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Efficiency and Noise, Vibration and Harshness in systems transmitting power with gears

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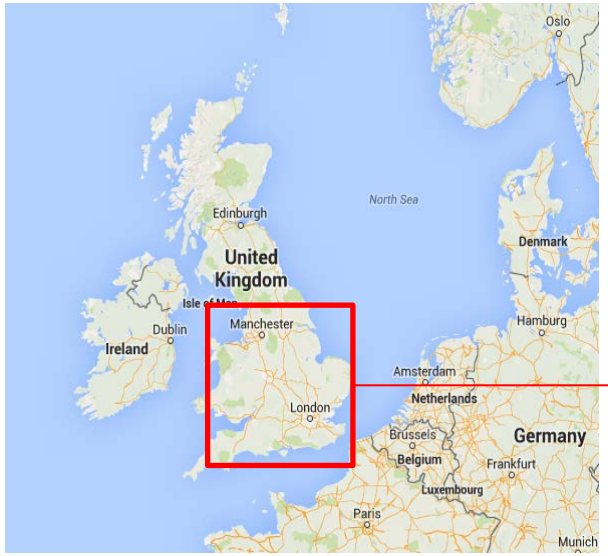

In 2015 Loughborough University opened a second campus in Queen Elizabeth Olympic Park, London. This is hosting the Advanced Propulsion Centre (APC) spoke in *Digital Engineering and Test*.

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About Loughborough University

- **7th position (The Complete University Guide 2017)**
- **13732 Full time Students**
- **1874 Part time Students**
- **763 Others – Full and Part time (Research exchange etc.)**

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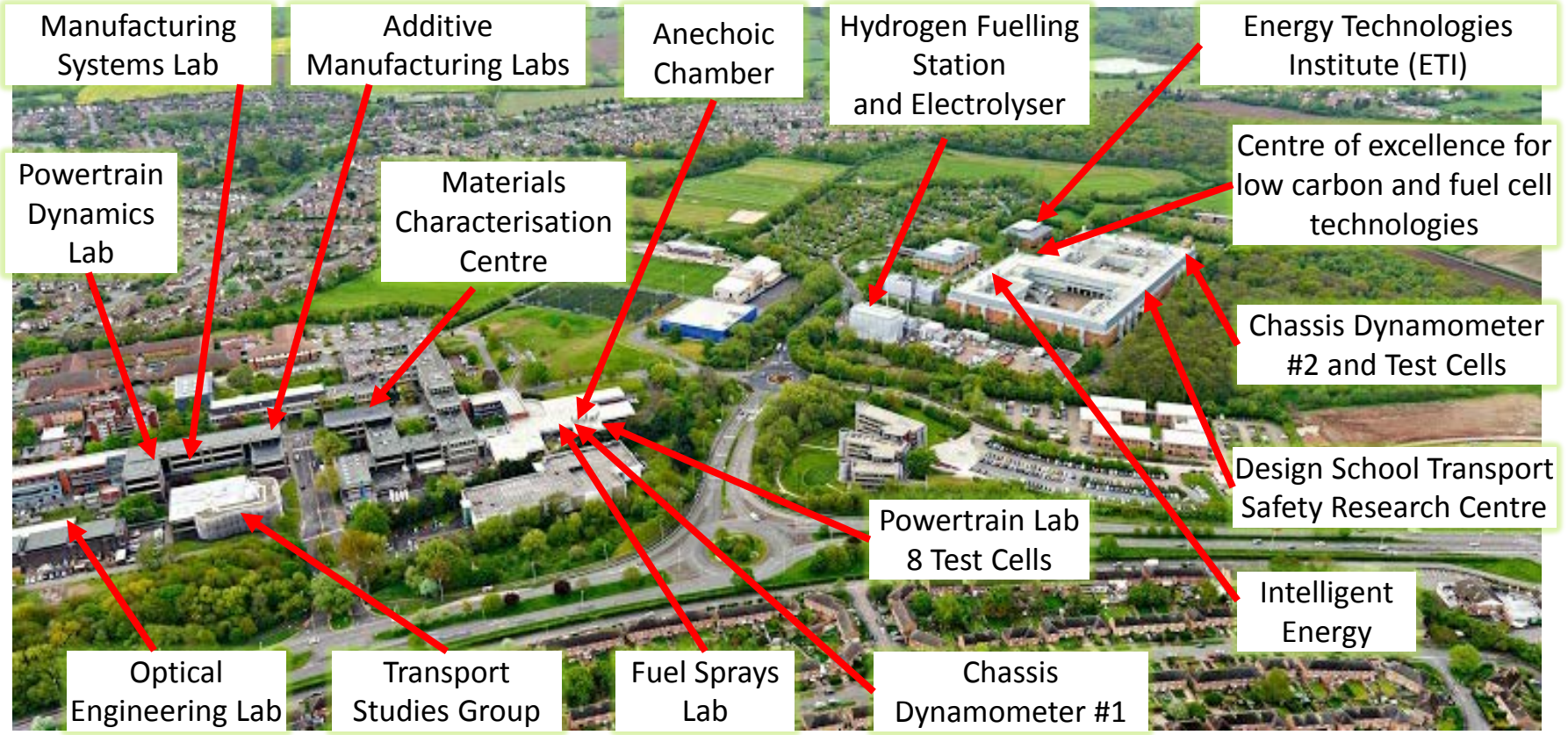
Some Centres and facilities in the Loughborough University Campus



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Wolfson School of Mechanical, Electrical and Manufacturing Engineering

- 6th position (Complete University Guide 2017)

- 1054 Full time Undergraduate Students
- 162 Full time Postgraduate Students (MSc and PhD)
- 35 Part time Undergraduate Students
- 125 Part time Postgraduate Students (MSc and PhD)

- 70 academic staff
- 30 technical staff
- 20 admin/secretarial staff

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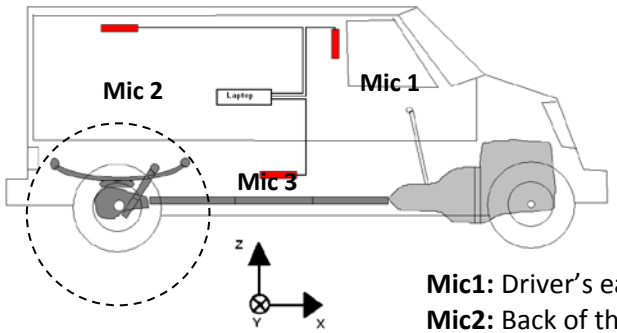
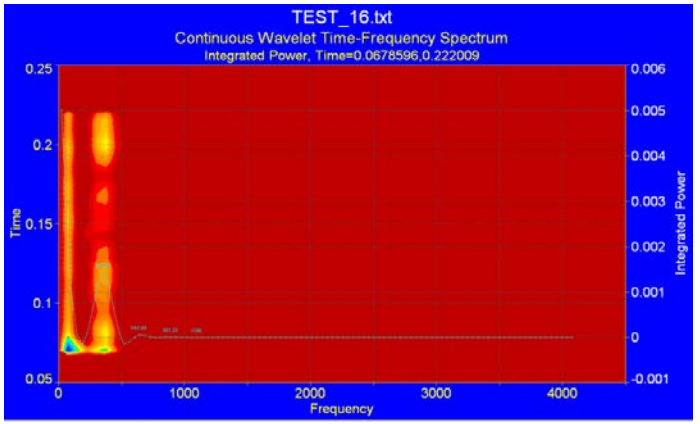
- **Problem definition (application: hypoid gears)**
- **Methodology**
- **Results**
- **Conclusions**
- **Published work**

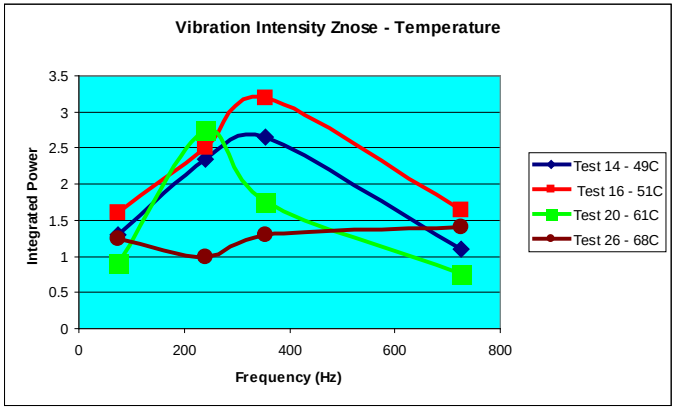
Problem definition



Mic1: Driver's ear
Mic2: Back of the cabin
Mic3: Underbody of vehicle

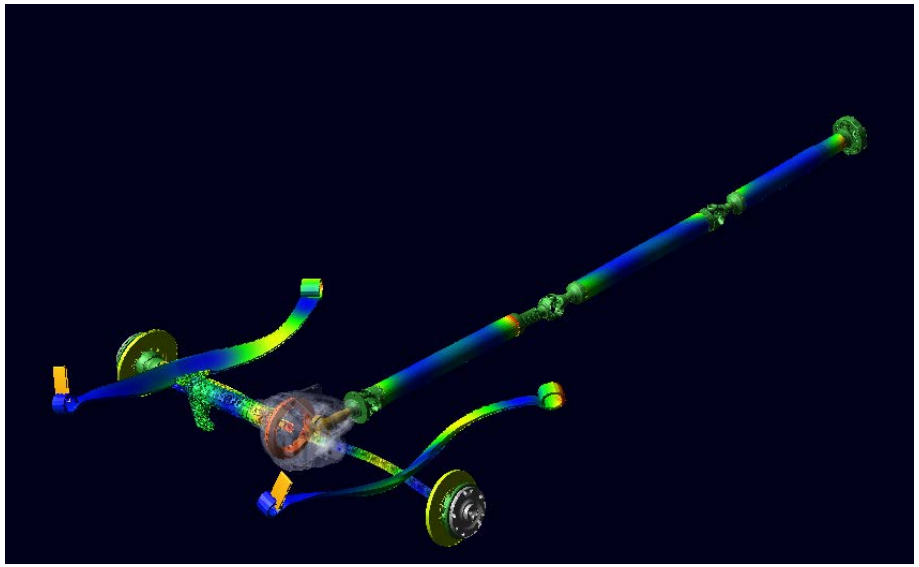


Wavelet of the rear cabin microphone signal

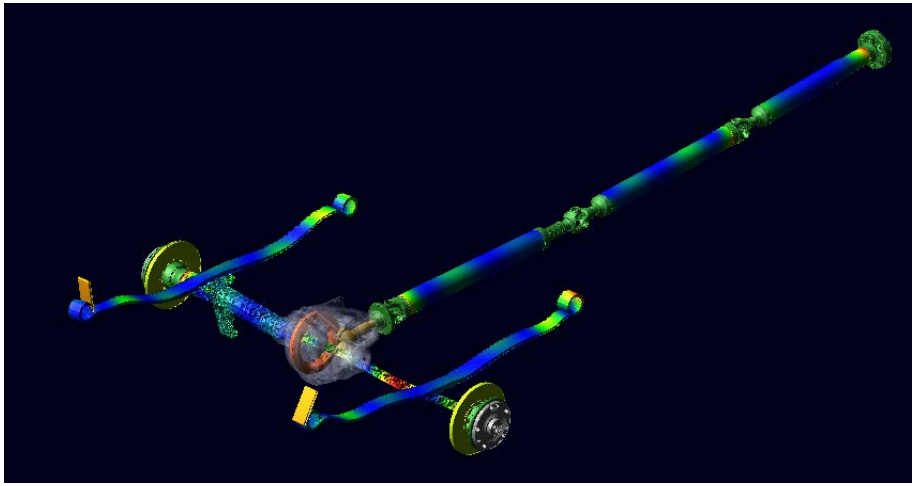


Koronias et al. Axle whine phenomenon in light trucks: a combined numerical and experimental investigation. *Proc. IMechE Part D*, 2011, 225 (7), 885-894.

