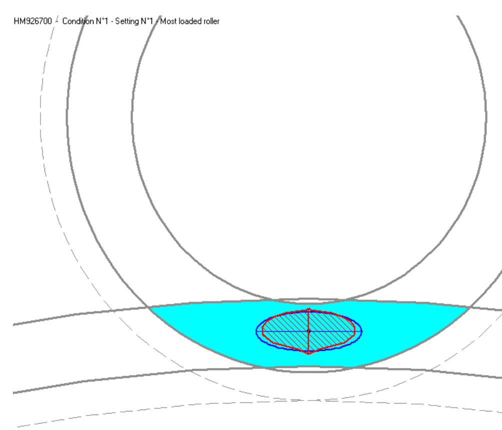
- System deflection (simple mechanics to full FEA)
- Roller-race and roller-rib(s) contact stresses
- Sub-surface stresses
- Hoop stress
- Bearing torque
- Heat generation

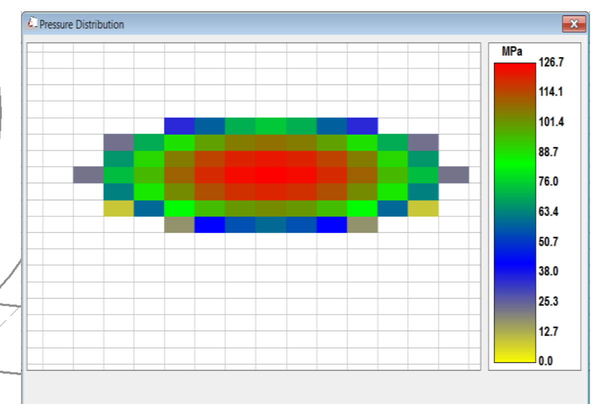








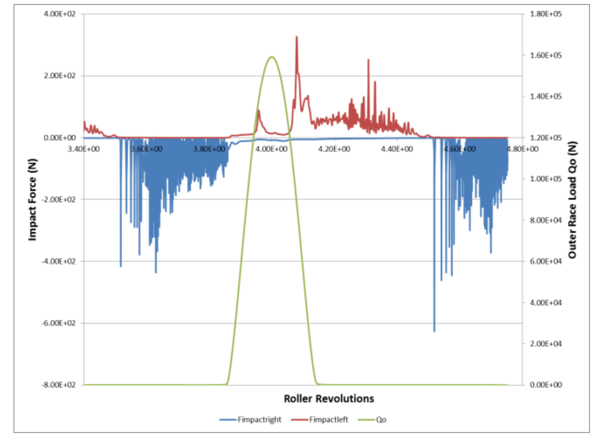


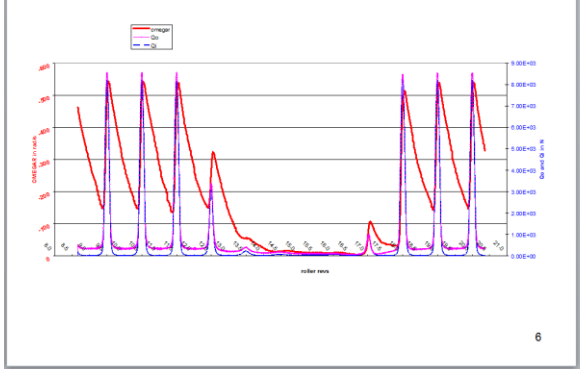


Concept Validation — Dynamic Analysis

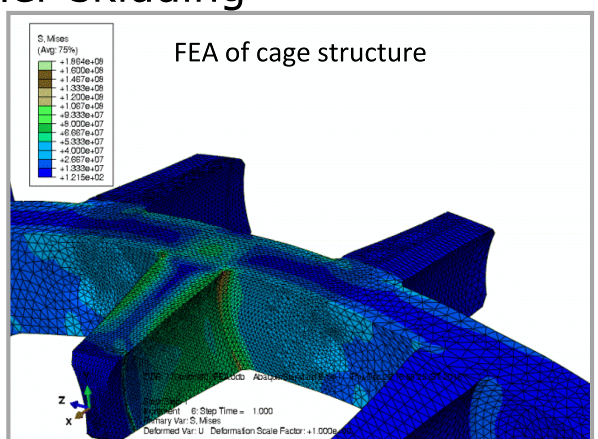
- Analyze dynamic behavior of the roller-cage interaction in a given time window.
- Allows assessment of vibration & transient conditions (accelerations) influence
- Multi-body simulation
  - Roller-cage impact forces leading to validation of stress level in cage bridges
  - Frictional forces between roller and raceway, leading to smearing avoidance
  - Cage slip determination leading to analysis of design to limit roller skidding

