# Investigating the effect of gearbox preconditioning on vehicle efficiency

**HIGH-TECH SYSTEMS 2015**

R. Gillot A. Picarelli M. Dempsey

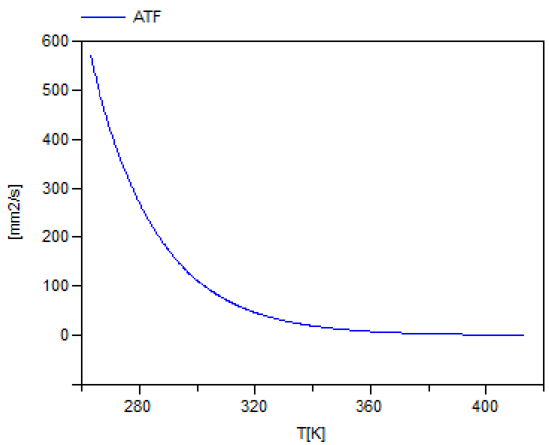
*romain.gillot@claytex.com*
*alessandro.picarelli@claytex.com*
*mike.dempsey@claytex.com*

# Claytex Services Limited

- Based in Leamington Spa, UK
  - Office in Cape Town, South Africa
- Established in 1998
- Experts in Systems Engineering, Modelling and Simulation
  - Focused on physical modelling to support control system design and development
- Business Activities
  - Engineering consultancy
  - Software sales and support
  - Modelica library developers
  - Training services
- Global customer base
  - Europe, USA, India, South Korea, Japan, RSA

# Vehicle System Preconditioning: Background & Motivation

- Discrepancy between certified and real world fuel economy can cause customer dissatisfaction
- Extreme climatic differences between certification routines can exacerbate the discrepancy
- Investigation to quantify and reduce the gap to real world is necessary for all subsystems contributing to overall vehicle efficiency
- Sub optimal lubricant temperature is one source of vehicle subsystem inefficiency with exponential rises in viscosity at very low temperatures:




ATF (Automatic Transmission Fluid) oil kinematic viscosity trend vs Temperature

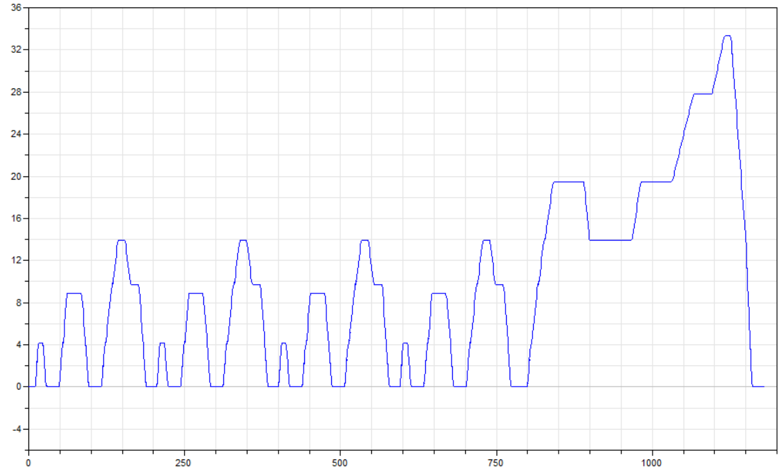
CLAYTEX

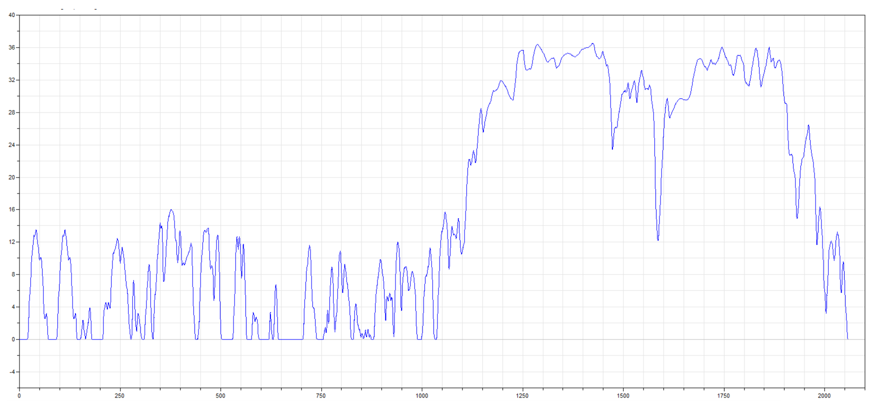
# The experiment

- As part of a larger project we concentrate, in this study, on the benefits of pre-conditioning the vehicle transmission fluid and the costs associated in doing so
- We assemble a complete vehicle model and the related subsystems using Dymola
- The vehicle includes a predictive thermal model of the transmission to quantify the thermal dynamics of the system including losses such as bearing and gear drag losses
- The vehicle is exercised over the standard NEDC (New European Drive Cycle) and combined Urban and Highway ARTEMIS drive cycles.
- The transmission oil is preconditioned to several temperatures before each test is started

# The experiment

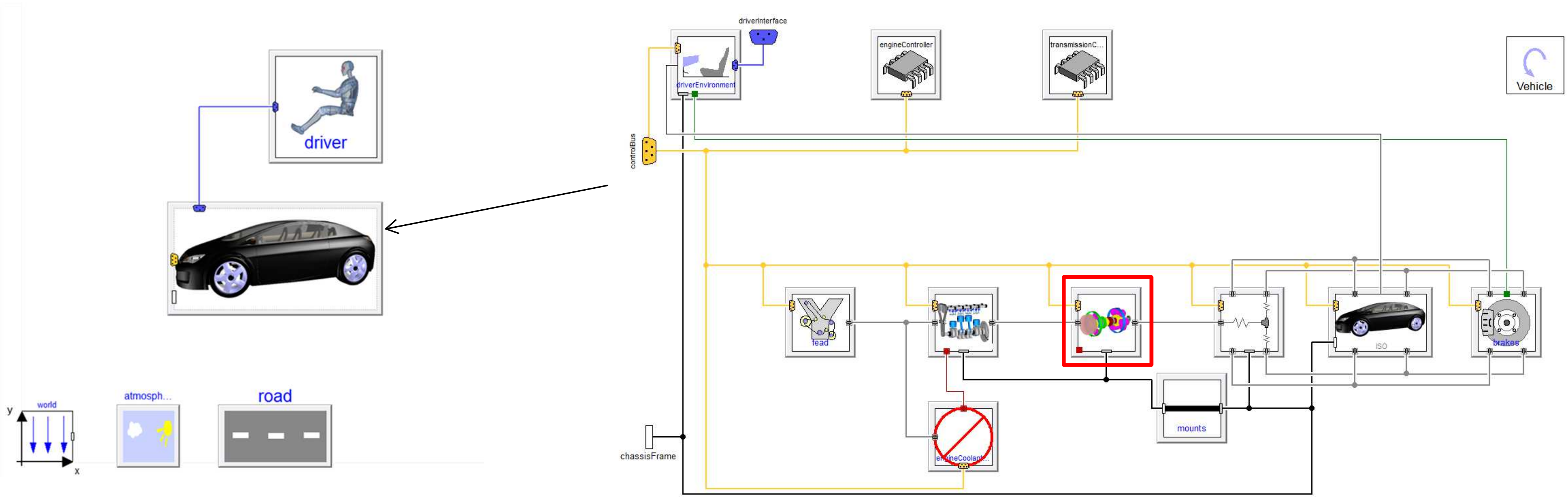
- NEDC drive cycle (1180s)
- ARTEMIS urban + highway (2061s)
- Rear wheel drive passenger car
- Automatic transmission (6 speed)
- 2L Petrol engine,  4 cylinders inline
- Several initial ATF (Automatic Transmission Fluid) temperatures:
  - “Normal”: 23 degC
  - Cold: -10 degC
  - Hot: 40 degC
  - Pre-warmed: 90 degC



