Systems Engineering Specialists

Multi-domain vehicle dynamics models for Driver-In-the-Loop simulation

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 and simulation using the open standards: Modelica and FMI
- Business Activities
  - Engineering consultancy
  - Software sales and support
    - Dassault Systemes
    - rFpro
  - Modelica library developers
  - Training services
- Global customer base

SOLUTIONS PARTNER

EDUCATION PARTNER Certified

rFpro

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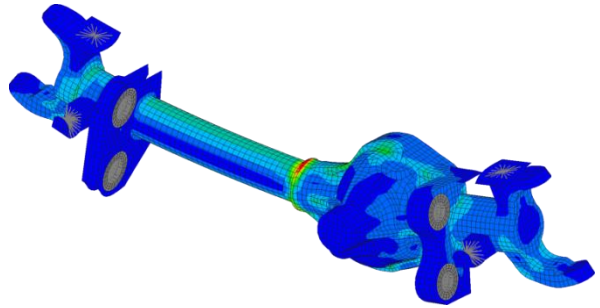
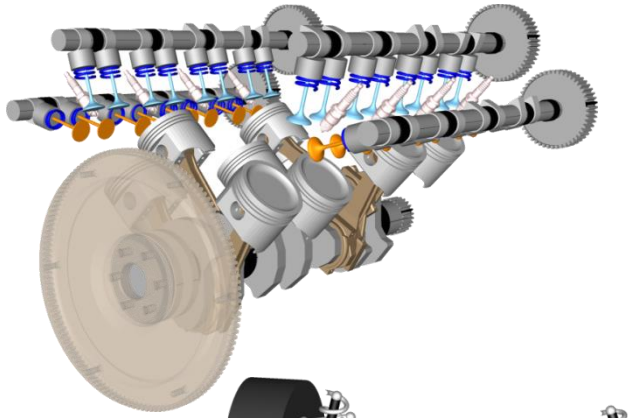
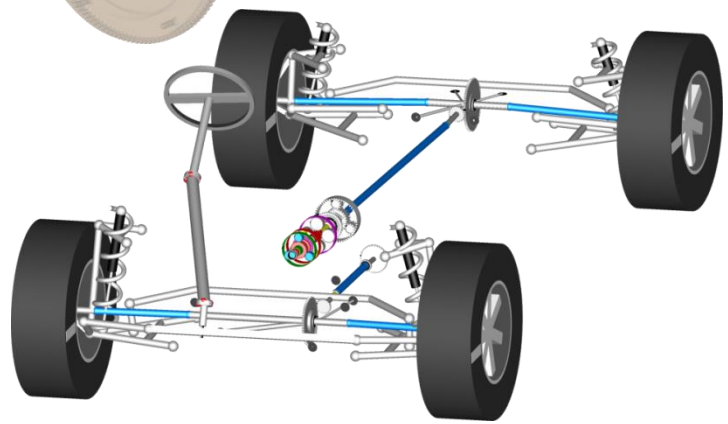
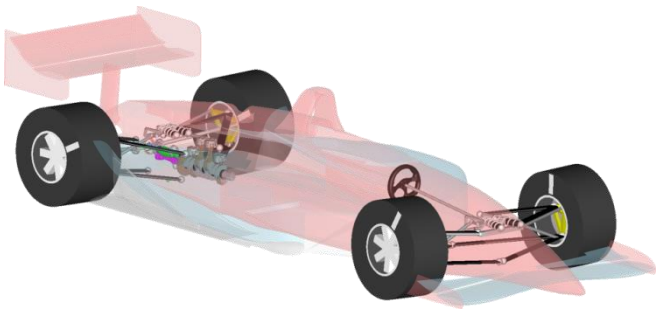
What does Claytex do?