Impact forces between cage and roller

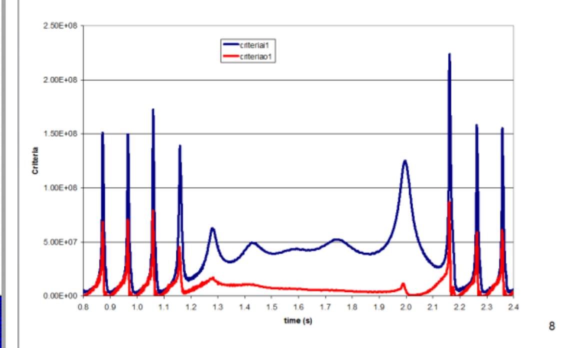




Roller rotational speed



FEA of cage structure



Risk of smearing

R. Evans, T. Barr, L. Houpert, 2011, "Smearing Wear Mechanisms in Wind Turbine Gearbox Cylindrical Roller Bearings," presented at STLE/ASME IJTC, Los Angeles, CA; paper submitted to STLE, 2013
L. Houpert, B. Hamrock, "Elastohydrodynamic calculations used as a tool to studying scuffing," Proc. 12th Leeds-Lyon Symp., 1985

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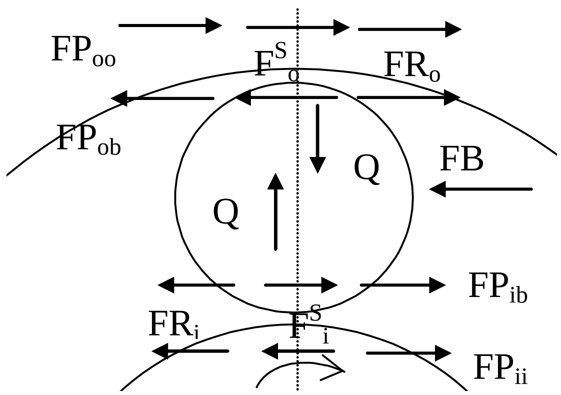
POWER LOSS CALCULATIONS

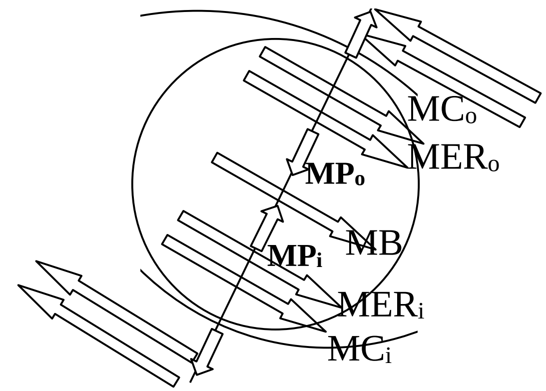
Calculate quasi-static equilibrium around roller:

List of contact forces



- FR (hydrodynamic rolling)
- FP=f(FR) (hydrodynamic Pressure)
- FS (sliding)
- (FRIB (rib)) TRB/CRB only

List of contact moments



- MER (elastic — rolling)
- MC (curvature)
- MP (pivoting)
- (MRIB (rib)) (TRB/CRB only

When forces and moments around roller are known, total torque can be calculated.

L. Houpert, "Ball Bearing And Tapered Roller Bearing Torque: Analytical, Numerical And Experimental Results," STLE Trib. Trans., Vol. 45, 3, pp 345-353, 2002

Power Loss Calculations

- Hydrodynamic forces
  - Hydrodynamic rolling force can be calculated as a function of the pressure gradient in the inlet of the EHL contact
  - Account for miscellaneous lubrication regimes (IVR to EHL), but also transition from point to line contact as the load increases