Problem definition



S-bend of leaf springs with twist of the rear axle (at 356 Hz)



Butterfly mode with multiple leaf spring bending (at 772 Hz)

Koronias et al. Axle whine phenomenon in light trucks: a combined numerical and experimental investigation. *Proc. IMechE Part D*, 2011, 225 (7), 885-894.

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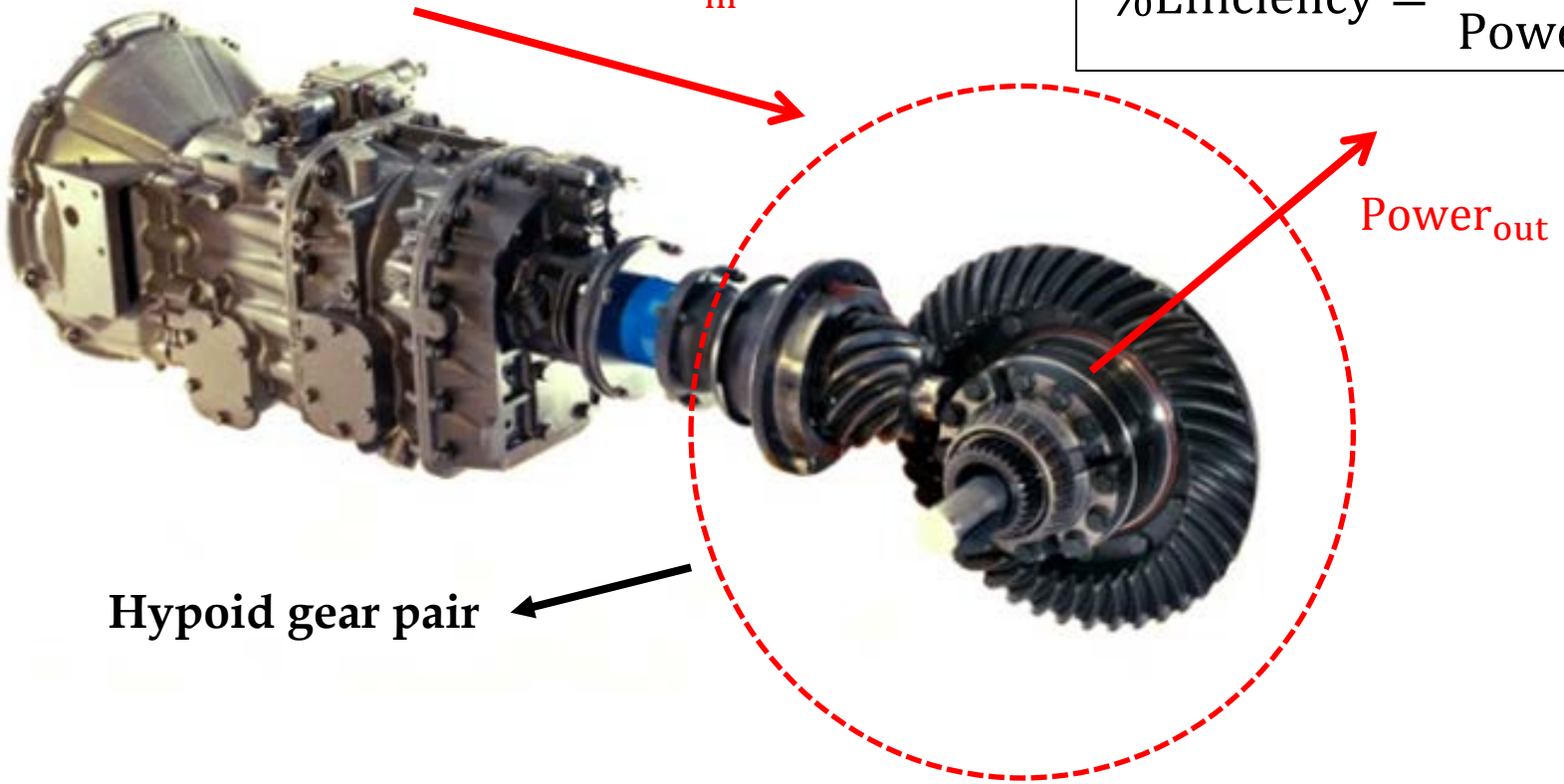
Problem definition

$$\%\text{Efficiency} = \frac{\text{Power}_{\text{out}}}{\text{Power}_{\text{in}}} \times 100\%$$



Tribodynamics

Friction (tribology) ⟷ Gear dynamics

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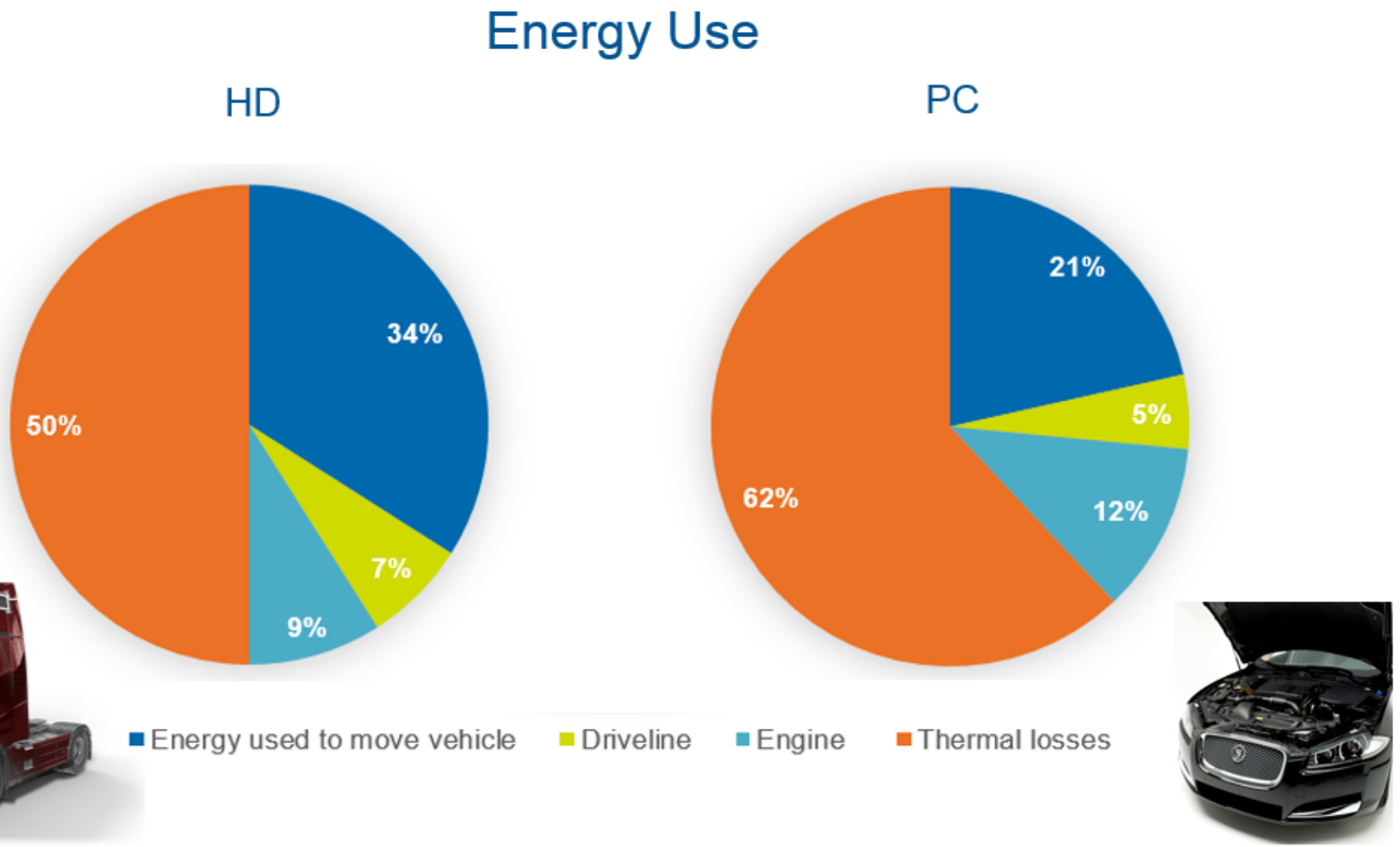
Problem definition



Source HD = Tribology International (Global energy consumption due to friction in trucks and buses – Kenneth Holmberg) K. Holmberg et al. / Tribology International 78 (2014) 94–114
Source PC = Tribology International (Global energy consumption due to friction in passenger cars – Kenneth Holmberg) K. Holmberg et al. / Tribology International 47 (2012) 221–234

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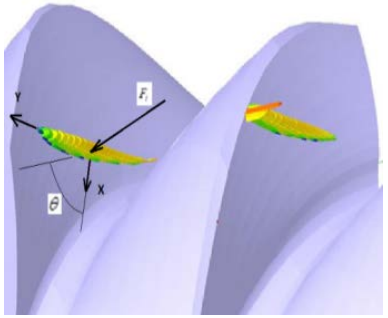
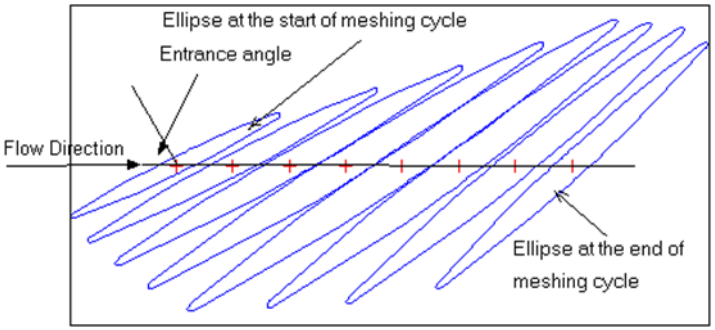
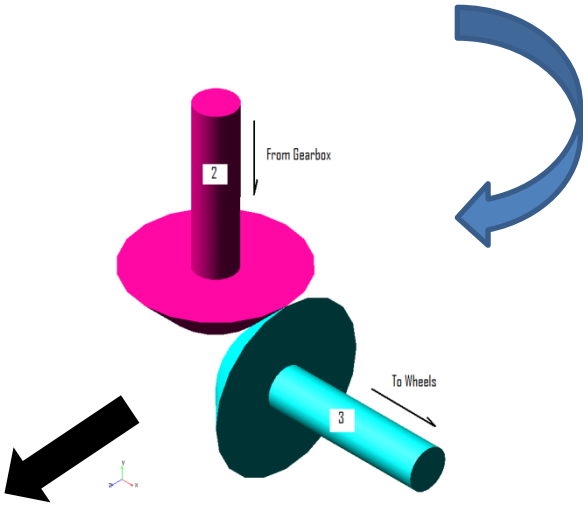
Methodology