# Model Architecture

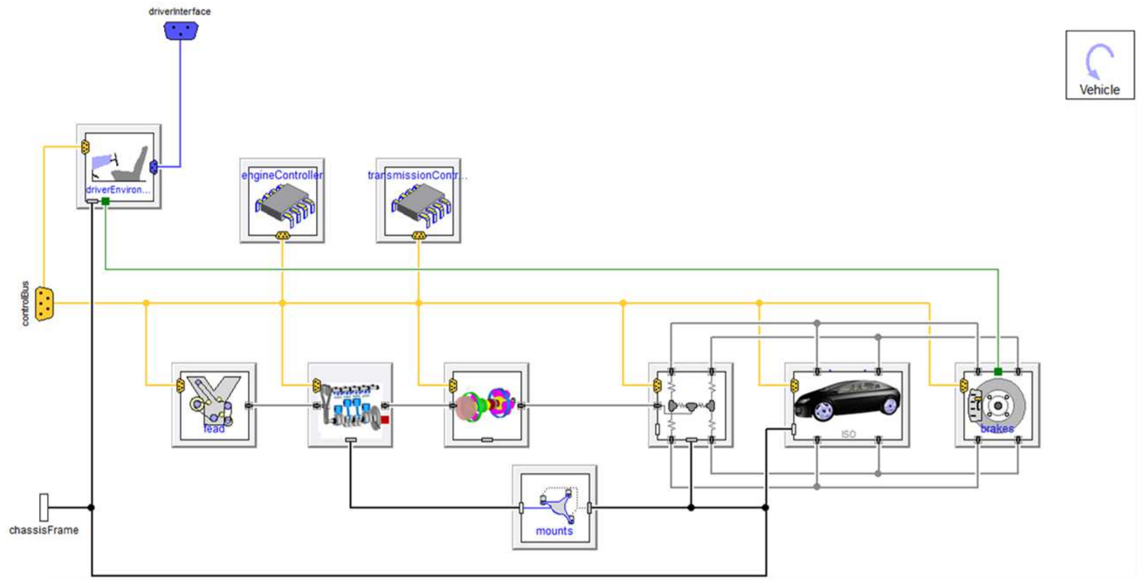
- Built on the VehicleInterfaces standard from Modelica Association
  - Designed to promote the easy coupling of libraries from different vendors
  - Defines a minimum set of connectors required in each subsystem

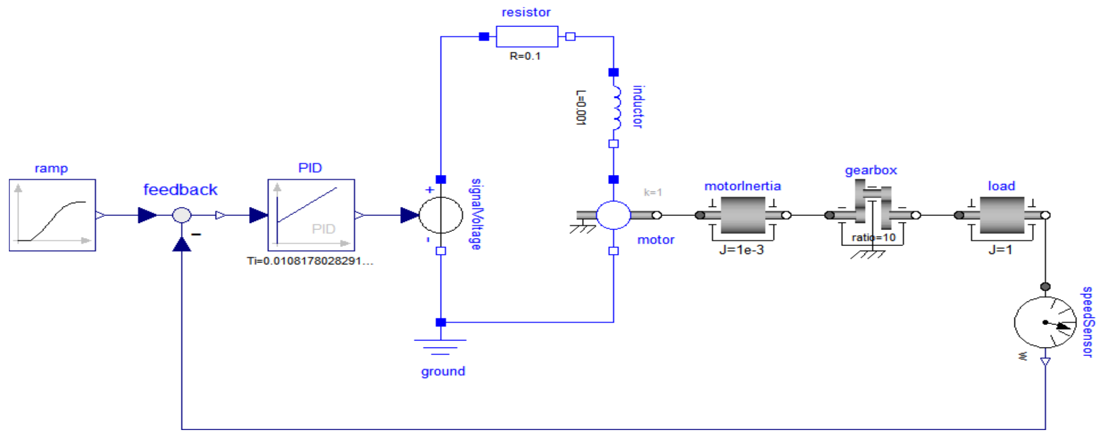



CLAYTEX

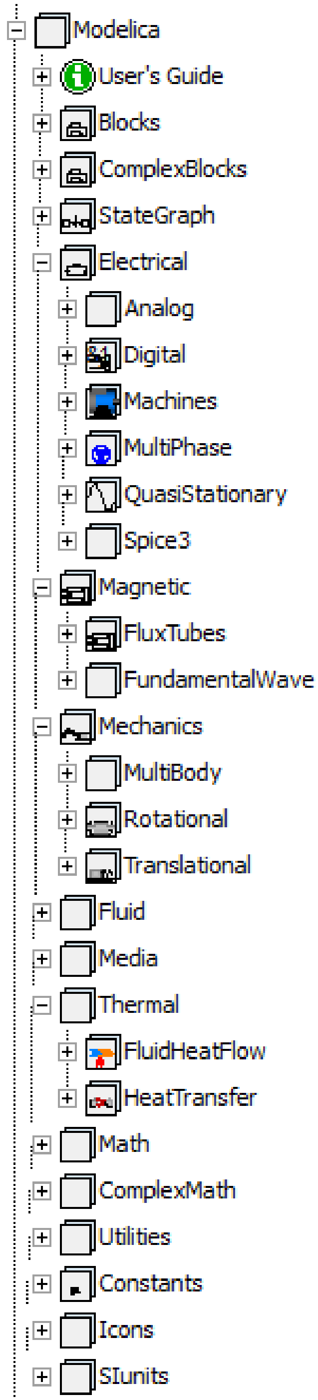
# Component Orientated Modelling

- Modelling and simulation of systems integrating multiple physical domains
  - Mechanics (1D, MultiBody), 1D Thermofluids, Control, Thermal, Electrical, Magnetics and more
- Promotes extensive model reuse at component and system level
  - Components represent physical parts: valves, gears, motor
  - Connections between parts describe the physical connection (mechanical, electrical, thermal, signal, etc.)
- Store your own component and system models in libraries to easily share and reuse them across the business