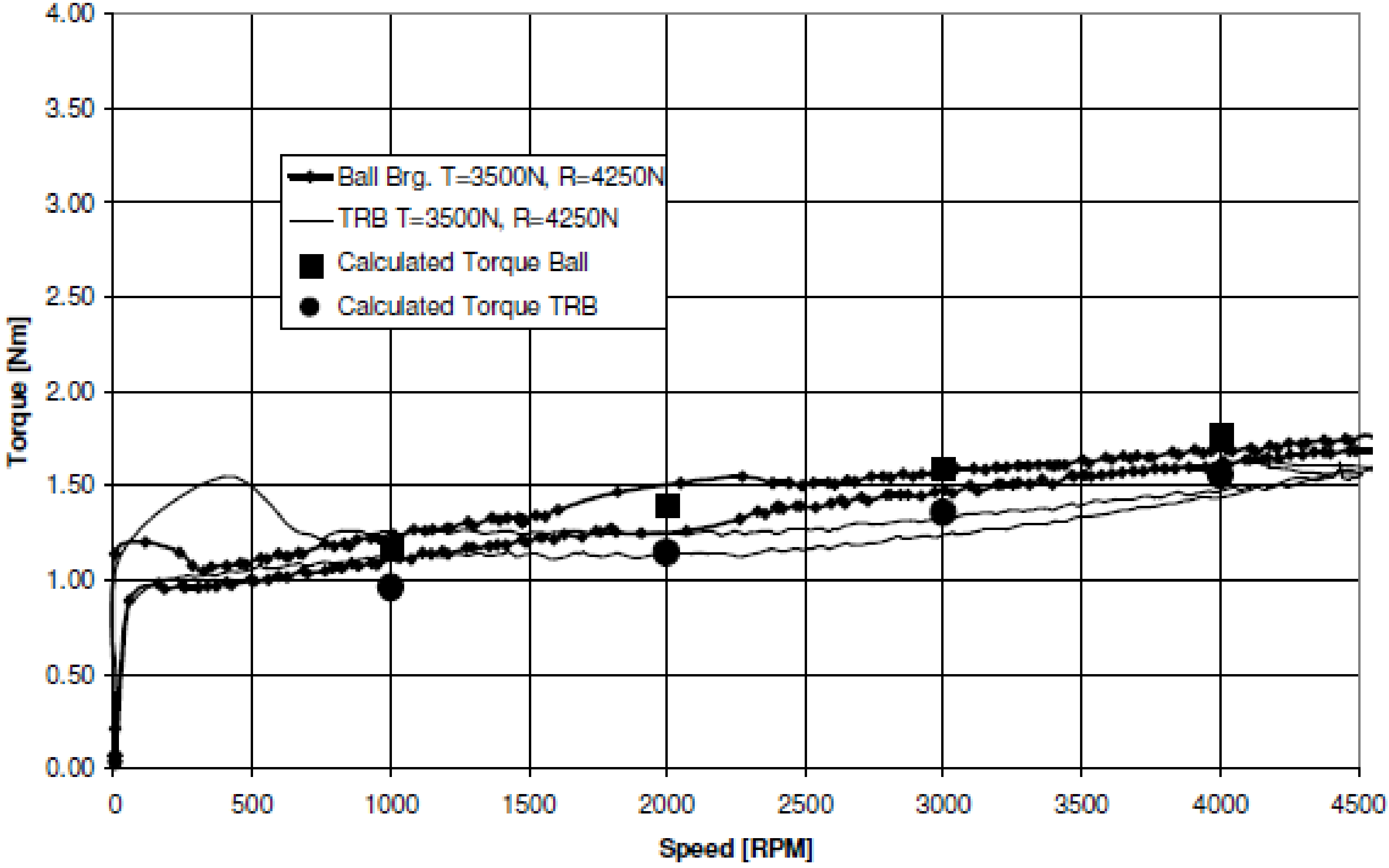
- Traction forces
  - Consider non-linear viscous or visco-plastic lubricant properties (function of the pressure and temperature, with temperature increases and roughness effects included)
  - Friction coefficient varies as a function of the shear rate (sliding speed/film thickness) at different load level Q

- Rib & Elastic Rolling
  - The rib-torque can be calculated as a function of the friction coefficient at the rib, the rib load depending on the roller included angle and the width and height of the contact ellipse
  - Friction coefficient may vary with the speed at the roller-rib contact, the friction increase at low speed being due to roughness or lambda (film/roughness) effects
  - The elastic rolling torque is attributed to hysteresis losses and rolling creep effects

- Pivoting and curvature moments
  - Resulting friction moment M_C due to curvature effects
  - Resulting friction moment M_P due to pivoting effects

Power Loss Testing and Calibration

The test results show good agreement with the calculated results:



M. Gradu, "Tapered Roller Bearings with Improved Efficiency and High Power Density for Automotive Transmissions," SIA paper 2000-01-1154, 2000