- Engineering consultancy
  - Process development and improvement
  - Model development and analysis services
  - Integration of models with HiL, MiL, DiL tools and processes
    - Optimisation of models for real-time fixed step simulation
    - Coupling to Driver-in-the-loop platforms including commercial solutions from Ansible Motion and McLaren Applied Technologies and bespoke solutions
- Software distributors
  - Dassault Systemes partner specialised in Systems Engineering tools: Dymola, Reqtify, ControlBuild, AUTOSAR Builder and CATIA Systems portfolios
  - rFactor Pro: DiL simulators for vehicle dynamics engineering
- Modelica library developers
  - Solutions for: Engines, Powertrain Dynamics, Vehicle Dynamics, DiL and related libraries compatible with Dymola
- FMI tool developers
  - Including the FMI Blockset for Simulink







Introduction

- Driving simulators increasingly used in both Motorsport and Automotive
- Originally introduced in Motorsport for driver training
- Allows tests to be completely safe and in repeatable conditions
- Due to testing restrictions now used to evaluate new designs, new technologies and work on car setup before arriving at the race track
- Broad range of approaches to suit different needs
  - Desktop system
  - Small motion systems with 3-4 dof
  - Full motion platforms with 6 dof
    - Entertainment systems
    - Engineering development systems

Example Motorsport System

- Simulators for engineering development
- Ansible Motion Series 1 platform
  - 6 degrees of freedom
  - Large excursions possible on all axes
  - High frequency range for realistic motion cueing
- rFactor Pro graphics, sound and track data
  - Low latency and high bandwidth offering the fastest video & audio pipelines
  - Extensive range of tracks available for Motorsport and Automotive applications
- Dymola based vehicle dynamics model
  - Multi-domain vehicle model

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Example Desktop System

- Able to evaluate baseline capability of a vehicle or enable detailed assessment and development of a control system, steer-by-wire system, etc.
- Key features:
  - rFactor Pro provides the core capability
    - Range of test scenarios (race tracks, proving ground)
    - High quality graphics on multiple monitors
  - Dymola vehicle model
    - Full MultiBody chassis model
    - Multi-domain vehicle model
  - Telemetry system
  - Steering wheel
    - Gaming systems or sophisticated handwheel motor
      - Sensodrive, Ansible Motion, etc.
  - 1 PC used for the complete simulator system
  - Connect laptop with calibration and telemetry tools
  - HiL system
    - Concurrent, dSpace, etc.

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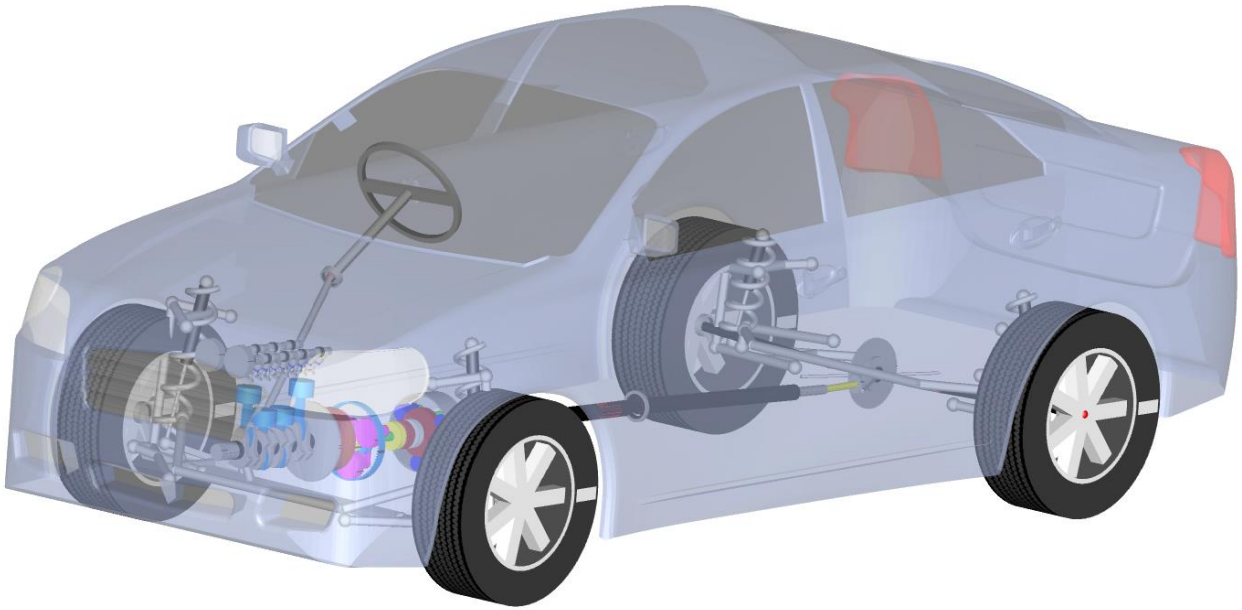
Physics Model