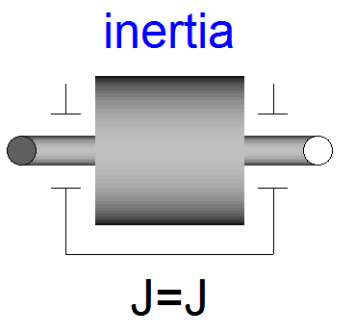



- A freely available, open source, standardised modelling language
- Developed and maintained by the Modelica Association
  - An independent, international not-for-profit organisation
  - Established in 1996
  - Currently about 100 members from academia, tool vendors and industrial end-users
    - Anyone can get involved
  - Organised into project groups for the Modelica Language, Modelica Standard Library and FMI Standard
- The Modelica Standard Library contains basic models in many engineering domains
  - Delivered as standard in Dymola



# Model Definition

- Models are defined using the Modelica modelling language
  - A generic modelling language
  - Design for convenient, component orientated modelling of complex multi-domain systems
- Dymola provides access to the Modelica code behind models

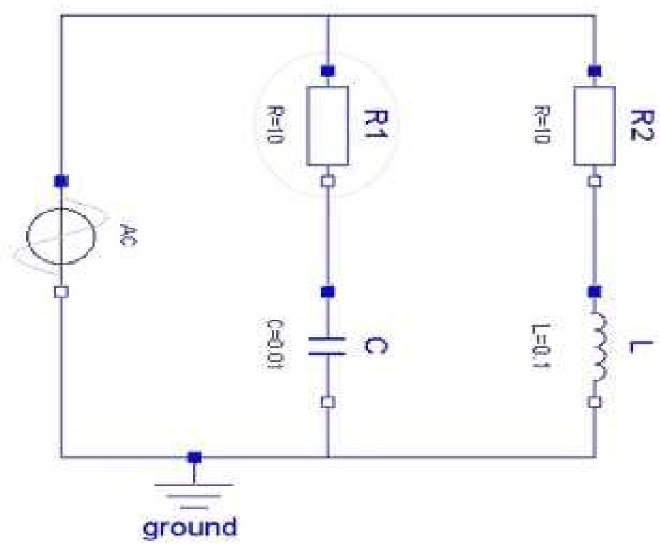



```
model Inertia
  extends Interfaces.Rigid;
  parameter SI.Inertia J=1 “Moment of Inertia”;
  SI.AngularVelocity w “Angular velocity”;
  SI.AngularAcceleration a “Angular acceleration”;
equation
  w = der(phi);
  a = der(w);
  flange_a.tau + flange_b.tau = J * a;
end Inertia;
```

# Symbolic Manipulation

- The model equations are automatically transformed in to the required solution for simulation
- Advanced mathematical techniques are used to reduce the size of the problem without removing detail from the model

DAE:

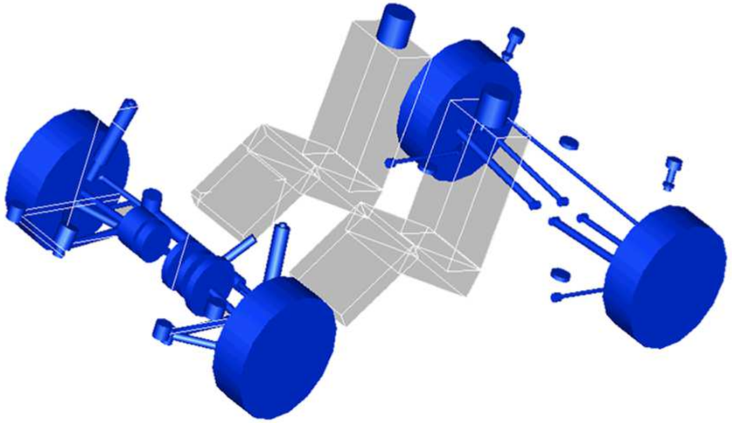



CLAYTEX

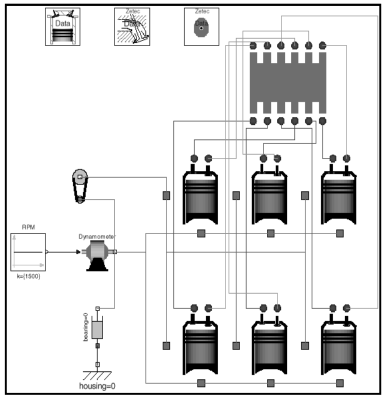
# What does this mean in practice

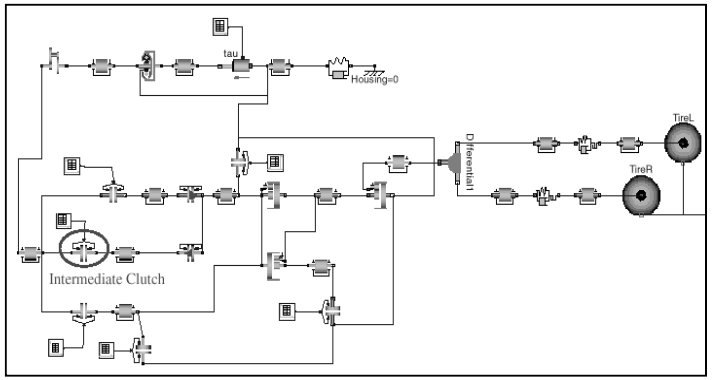
- Example: Vehicle model with detailed engine, transmission and suspension system
  - ~ 250,000 equations before reduction
  - ~ 25,000 equations after reduction

Source: Paper presented by Mike Tiller, Ford Motor Company at the Modelica Workshop, 2000