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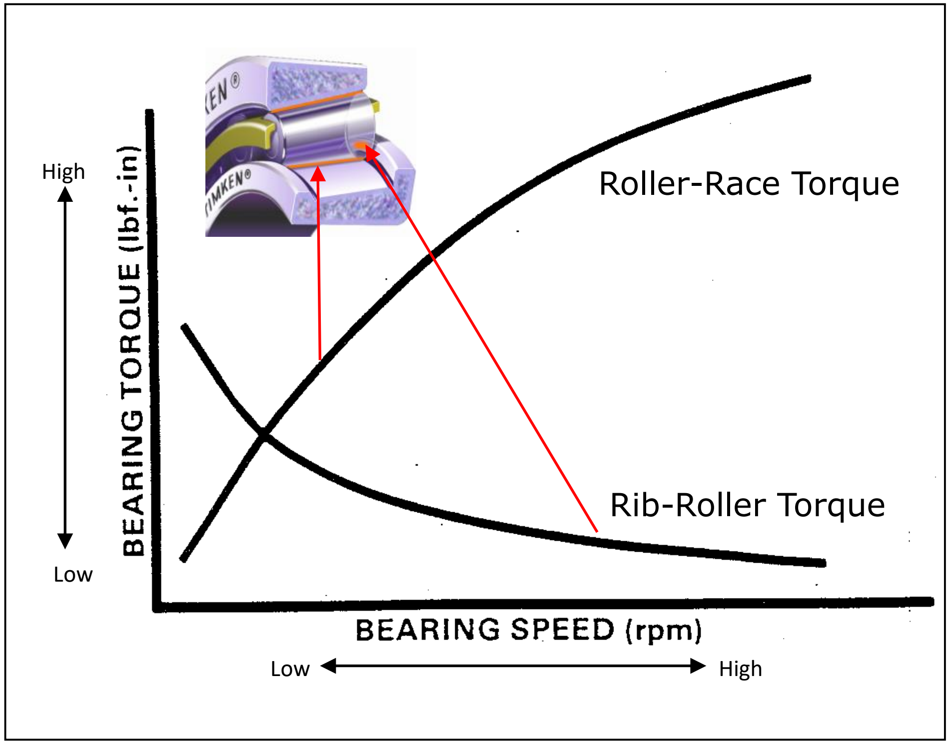
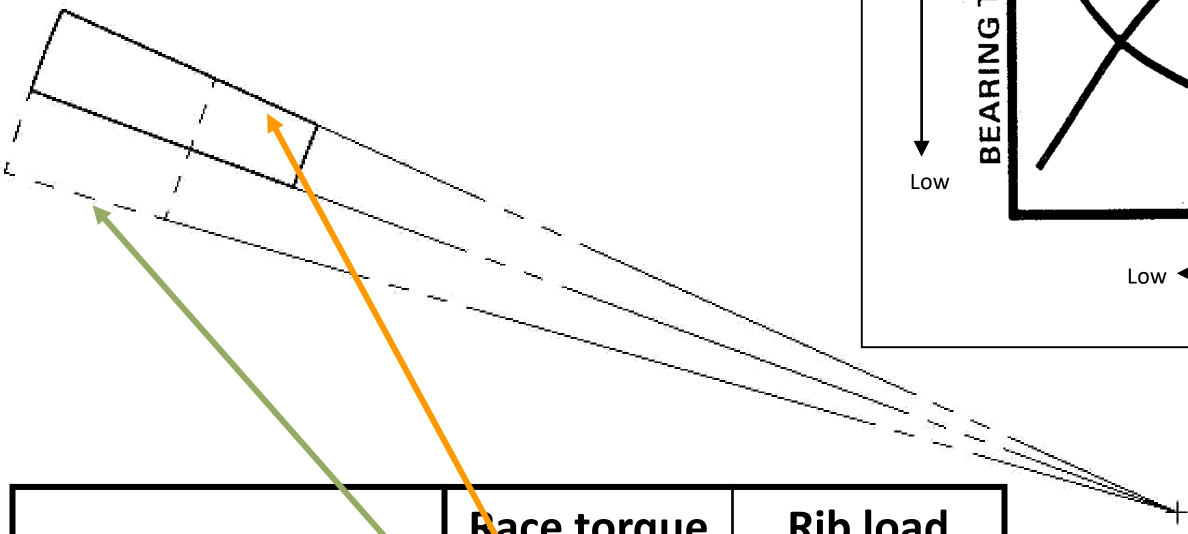
Tapered Roller Bearing-Specific Optimization

- With higher speeds, the roller-race torque becomes more significant
- Shorter, larger diameter and fewer rollers leads to lower generated torque in most applications