- Has to provide an accurate representation of the complete vehicle
  - Tyres
  - Suspension
  - Powertrain
  - Multi-domain system: mechanics, control, electrical, fluids, etc.
- Has to run in real-time, typically 1kHz for a full motion driving simulator
- Has to give the driver the right “feeling” about the behaviour of the car
  - Feedback through the steering wheel
  - Transient behaviour



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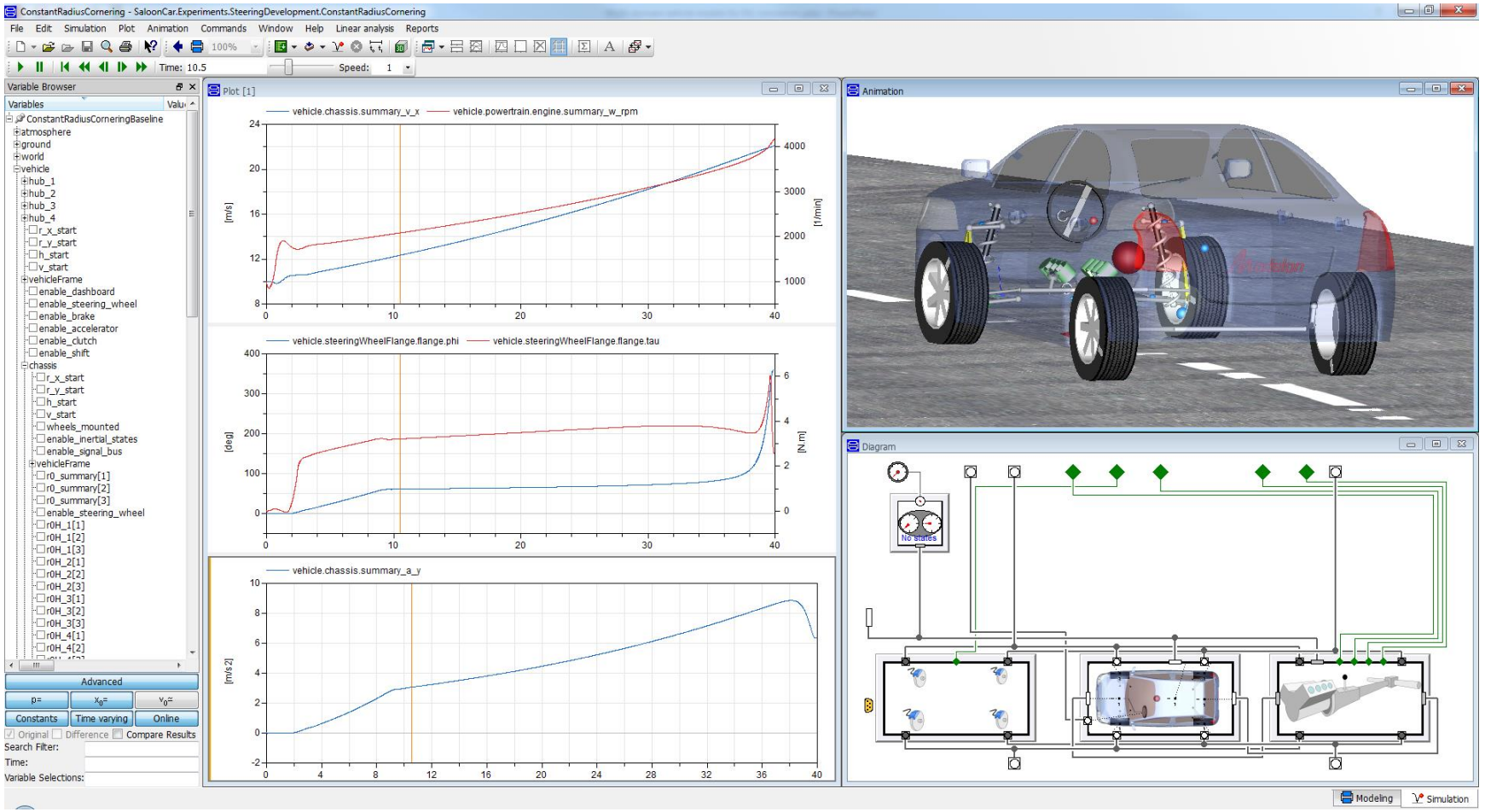
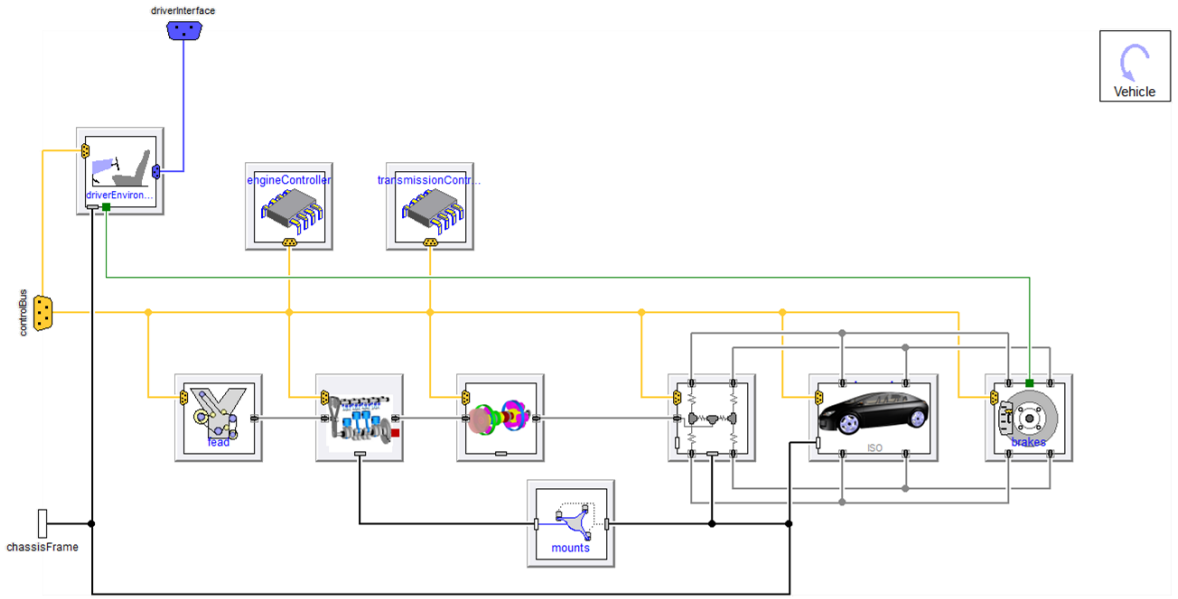
Dymola