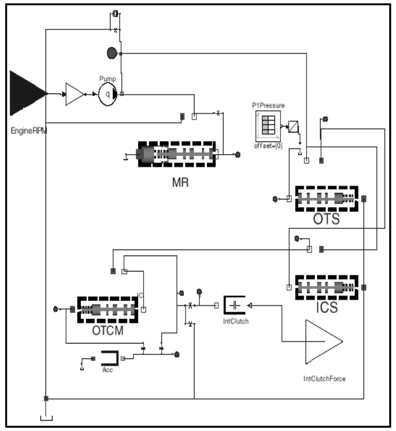
**Engine including combustion**





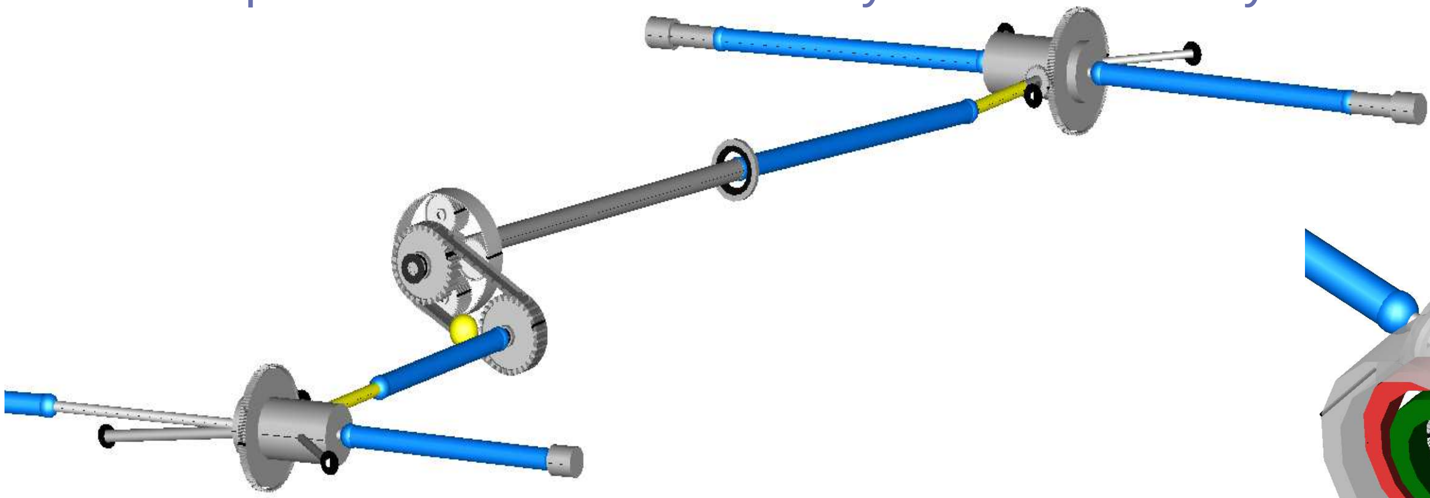

**Automatic gear box**

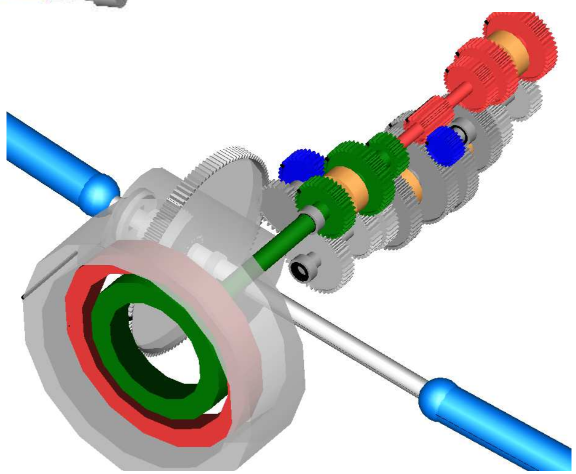
**Hydraulics**

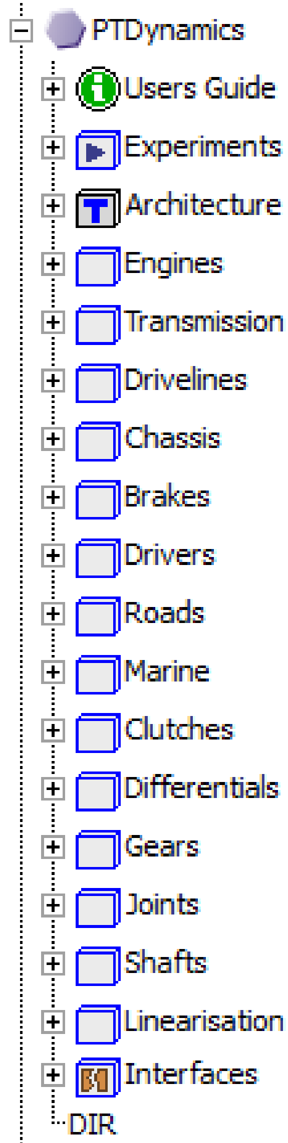


# Powertrain Dynamics Library

- Powertrain Dynamics Library, a library for modelling rotating MultiBody systems
  - Automotive powertrains, Aerospace and Marine transmissions
  - Convenient modelling approach for complex powertrains
  - Wide range of components available for modelling powertrain systems
  - Easily reduce models from full multibody system to near 1D performance – from drive cycle to driveability