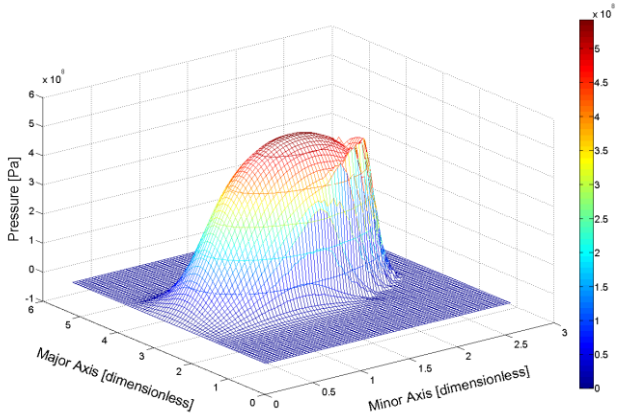
Gear geometry and assembly data







Elasto-hydrodynamic model



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Methodology - Hypoid gear pair contact geometry

Tooth Contact Analysis (**TCA**):

- ✓ Numerical solution
- ✓ Commercial software CALYX
- ✓ Contact geometry/kinematics

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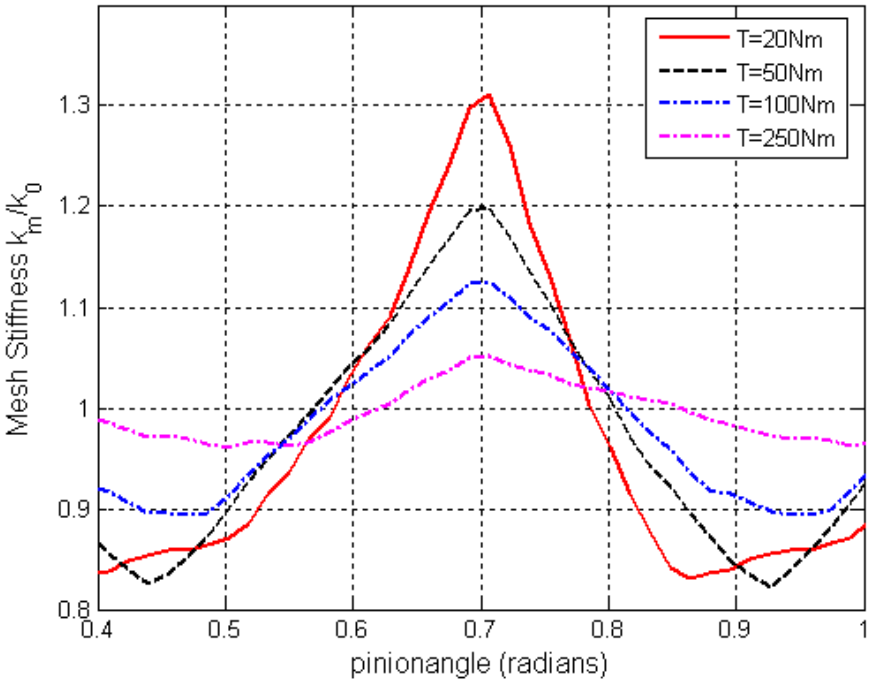
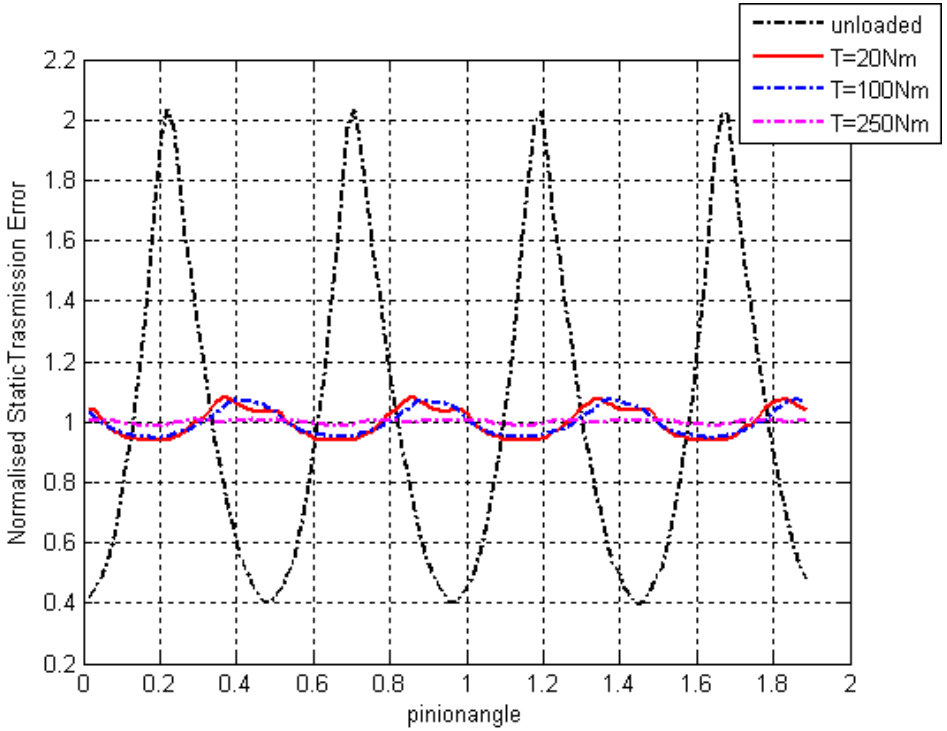
Methodology - Teeth meshing properties (I)



Mesh Stiffness k_m



Static Transmission Error

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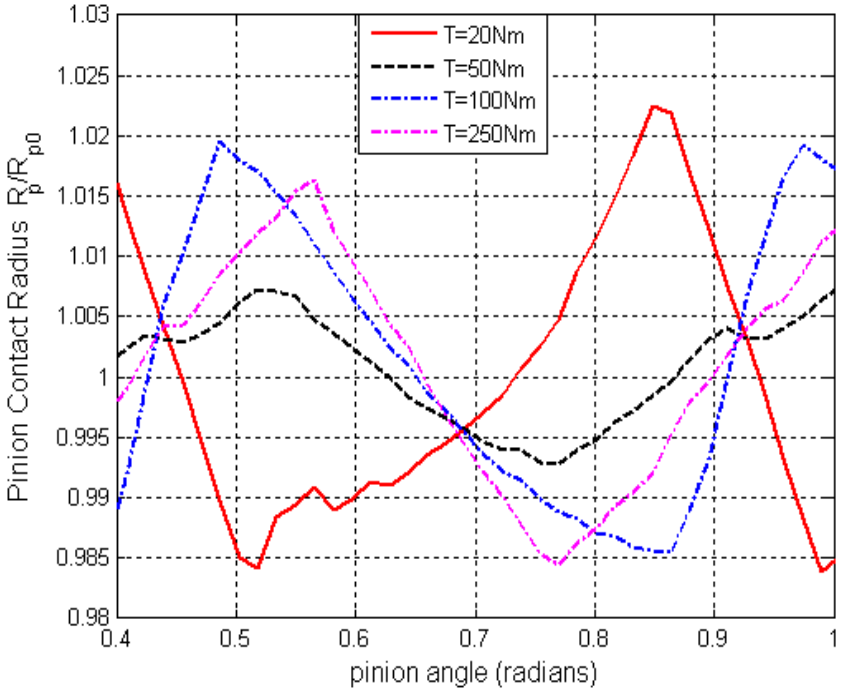
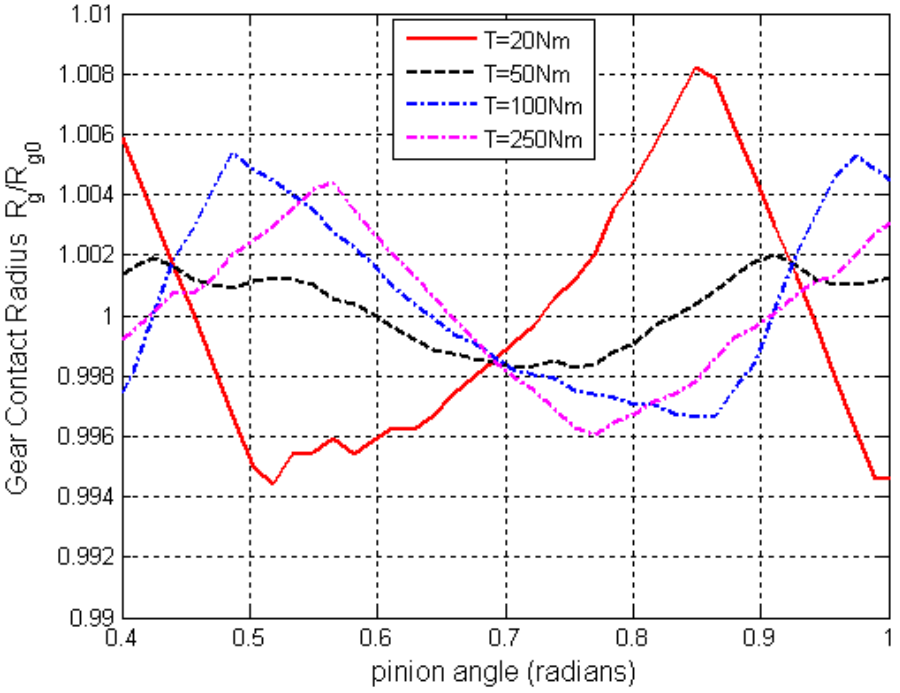
Methodology - Teeth meshing properties (II)