	Race torque	Rib load
Standard Roller	High	Low
Energy efficient roller	Low	High

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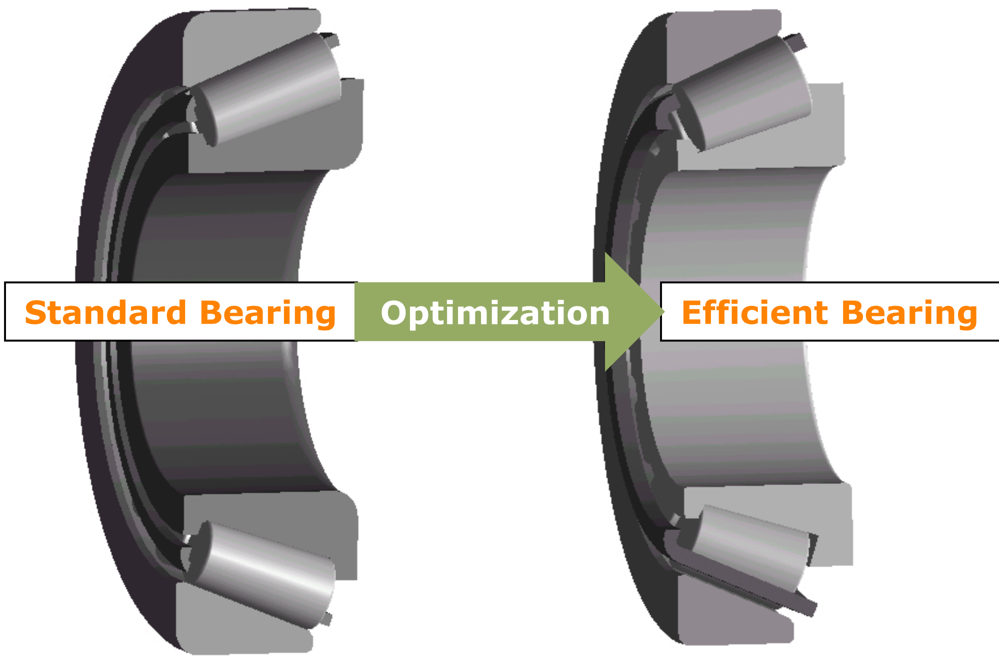
Optimization — Macro Geometry

$$C_{90} = \mathrm{H}\,\mathrm{M}\,(\mathrm{Z}\,\mathrm{L}\cos\alpha)^{4/5}\,\mathrm{N}^{7/10}\,\mathrm{D}^{16/15}$$



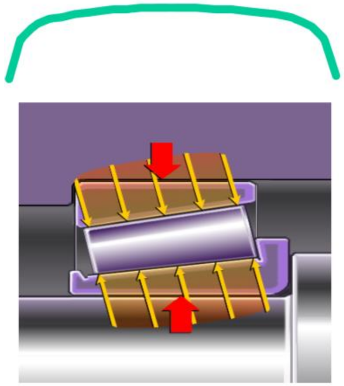
M = Material constant
H = Geometry factor
Z = Number of bearing rows in assembly
L = Effective roller contact length
α = ½ included cup angle
N = Number of rollers per rating row
D = Mean roller diameter

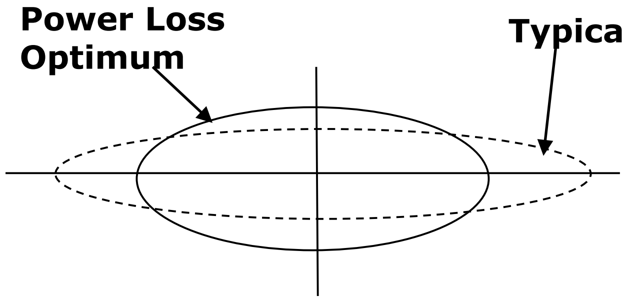
- **Shorter rollers**
- **Fewer rollers**
- **Larger roller diameter**

Dominik, W. (1984), "Rating and Life Formulas for Tapered Roller Bearings," SAE Paper #841121, Warrendale, USA.
Moyer, C., Nixon, H., and Bhatia, R. (1988), "Tapered Roller Bearing Performance for the 1990's," SAE Paper #881232, Warrendale, USA.