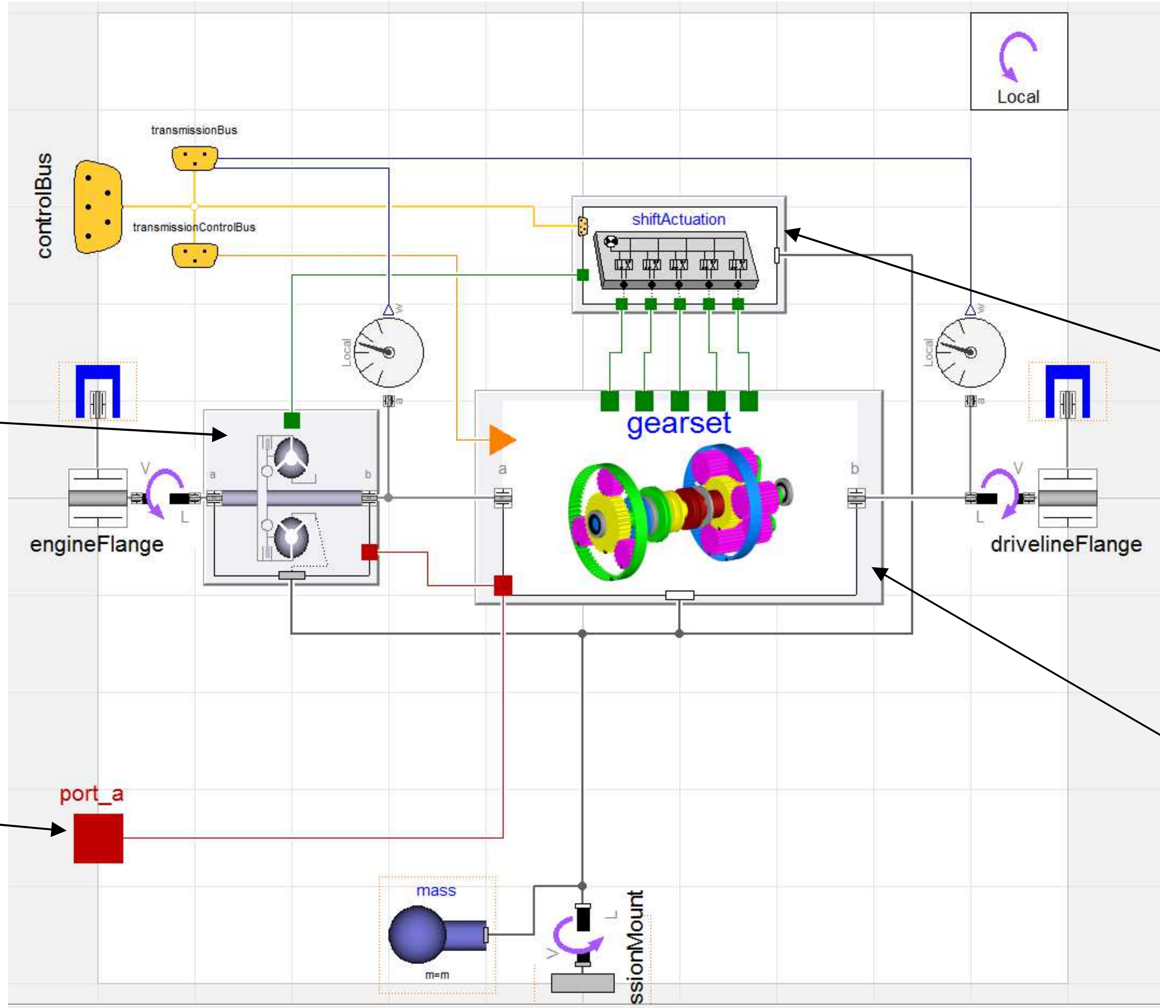


# Powertrain Dynamics Library

- Clutches
  - Wet clutches, Band brakes, Cone, dog and one way clutches
- Bearings
  - 1-6 DOF compliance
  - Force dependent Coulomb, hydrodynamic and rolling friction models
- Shafts
  - Torsional compliance with elastic and plastic deformation
- Joints
  - Constant velocity, universal and plunging joints
- Gears
  - Spur, helical, bevel, differential and epicyclic
  - Single & multiple contacts
    - Backlash, mesh stiffness, friction and 3D mesh forces
- Mounting systems
  - Elastomeric models: Maxwell, frictional solid, and hydraulic bearing with Eigen dynamic
- Engines
  - Mapped performance and emissions
- Drivers
  - (closed & open loop) drive cycle and driveability tests

# Automatic gearbox subsystem

**Torque converter model**
Dynamic type (not table based) modelling heat fluctuation from working the fluid




**Shift actuation**
Multibody mechanics and valves used to control the clutches within automatic transmission

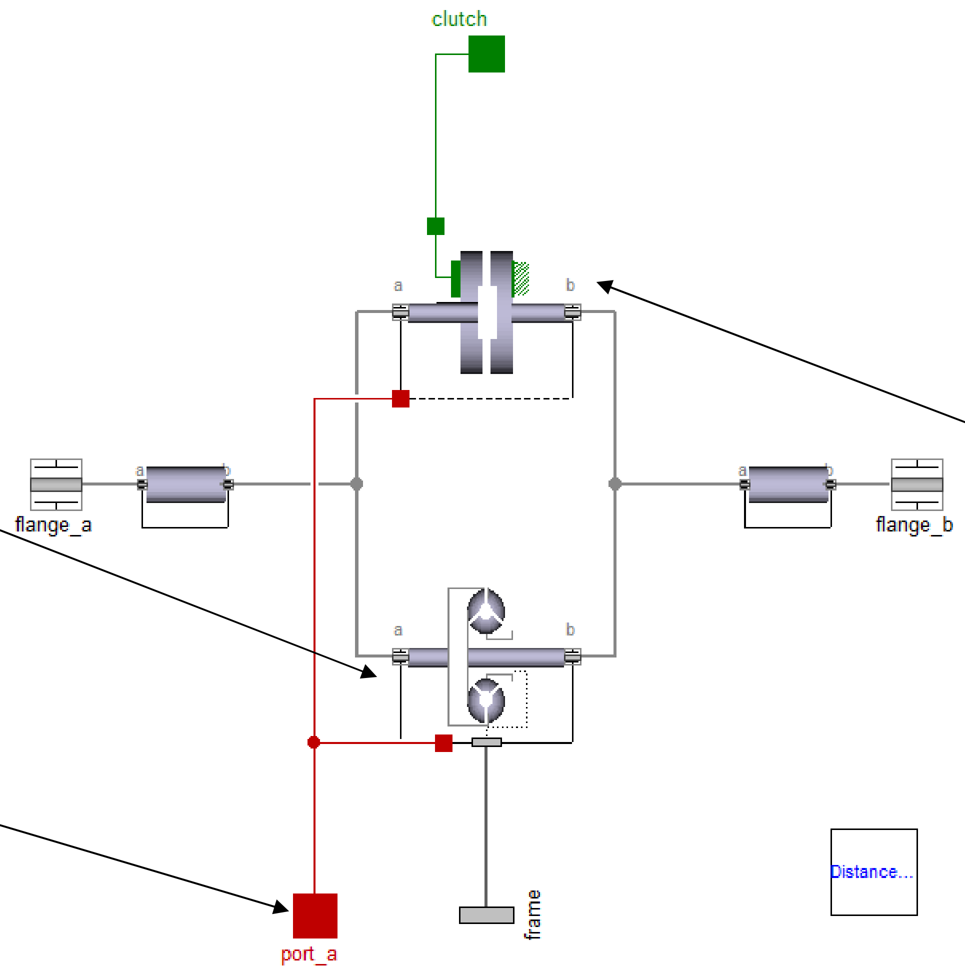
**Gear set**
Multibody mechanics model of the gear set, shafts bearings and clutches