Pinion Contact Radius



Gear Contact Radius

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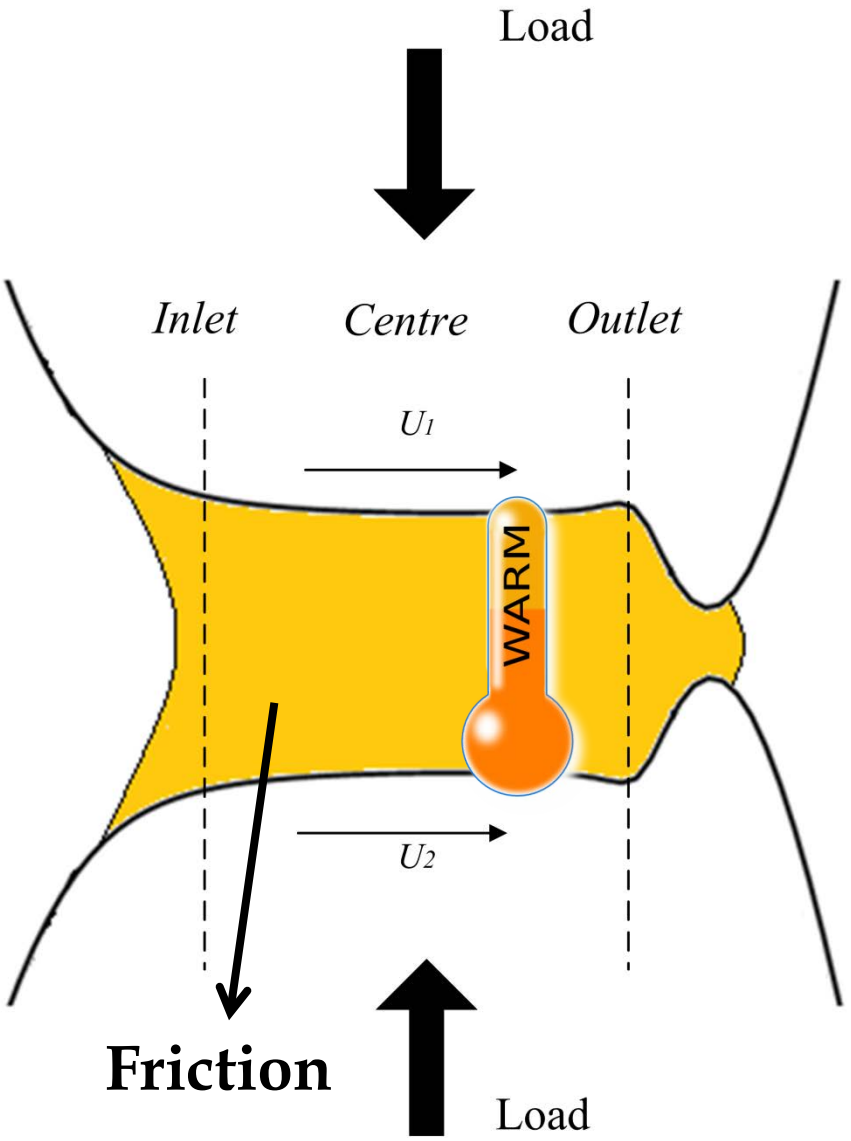
Methodology - Elastohydrodynamic (EHD) regime of lubrication

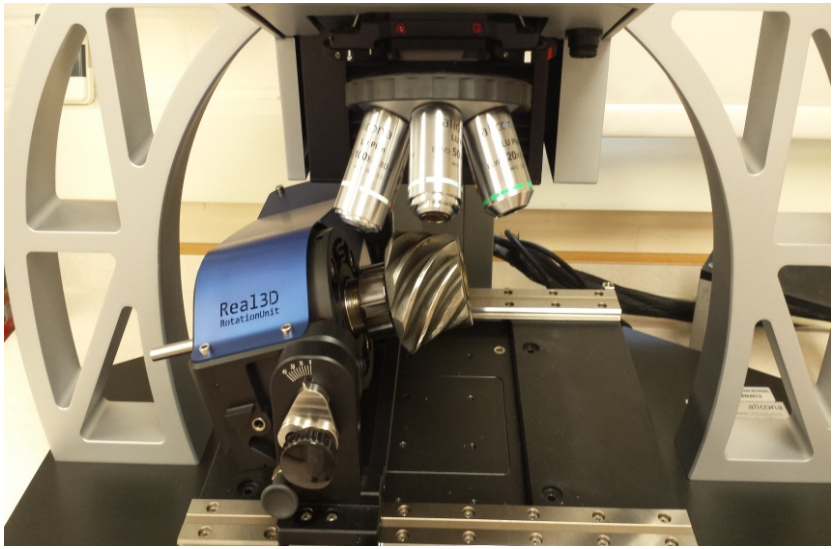
Variation of viscosity with

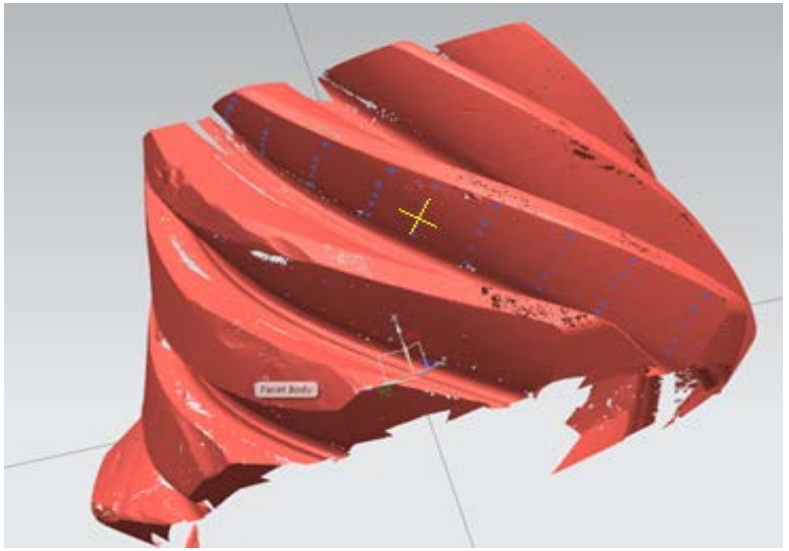
- Pressure
- Shear rate
- Temperature

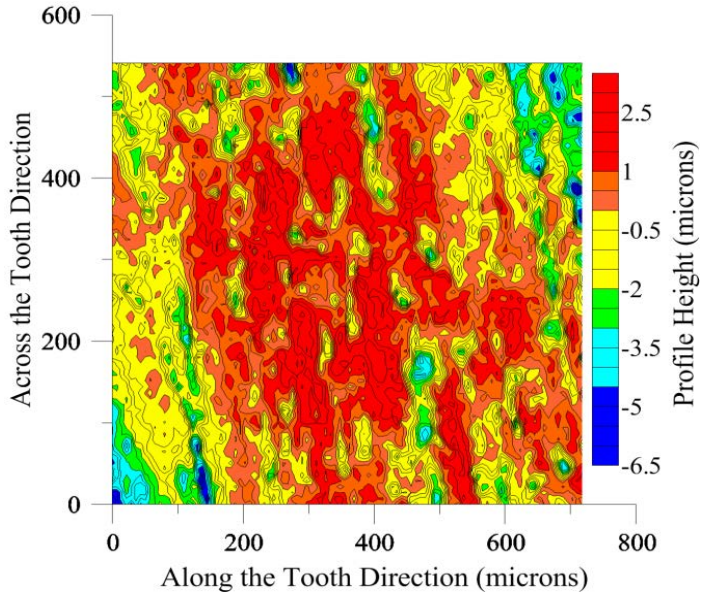


Friction Model (viscous)

Methodology - Friction Model (boundary)







Asperity friction:

- Surface scan of gear teeth
- Surface model of the teeth
- Distribution of the asperity heights

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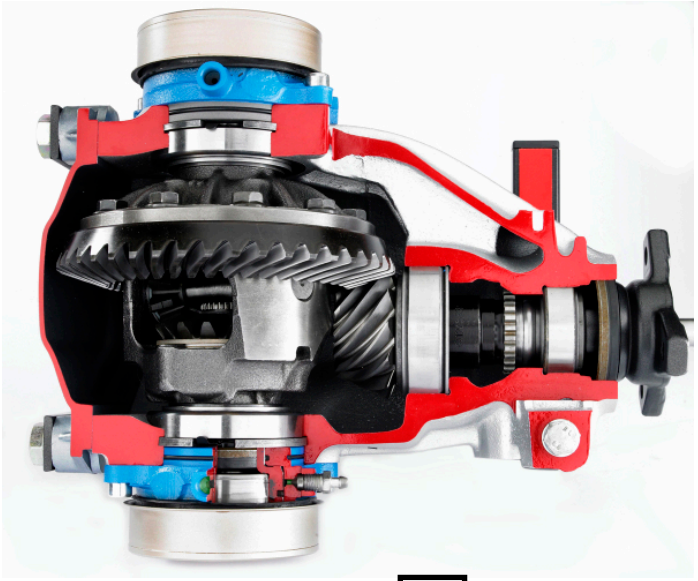
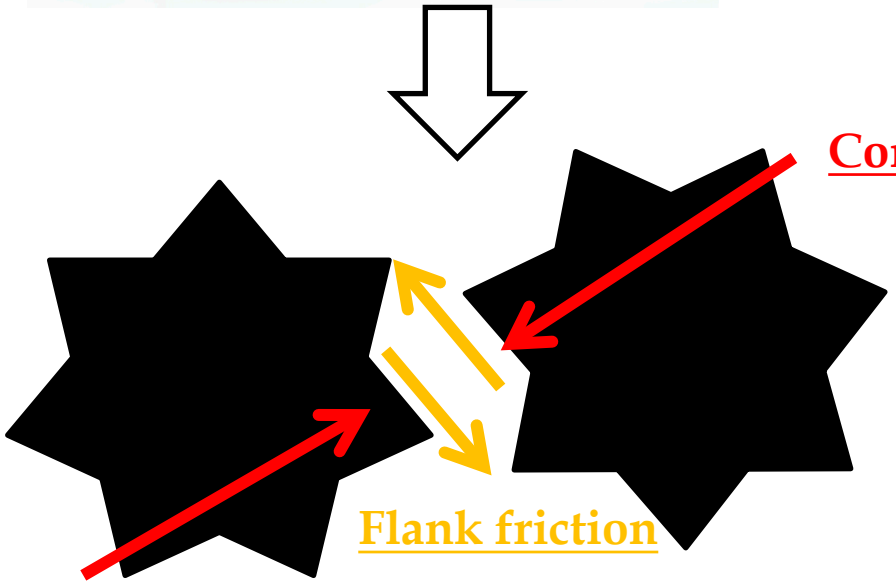
Methodology - Gear dynamics



The gear dynamics (time varying contact load) causes fluctuations to the coefficient of friction and the power loss.