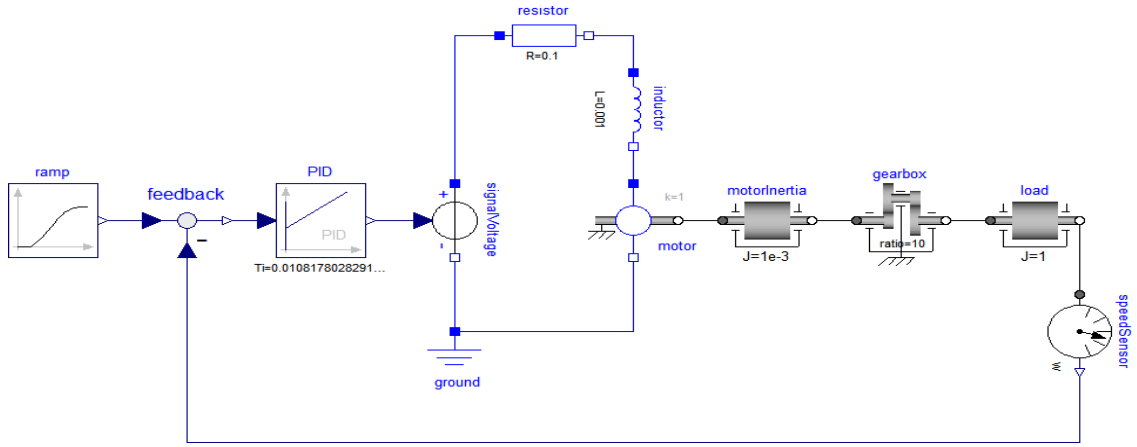
- Component orientated, physical modelling tool
- Modelling and simulation of systems integrating multiple physical domains
- Based on Modelica
- Supports the FMI standard
- Application libraries to model the whole car
- Part of the CATIA brand