**Heat port**
Allows a physical acausal thermal interface with other vehicle subsystems

# Torque converter with lock-up clutch

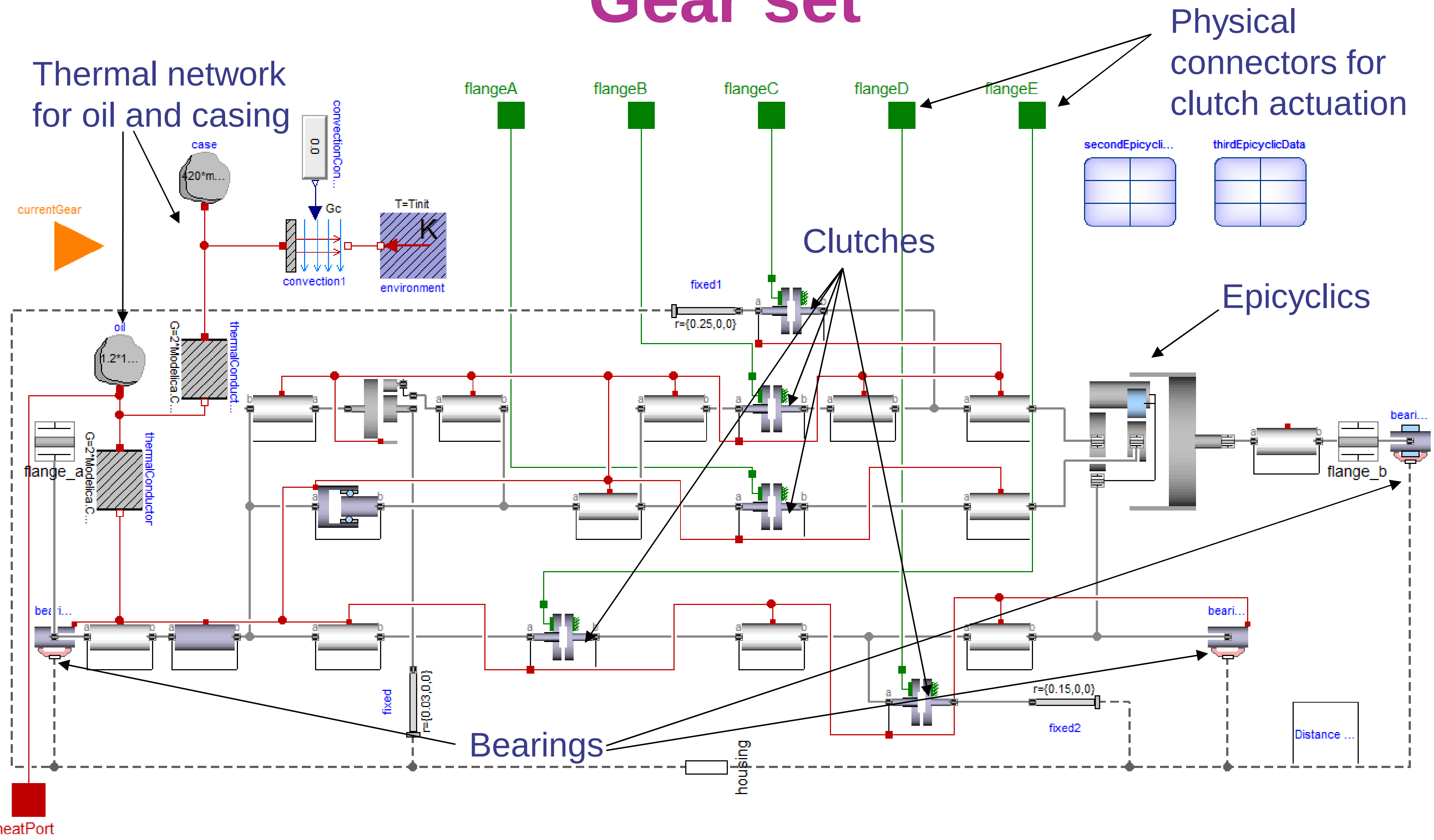
**Torque converter**
Dynamic torque converter model

**Thermal port**
Couples losses due to lock-up clutch and torque converter



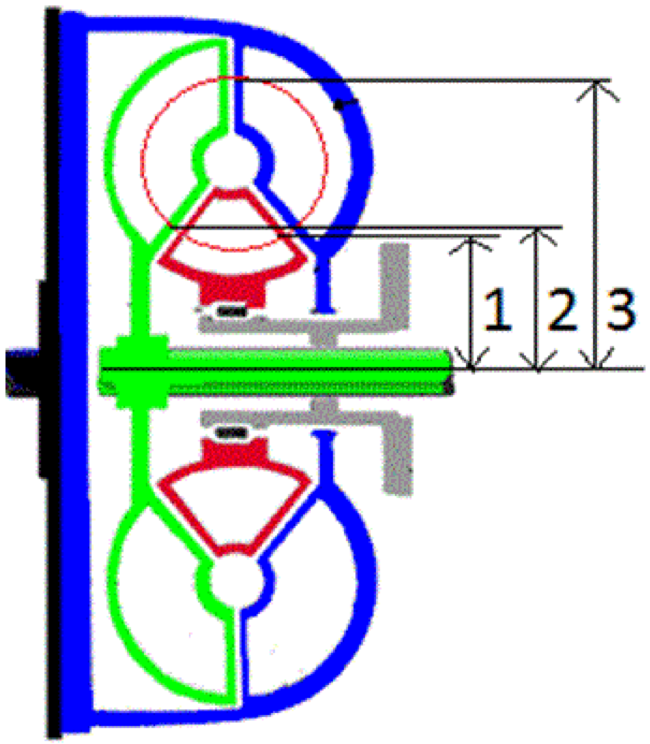

**Lock-up clutch**
Lockup clutch for locking the torque converter in higher gears to reduce slip losses

# Gear set


Thermal network for oil and casing
Physical connectors for clutch actuation
Clutches
Epicyclics
Bearings
flangeA
flangeB
flangeC
flangeD
flangeE
secondEpicycli...
thirdEpicyclicData
case
currentGear
convection1
environment
T=Tinit
Gc
fixed1
r={0.25,0,0}
oil
flange_a
flange_b
fixed
fixed2
r={0.15,0,0}
housing
Distance ...
heatPort