Flank friction ~ Contact load

Methodology - Gear dynamics

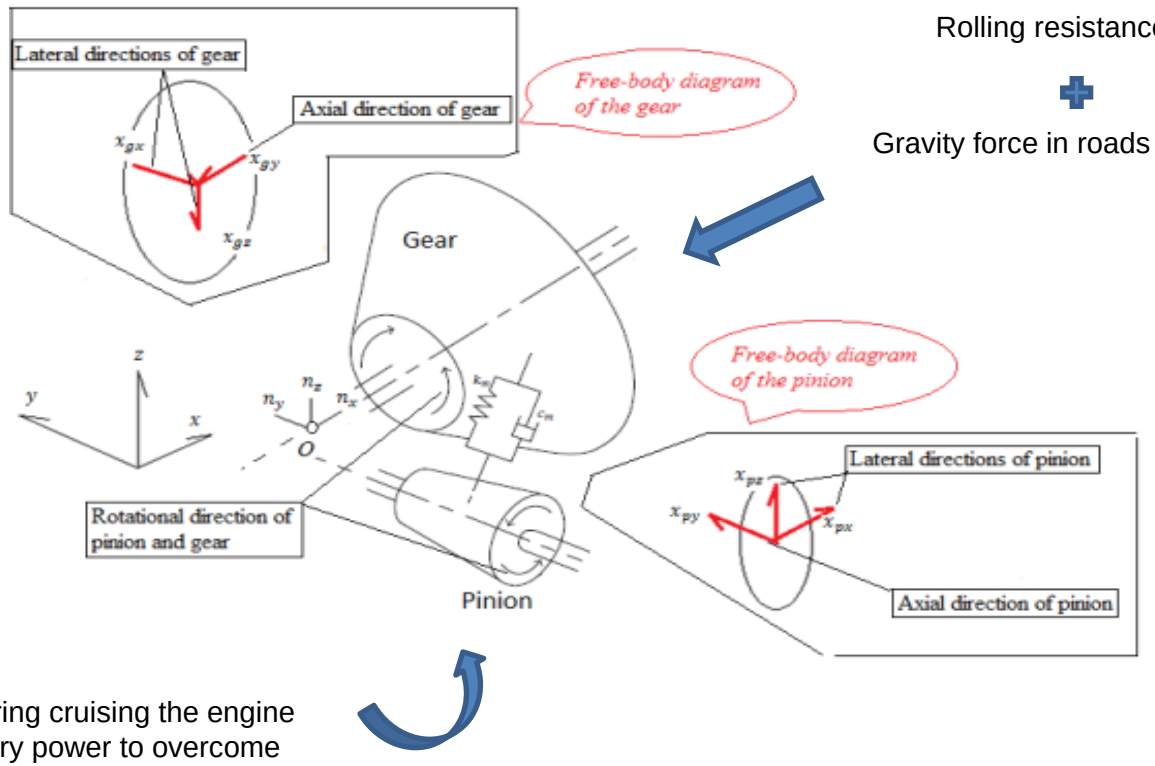
Aerodynamic force

+

Rolling resistance force

+

Gravity force in roads with slope



It is assumed that during cruising the engine provides the necessary power to overcome the resisting torque on wheels

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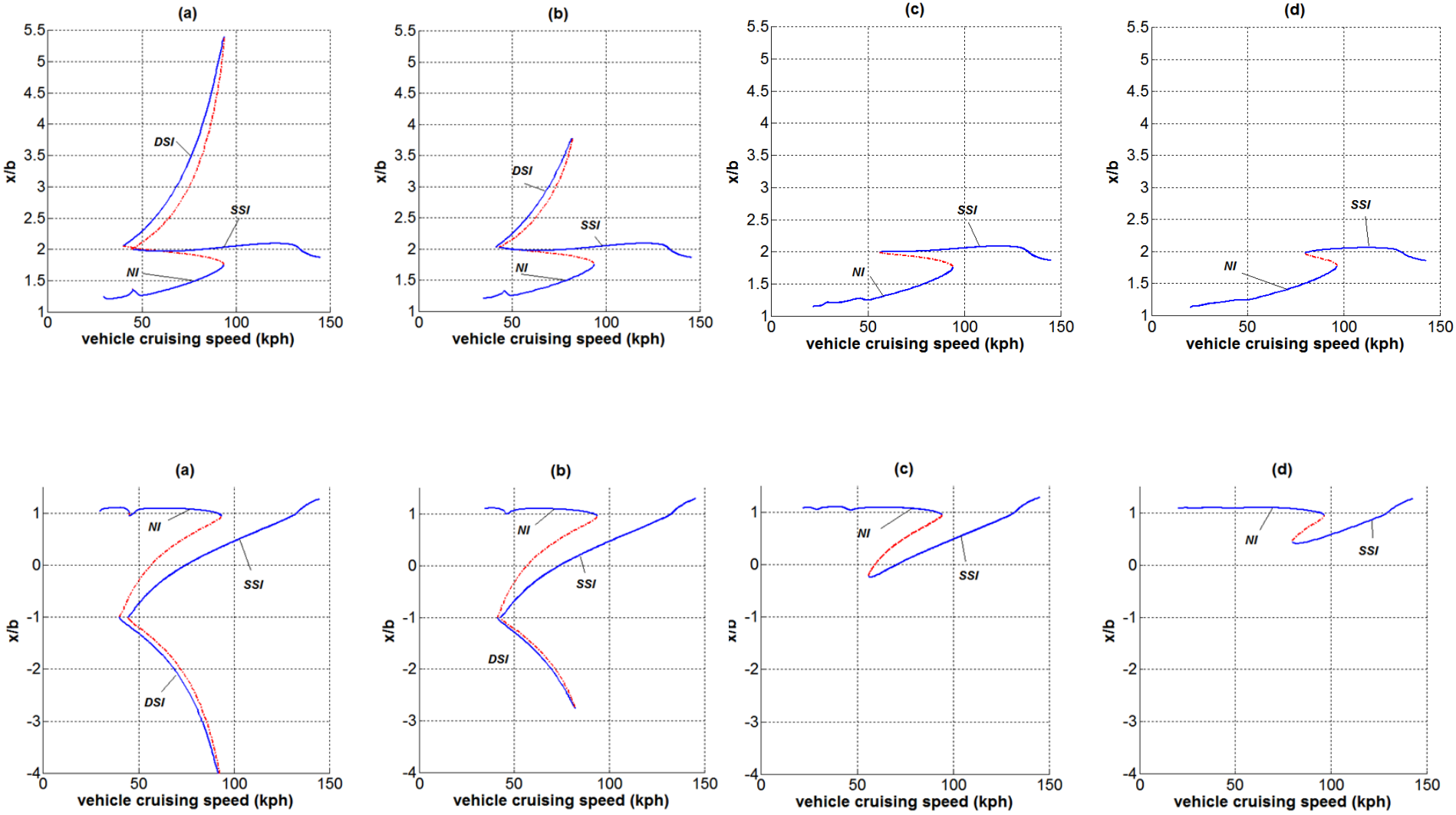
Results – Damping effect



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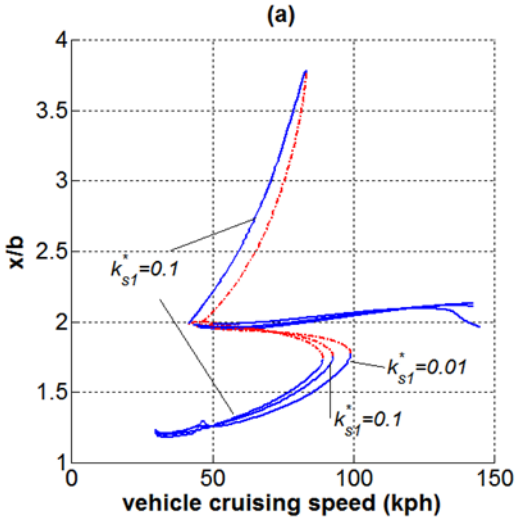
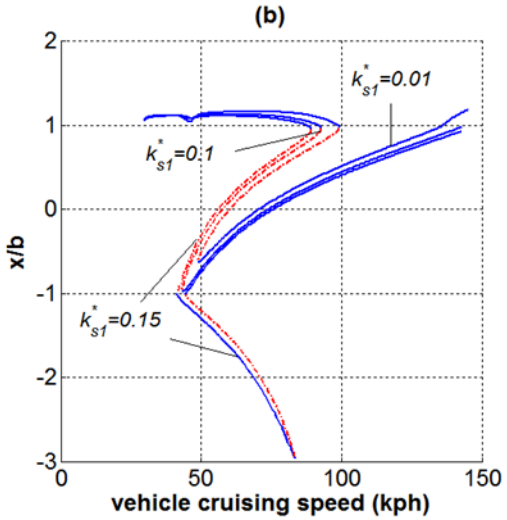
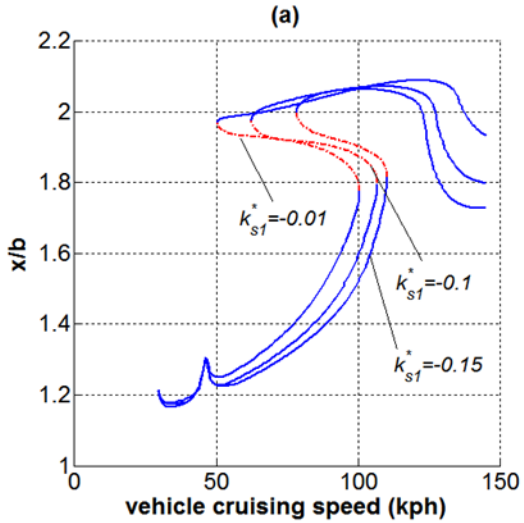
Results – Mesh stiffness effect