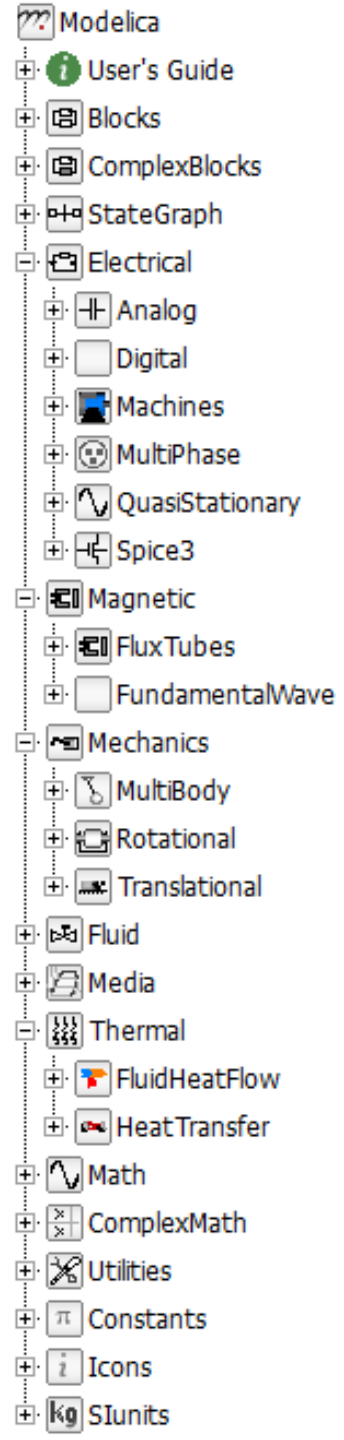
Component Orientated Modelling

- 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



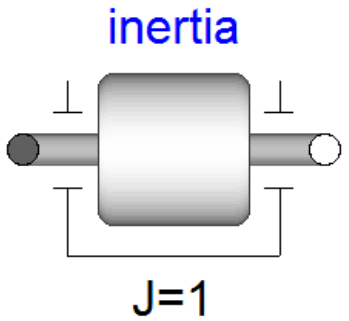


- Models are defined using the Modelica modelling language
  - A generic modelling language
  - Design for convenient, component orientated modelling of complex multi-domain systems
  - Models are defined as differential algebraic equations (DAE)
- A freely available, open source, standardised modelling language
- Developed and maintained by the Modelica Association
  - An independent, international not-for-profit organisation
  - Established in 1996
  - Currently over 100 members from academia, tool vendors and industrial end-users
    - Anyone can get involved
- The Modelica Standard Library contains basic models in many engineering domains



Model Definition

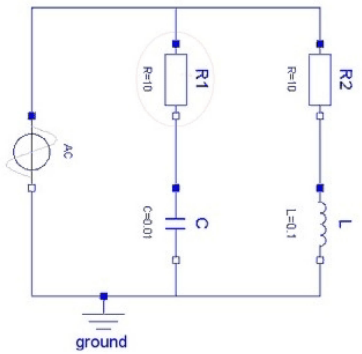
- Models are defined using the Modelica modelling language



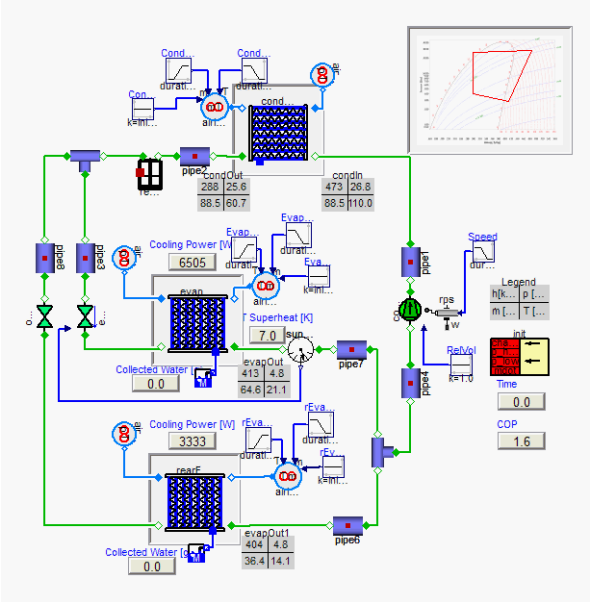

```
model Inertia
  extends Interfaces.Rigid;
  parameter SI.Inertia J=1 "Moment of Inertia";
  SI.AngularVelocity w "Angular velocity";
  SI.AngularAcceleration a "Angular acceleration";
equation
  w = der(phi);
  a = der(w);
  flange_a.tau + flange_b.tau = J * a;
end Inertia;
```