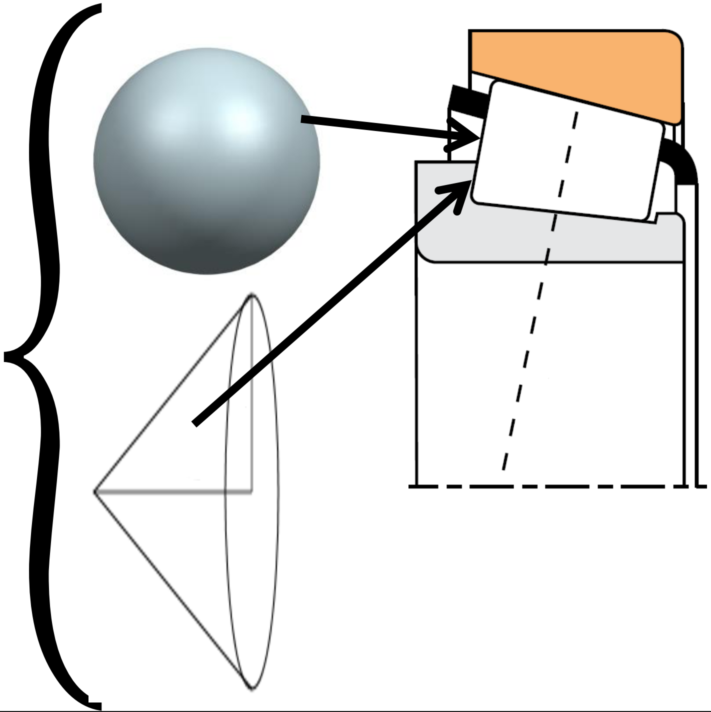
Optimization — Micro Geometry

Special race profiles



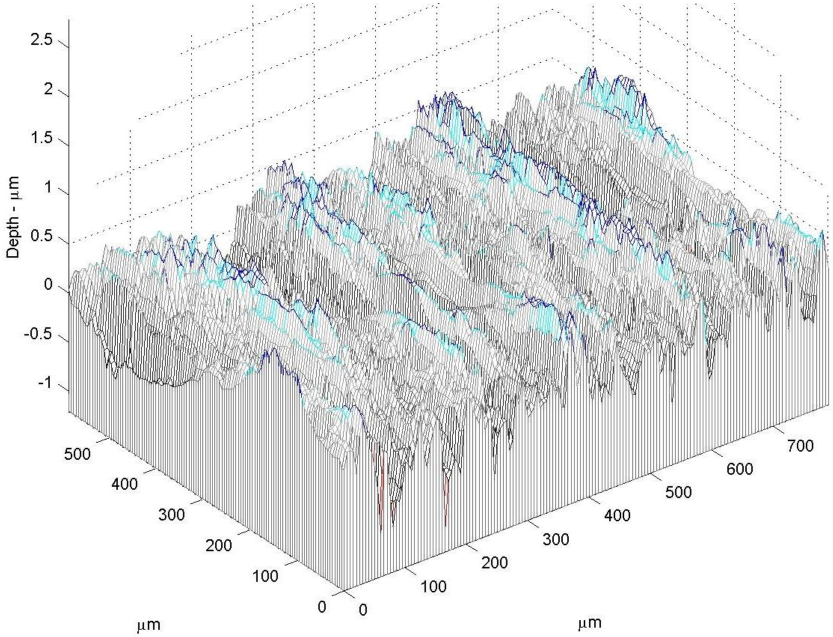


Rib-roller end contact

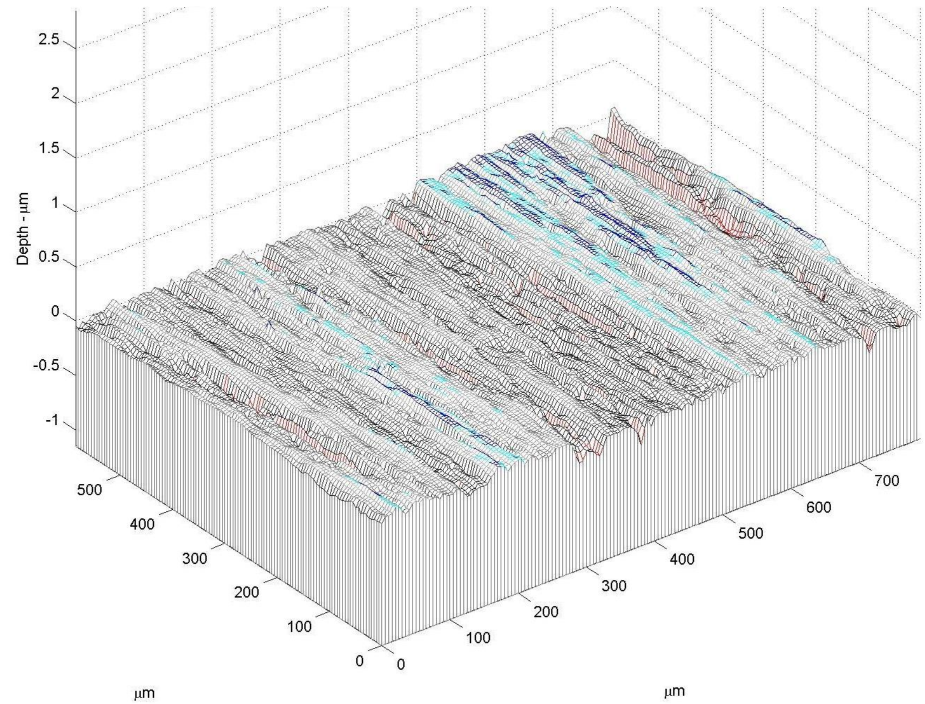


OPTIMIZATION — MICRO GEOMETRY (CONT'D.)