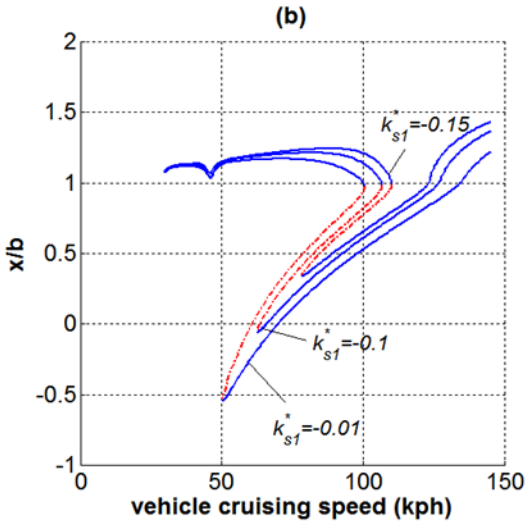




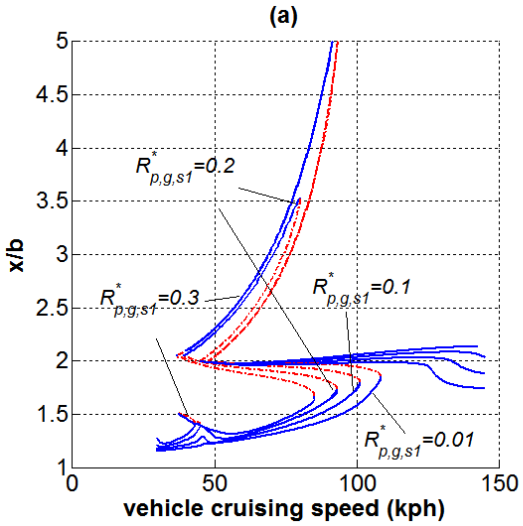
Out of phase with TE

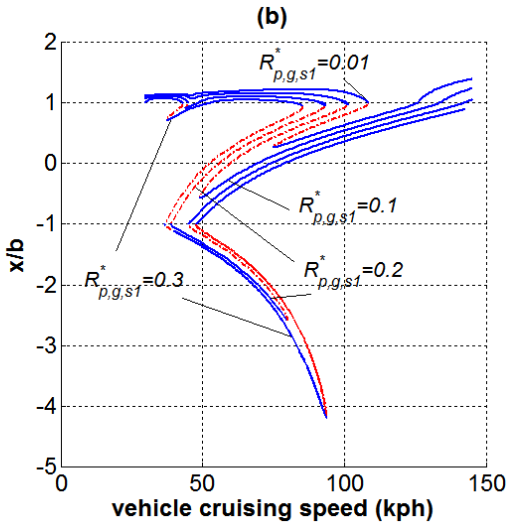
In phase with TE





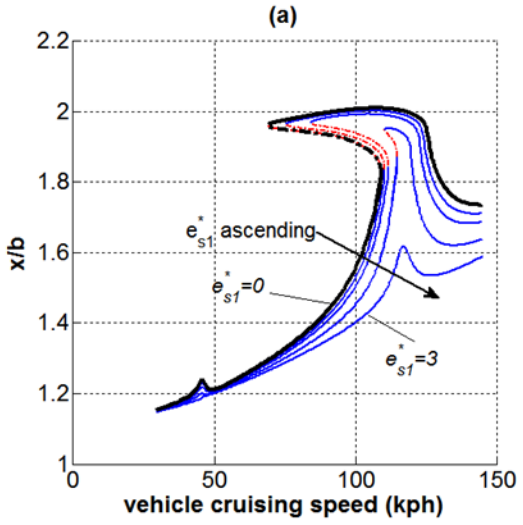
Results – Contact radii and TE effect

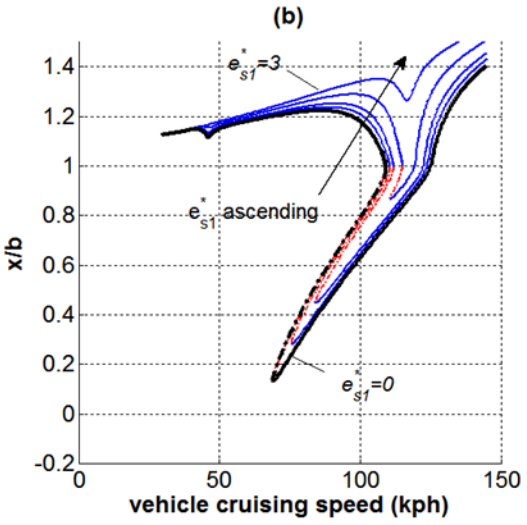




Contact radii <u>in phase</u> with the mesh stiffness and <u>out of phase</u> with the TE

Contact radii <u>in phase</u> with the TE





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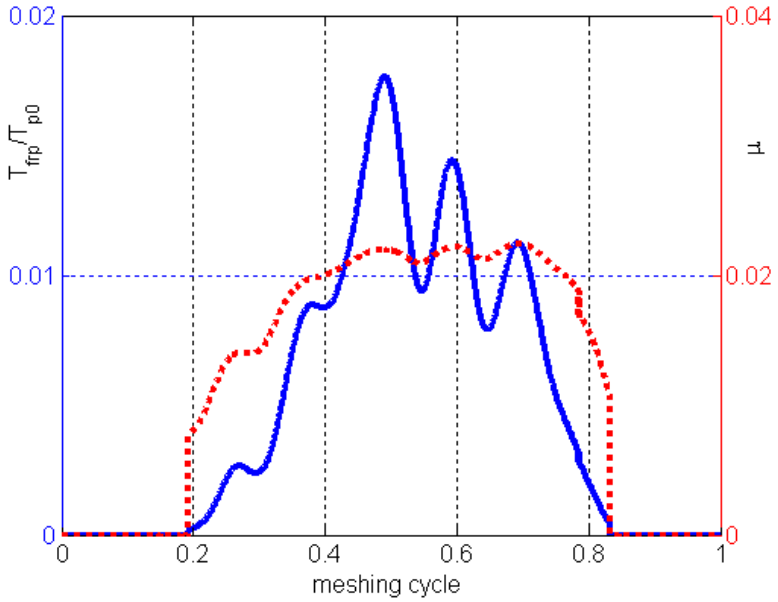
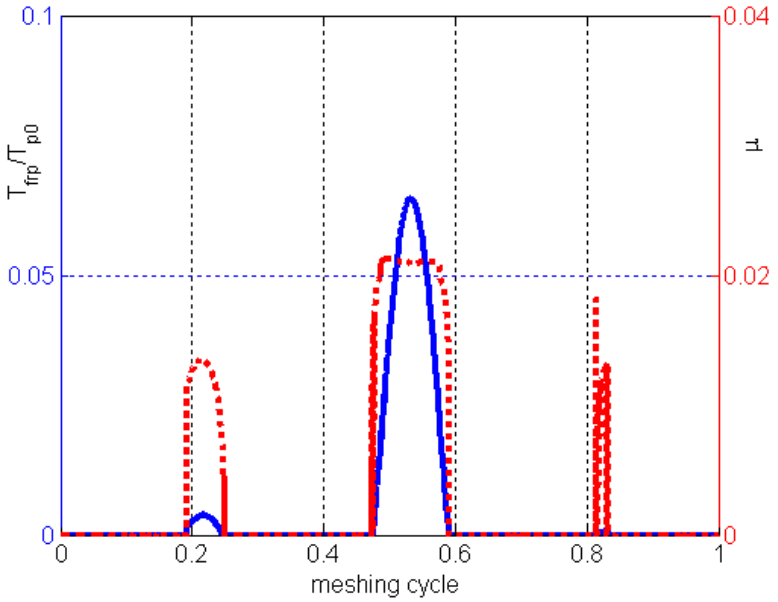
Results – Friction coefficient and corresponding Torque

Pinion speed 1800 RPM (continuous contact)



Pinion speed 3600 RPM (loss of contact)



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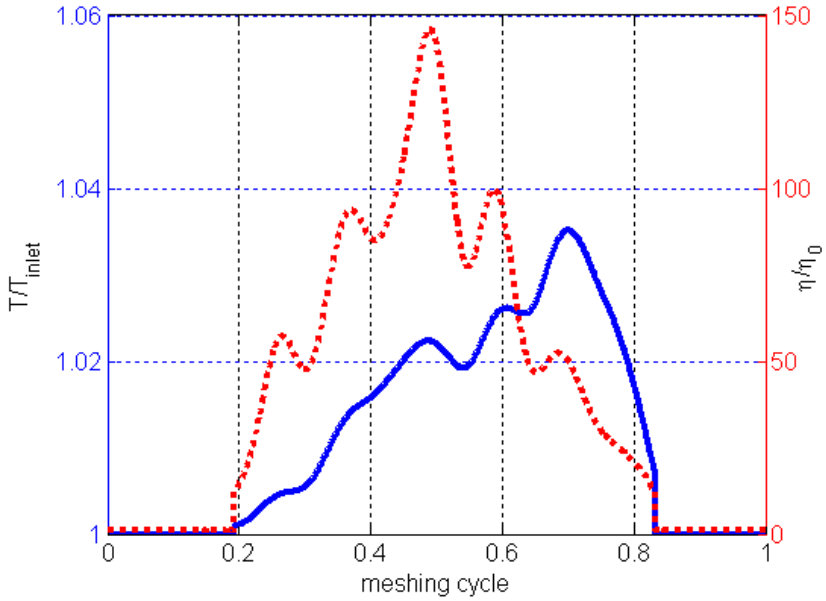
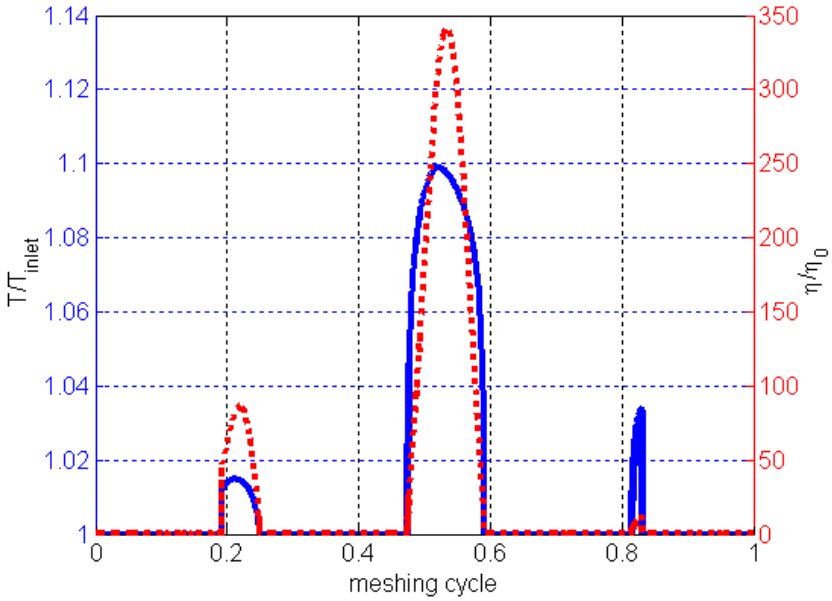
Results – Lubricant Temperature and viscosity variation

Pinion speed 1800 RPM (continuous contact)



Pinion speed 3600 RPM (loss of contact)