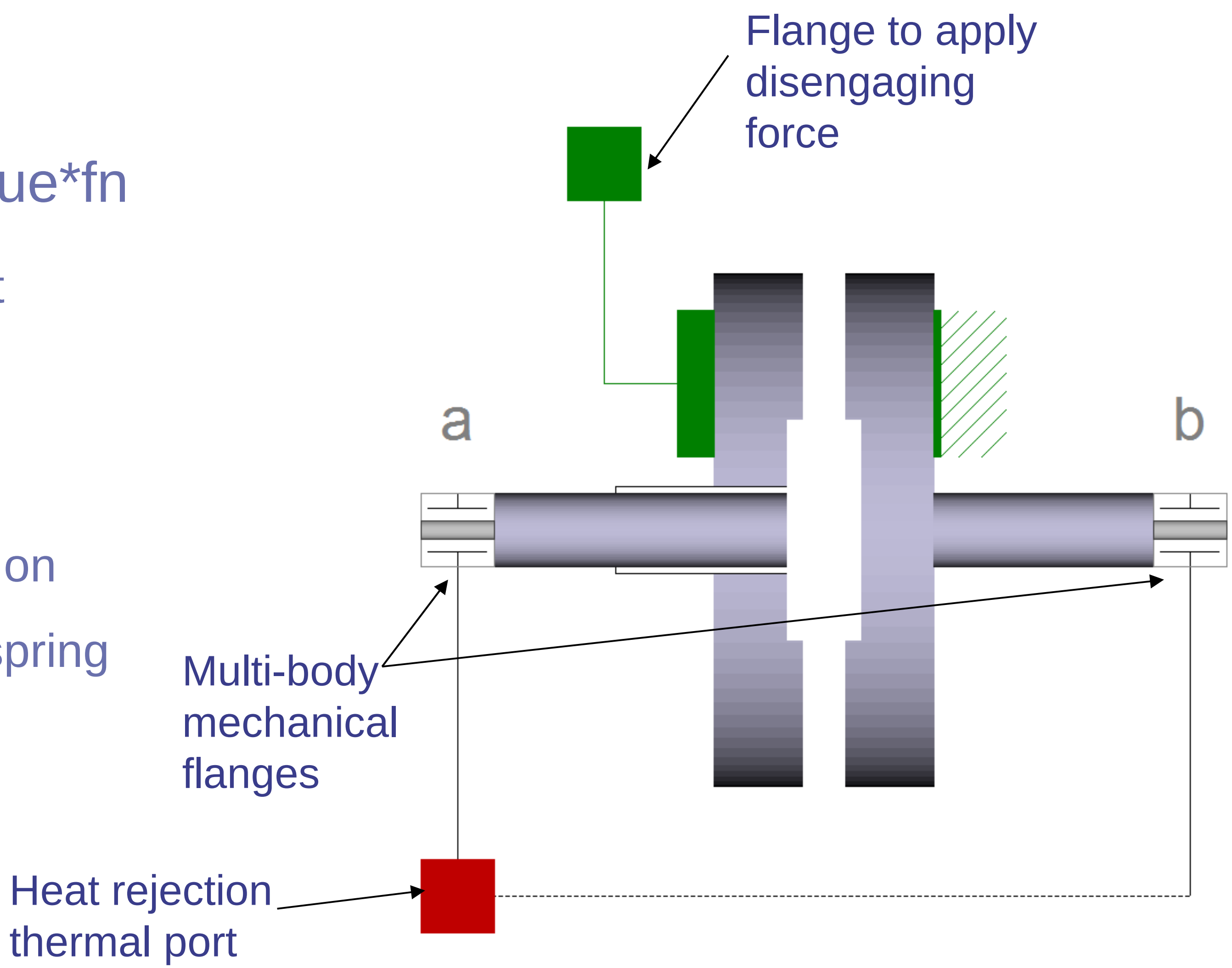
# Torque converter

- 3 fluid control volumes: impeller, turbine and stator
- Models the fluid momentum as it is pumped through the 3 control volumes
- As the temperature increases, the oil viscosity decreases and the efficiency increases
- Mapped versions are available for less detailed experimentation



# Torque converter lock-up clutch model

- Frictional torque = cgeo*mue*fn
  - **cgeo** is a geometry constant
  - **mue** is a velocity dependent friction coefficient
  - **fn** is the normal force acting on the clutch due to the clutch spring



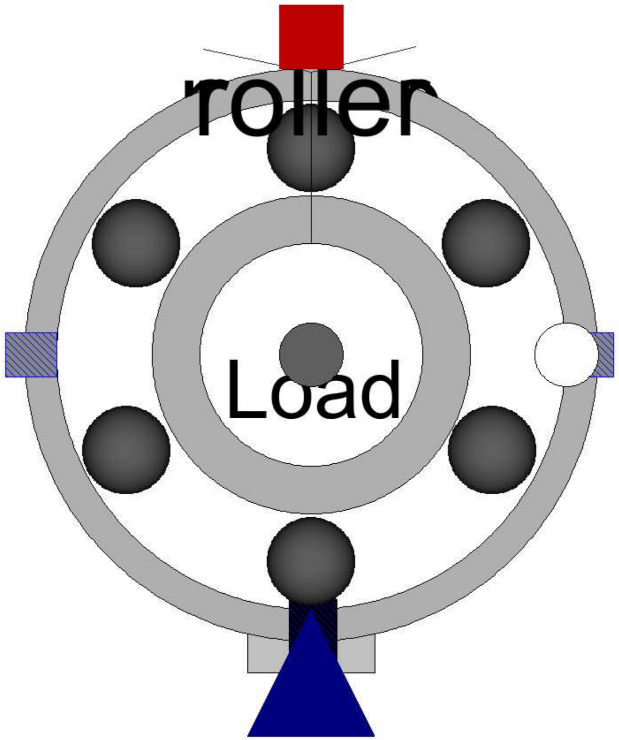
# Roller bearing friction model

Friction torque:

tau = fn*coeff*radius + Tseals + Tdrag

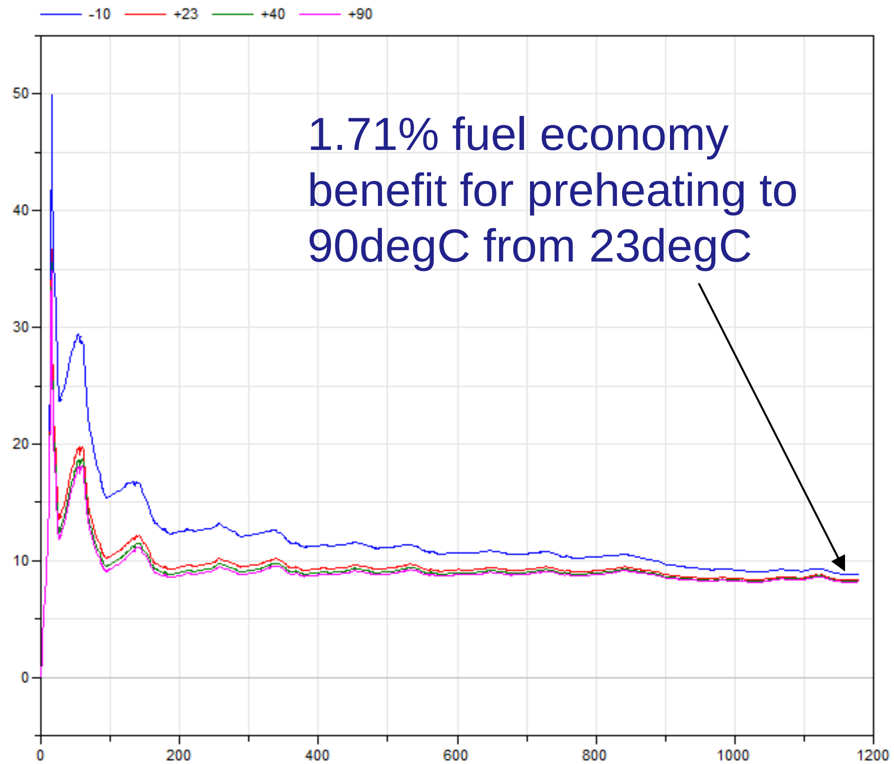
Computes the friction force due to:

- Load on bearing
- Friction coefficient relating to the type of rollers
  - Ball
  - Pin
  - Taper pin, etc.
- Oil seal drag on shaft (optional)
- **Oil churning drag related to viscosity of lubricant**