Honed surface



Isotropic finish



- Micro geometry enhancements can reduce the torque in standard bearings between 10% and 20%
- In combination with the macro geometry enhancements, a torque reduction of about 30% can be achieved

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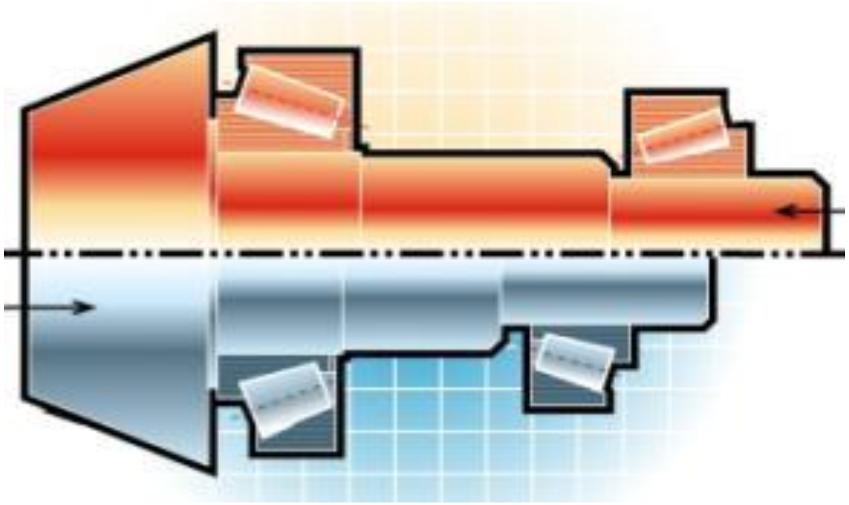
ACHIEVEMENTS THROUGH ENERGY EFFICIENT ENHANCEMENTS

- Sufficient life and capacity in similar or smaller envelope
- Reduce weight and size of the application
- Reduce power loss – balanced with reliability requirements.
- Increase lubricant life through cooler operating temperature
- Save material and reduce production cost