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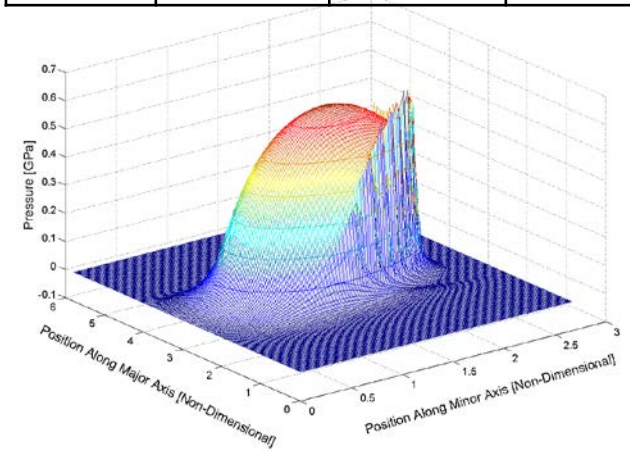
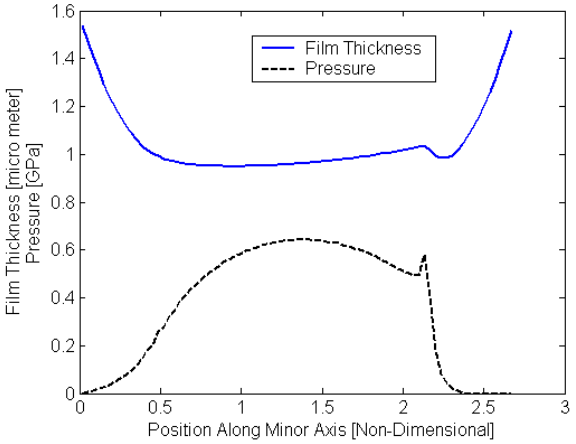
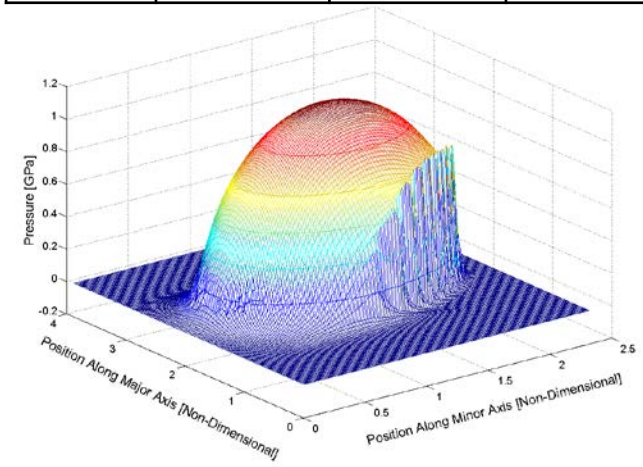
Results – Elastohydrodynamic Lubrication

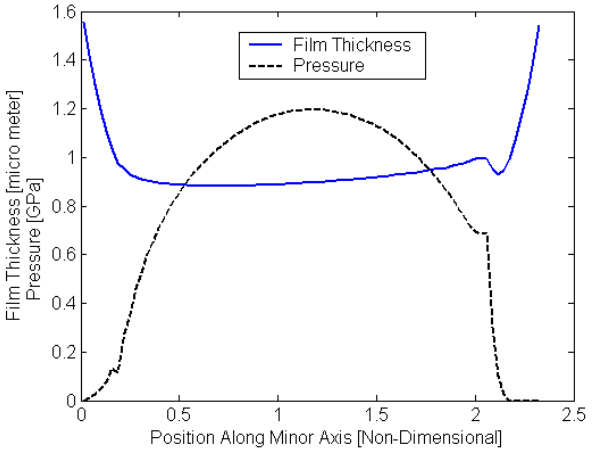
pinion angle	Load [N]	Magnitude of Velocity [m/s]	Velocity Along Minor Axis [m/s]	Velocity Along Major Axis [m/s]	Surface Radius in Minor Axis [m]	Surface Radius in Major Axis [m]
0.5027	744.5161	18.0398	7.9751	16.1813	0.0157	1.0067



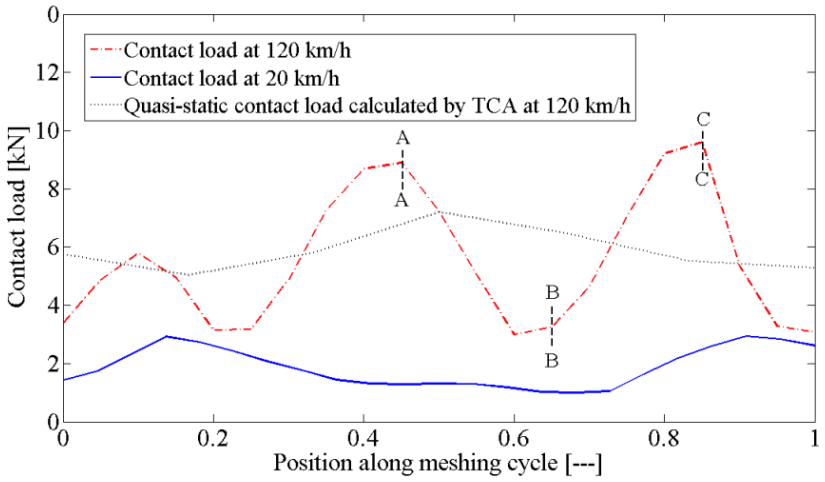


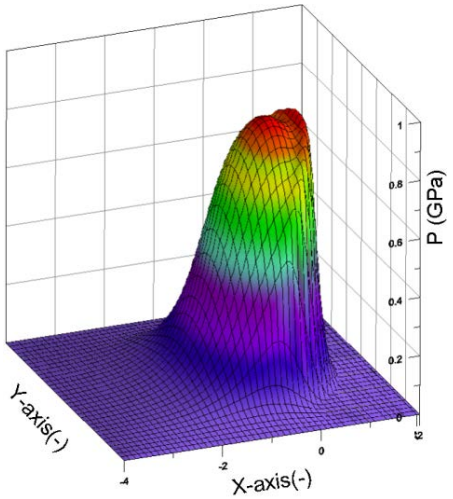
pinion angle	Load [N]	Magnitude of Velocity [m/s]	Velocity Along Minor Axis [m/s]	Velocity Along Major Axis [m/s]	Surface Radius in Minor Axis [m]	Surface Radius in Major Axis [m]
0.9582	5764.1	15.7962	8.9823	12.9938	0.0180	1.2578

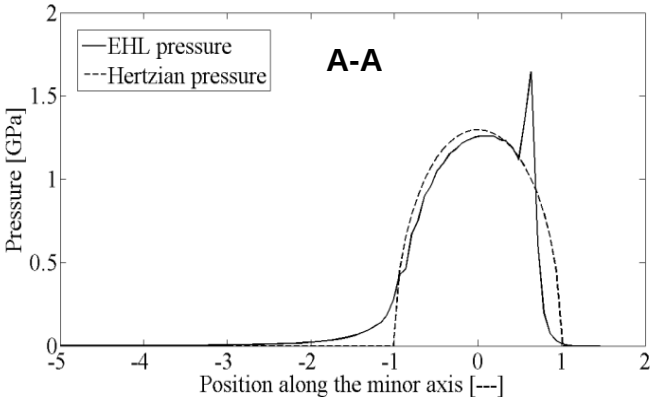


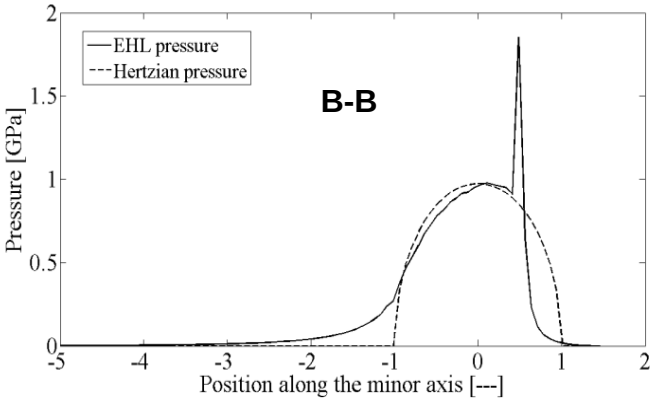


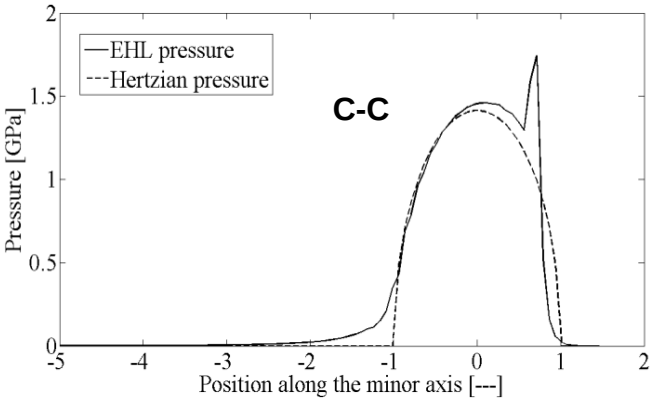
Results - Elastohydrodynamic Lubrication





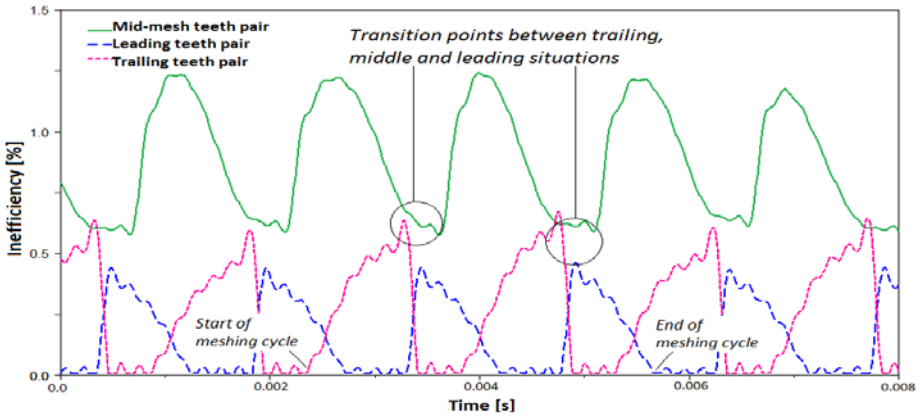




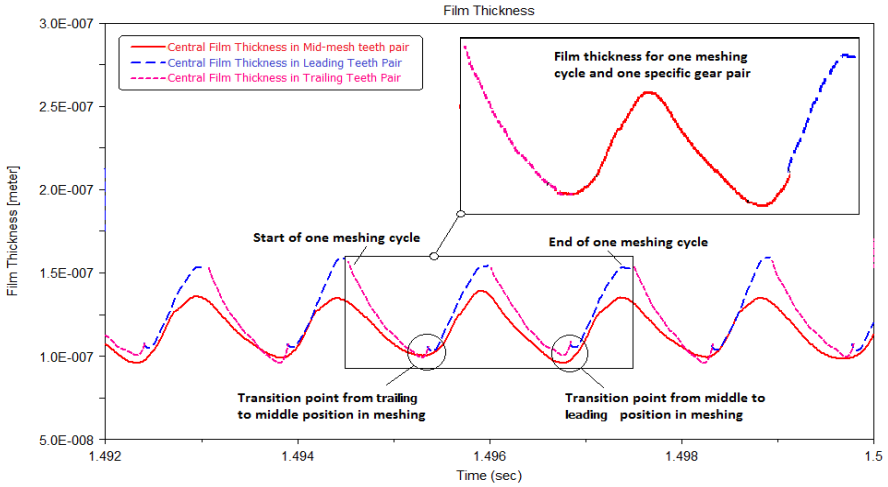


Mohammadpour et al. Transient mixed non-Newtonian thermo-elastohydrodynamics of vehicle differential hypoid gears with starved partial counter-flow inlet boundary. *Proc. IMechE, Part J*