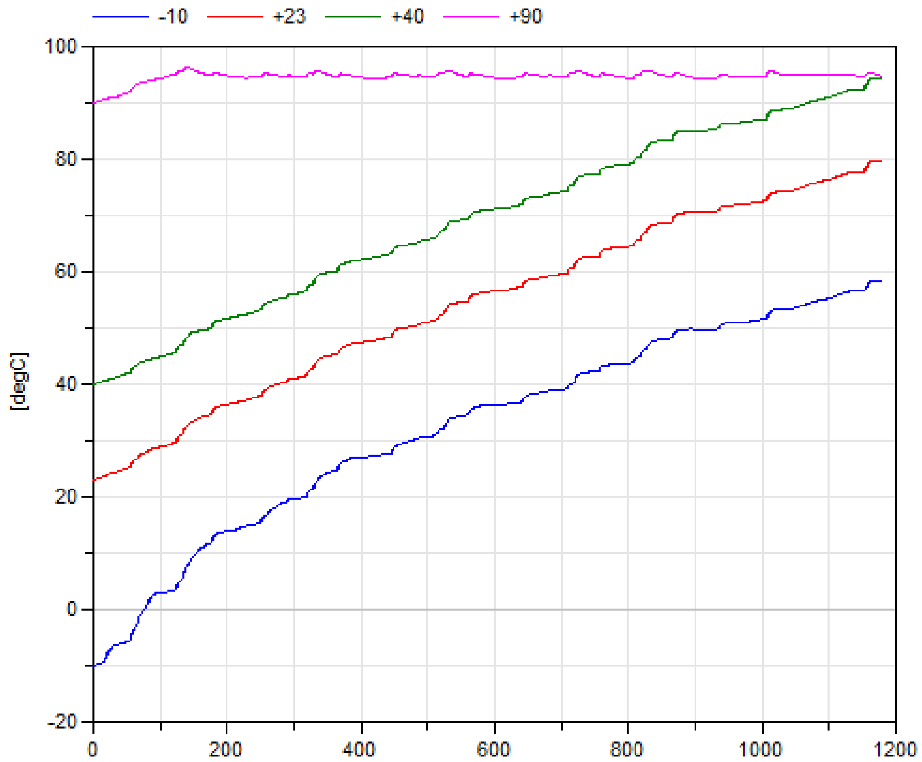


# Results NEDC cycle

## Average fuel consumption (l/100km)

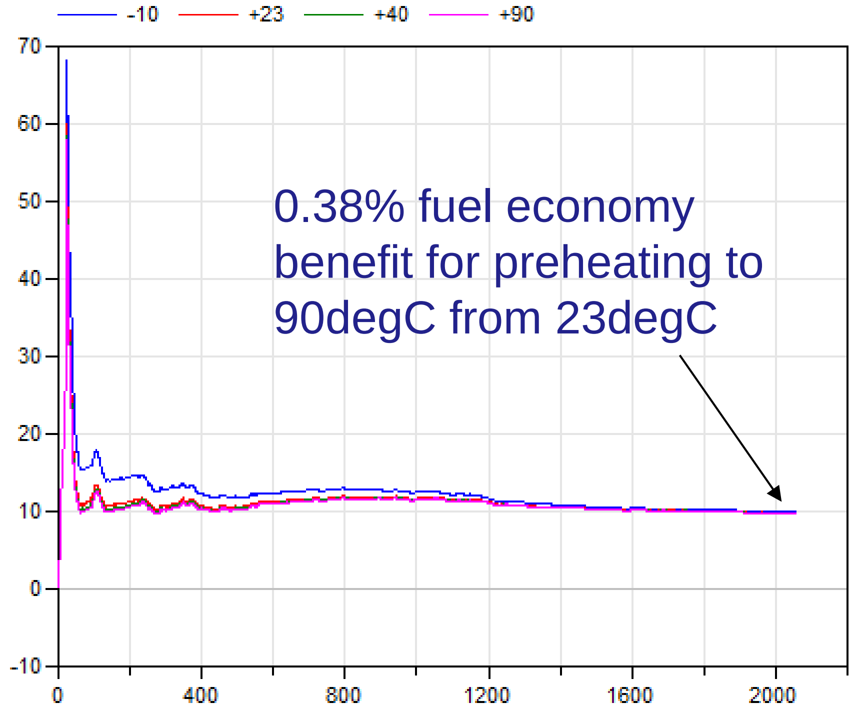



## Oil temperature (degC)

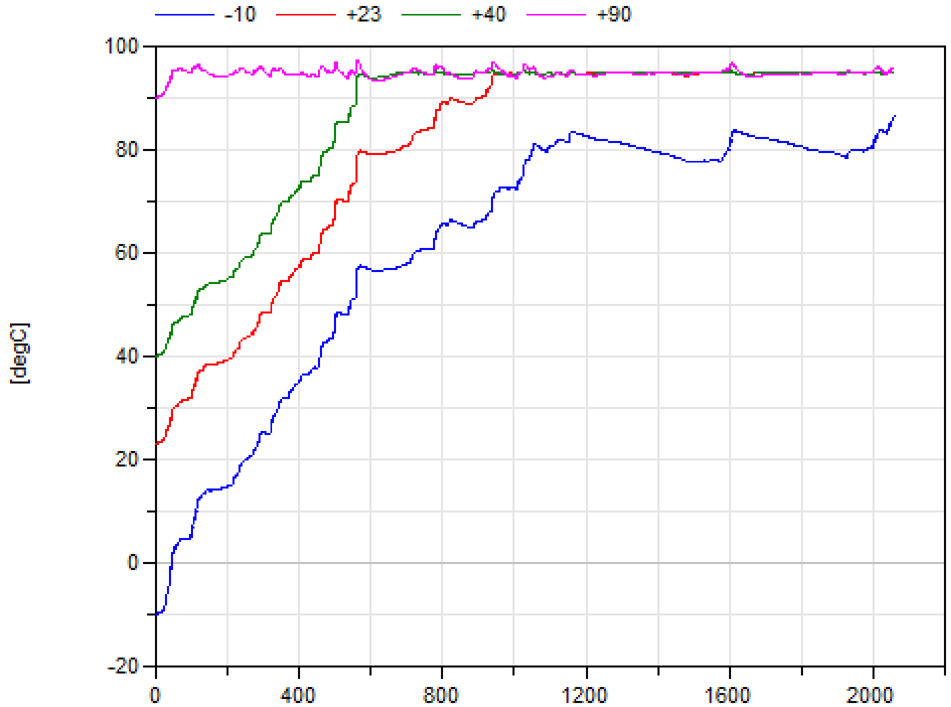


# Results ARTEMIS cycle (city + highway)

## Average fuel consumption (l/100km)




## Oil temperature (degC)



# Results

- With a heat flow of 100W, it takes 886s to heat the gearbox from -10 up to +90 degC.
- At a price of £0.15 per kWh, it costs £0.0037.

**<u>NEDC / ARTEMIS (city + highway):</u>**

Compare initial ATF temperatures: -10 vs. +23 degC

- Fuel economy benefit: 6.45% / 1.48%
- Fuel saved: 510 mL / 145 mL
- Savings: £0.56 / £0.16

Compare initial ATF temperatures: +23 vs. +90 degC

- Fuel economy benefit: 1.71% / 0.24%
- Fuel saved: 150 mL / 37 mL
- Savings: £0.17 / £0.04

Compare initial ATF temperatures: -10 vs. +90 degC

- Fuel economy benefit: 7.66% / 1.84%
- Fuel saved: 660 mL / 182 mL
- Savings: £0.73 / £0.20

CLAYTEX

# Further work

- Study the effects of pre-warming of the batteries and additional vehicle subsystems on performance and overall energy efficiency
- Emissions of pollutants: investigate a potential reduction on tailpipe emissions

CLAYTEX

# Conclusions

- The potential in fuel economy is real and could even be more significant if we pre-warm some additional vehicle subsystems.

- Pre-warming the gearbox could be very beneficial in a busy urban environment where the lubricant would usually take a long time to reach its ideal working temperature (see NEDC and ARTEMIS results).

CLAYTEX