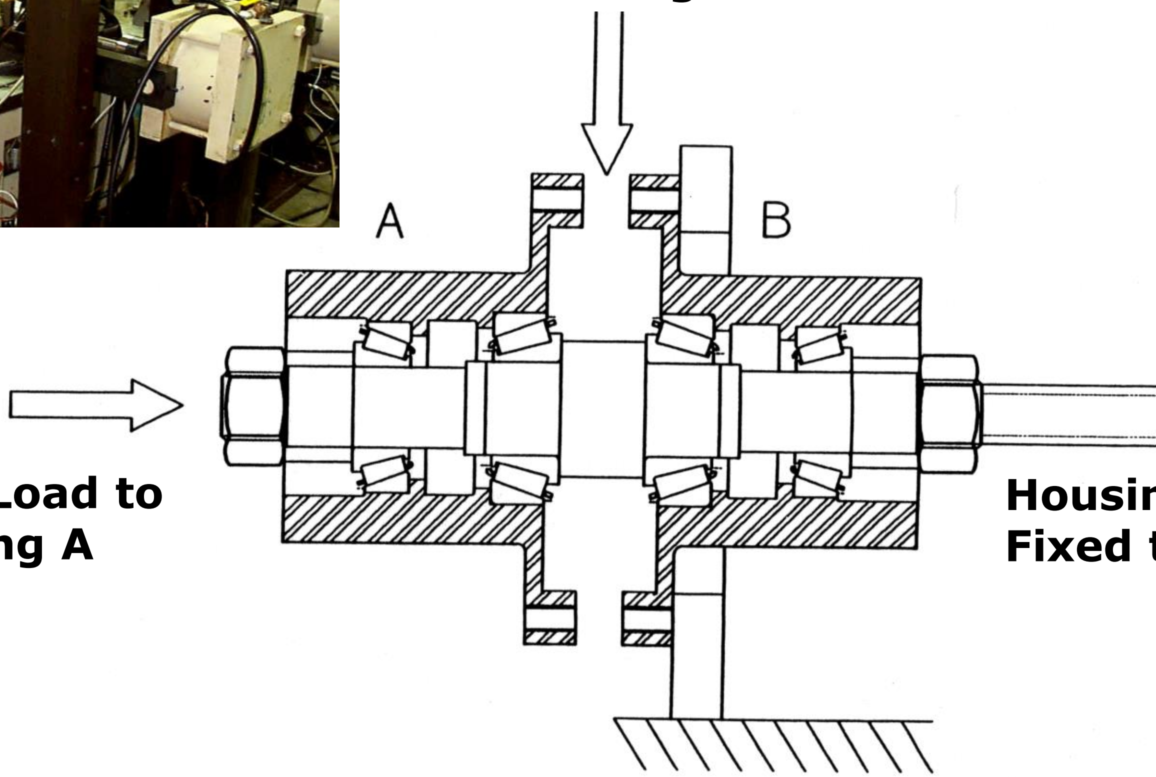
Standard Design



Energy-Efficient Design

STANDARD VS. ENERGY-EFFICIENT – TESTING

Radial Load to Housing A



Axial Load to Housing A

Housing B Fixed to Base

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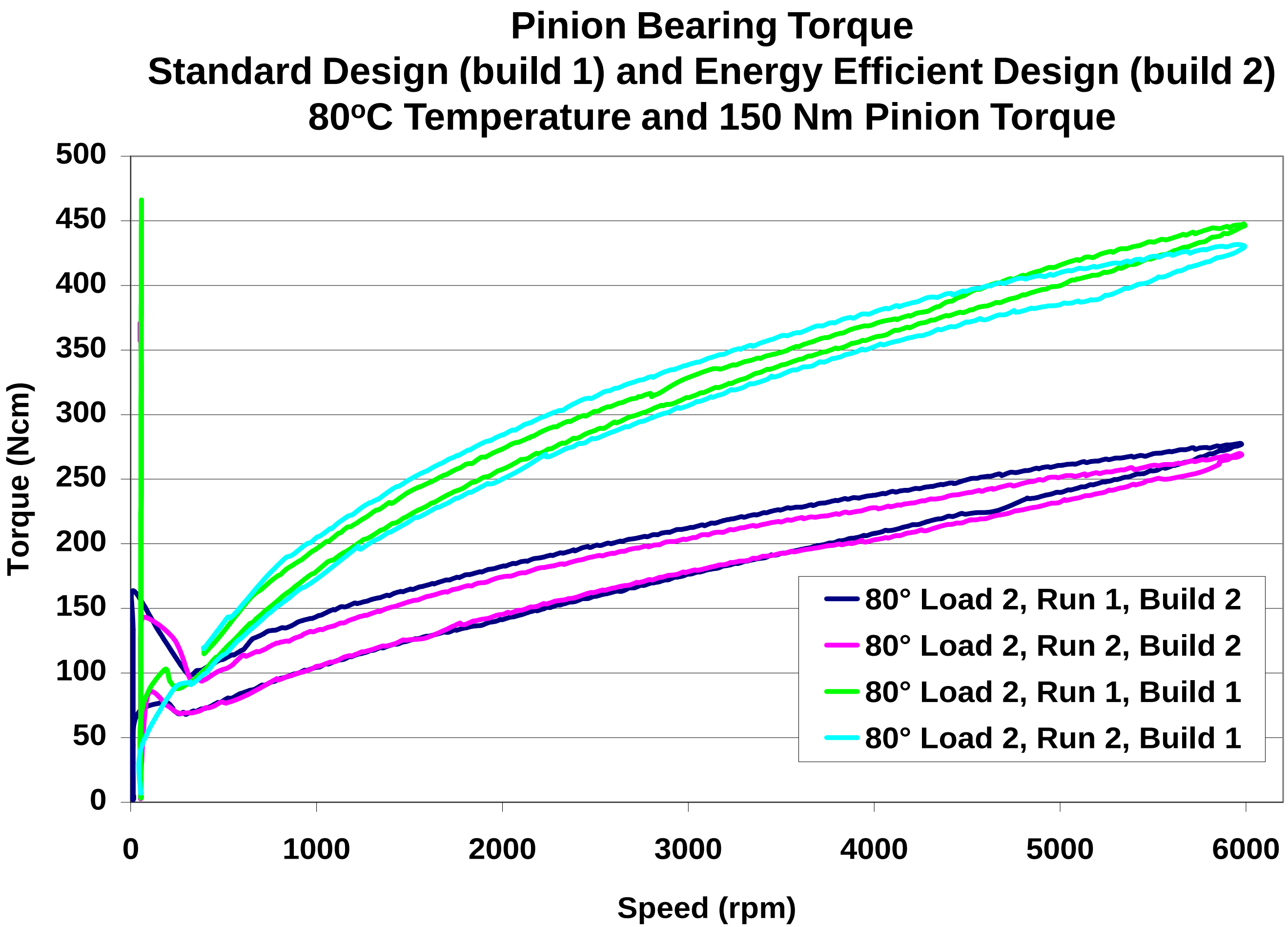
Standard vs. Energy-Efficient

The torque (y-axis) vs. the speed plots (x-axis) show that an energy-efficient bearing (Build 2) has significantly less torque than a standard tapered roller bearing (Build 1) as soon as a minimum speed is reached



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SUMMARY

To define a energy efficient bearing selection it is important:

- To understand the application
- To understand the bearing
- To have the appropriate tools

Steps to design an energy efficient application

1.) Selection of the bearing type appropriate (BB, CRB, TRB, SRB)

2.) Selection of the appropriate macro geometry of the chosen bearing type.

3.) Selection of the appropriate internal geometry.

4.) Validation of the bearing selection by calculation with the appropriate tools

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