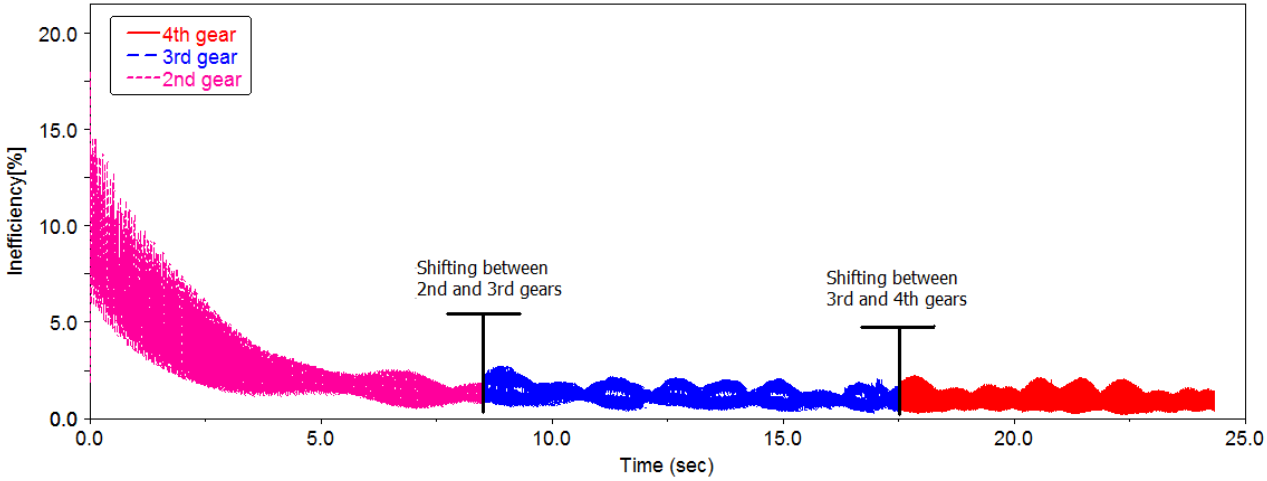
Results - Efficiency *(Viscous – Boundary Friction)*



Inefficiency variation per teeth pair contact

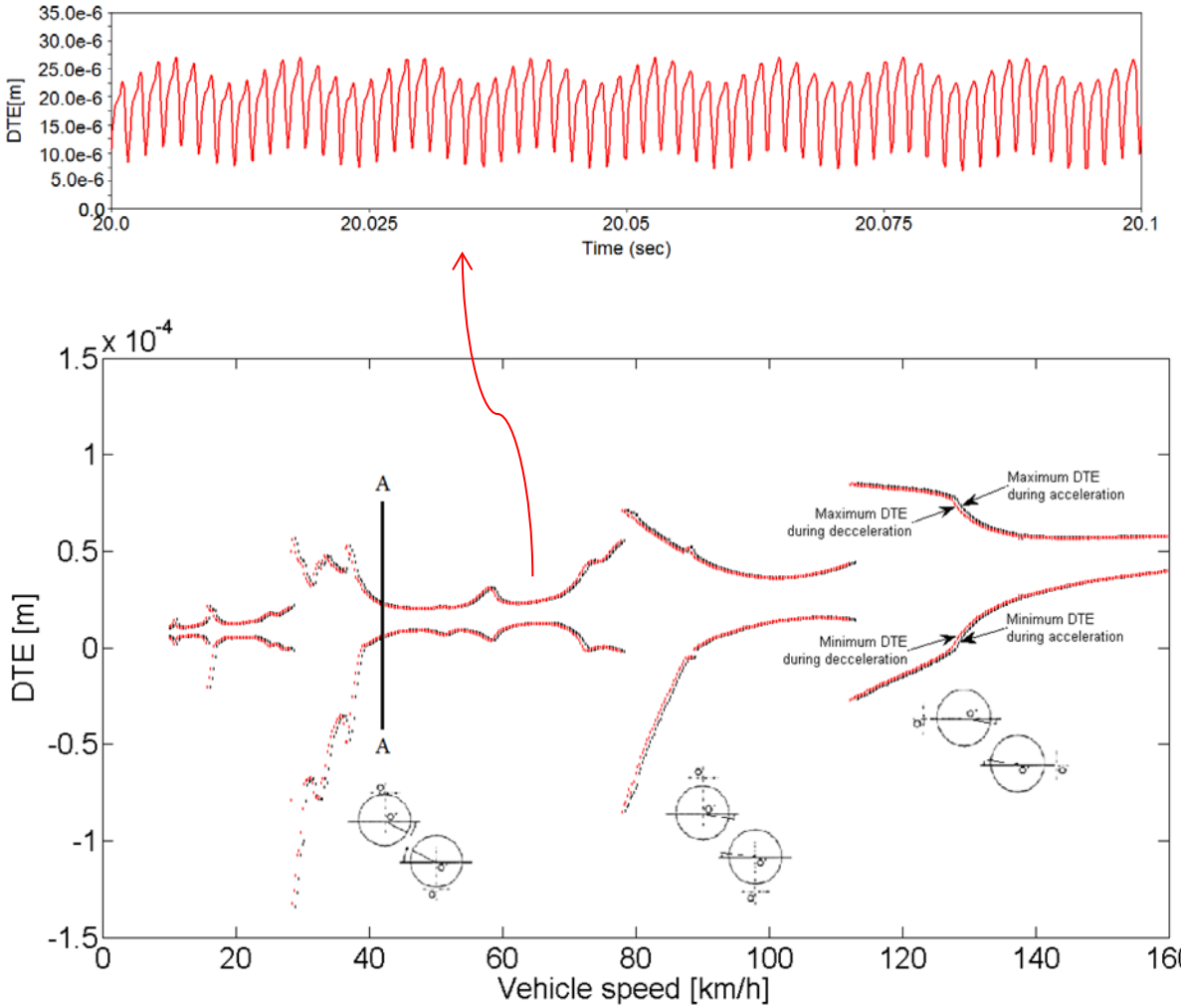


Film Thickness Time History



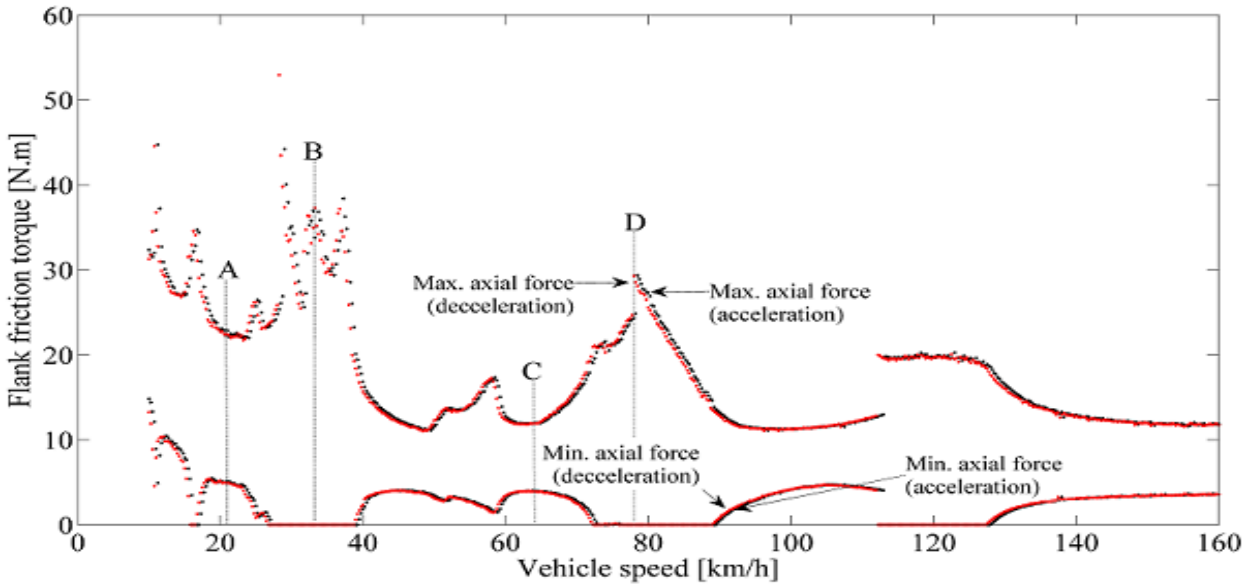
Mohammadpour et al. Transmission efficiency and noise, vibration and harshness refinement of differential hypoid gear pairs. *Proc. IMechE, Part K*, 2013, DOI: 10.1177/1464419313496559

Results - Dynamic Transmission Error (NVH)

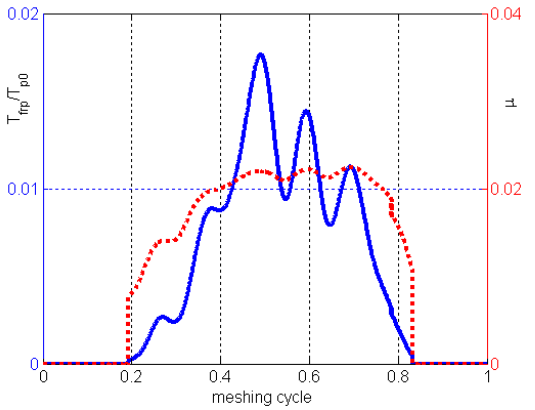


Mohammadpour et al. Multiphysics investigations on the dynamics of differential hypoid gears, ASME *Journal of Vibration and Acoustics,* 2014, DOI: 10.1115/1.4027403

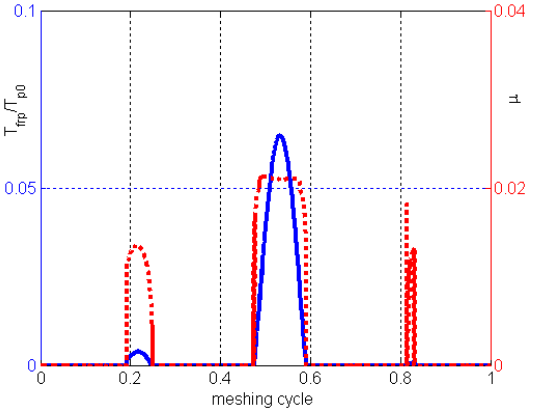
Results - NVH versus Efficiency



Continuous teeth contact (A, C)



Loss of teeth contact (B, D)



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Karagiannis et al. On the dynamics of lubricated hypoid gears. *Mechanism and Machine Theory,* 2012, 48, 94-120.

Points	A	B	C	D
Frictional energy loss during one meshing cycle (kJ)	12.75	7.37	7.15	1.58

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Conclusions

- *Dynamics and Tribology* are essential to study the parasitic losses (efficiency) of lubricated mechanical systems

- The two approaches need to be integrated and solved interactively due to their strong physical relationships

- The dynamics return the transient/steady state behaviour of the mechanical system, as a predictive tool for NVH severity

- Tribology / friction studies provide information about the energy efficiency of the mechanical system

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- Theodossiades, S, Mohammadpour M, Rahnejat H, Kelly P, (2013) Transmission efficiency and noise, vibration and harshness refinement of differential hypoid gear pairs, *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics*

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Thank you!