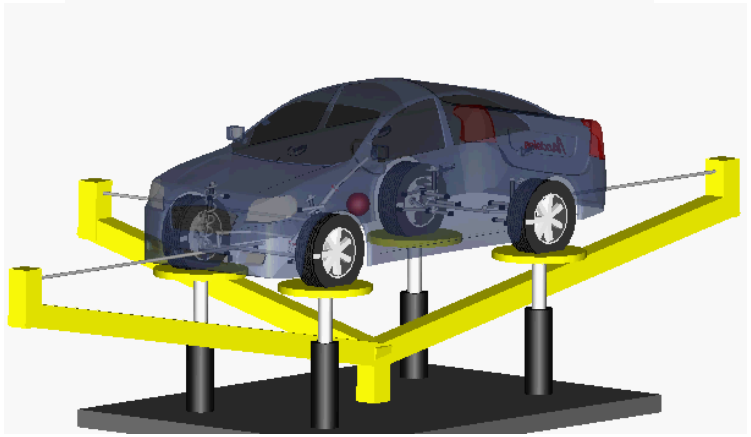
- Symbolic manipulation automatically transforms the models into efficient simulation code
- Can deliver real-time simulation performance of Vehicle Dynamics models with over 100,000 equations (at 1kHz)
- Supports multi-threading to make full use of multi-core machines

DAE:

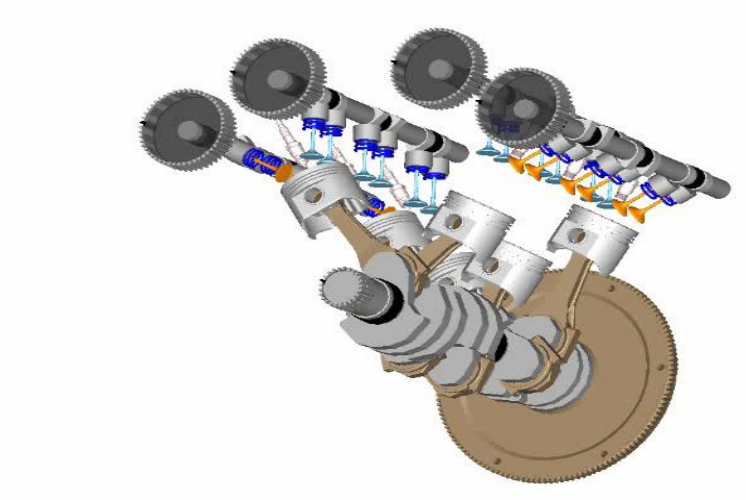


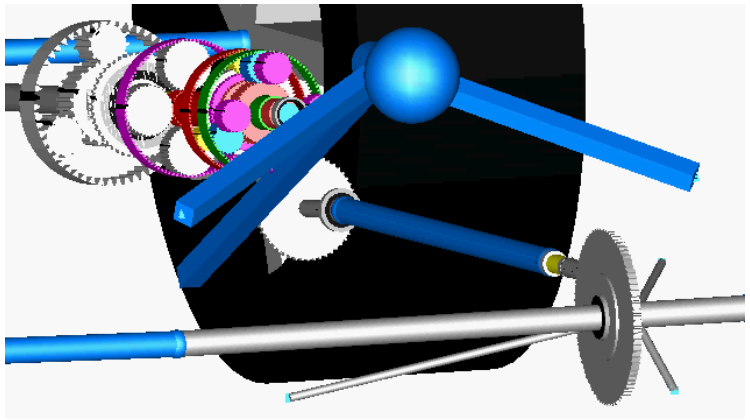
Modelica Application Libraries





- Air Conditioning
- Electric Power
- Engines
- FlexBody
- Flexible Bodies
- Flight Dynamics
- Fuel Cell
- Heat Exchanger
- Human Comfort
- Hydraulics
- Liquid Cooling
- Pneumatics
- Powertrain Dynamics
- Simulator
- Smart Electric Drives
- SystemID
- Terrain Server
- Thermal Power
- TIL Suite
- Vapor Cycle
- Vehicle Dynamics
- VDLMotorsports
- XMLReader





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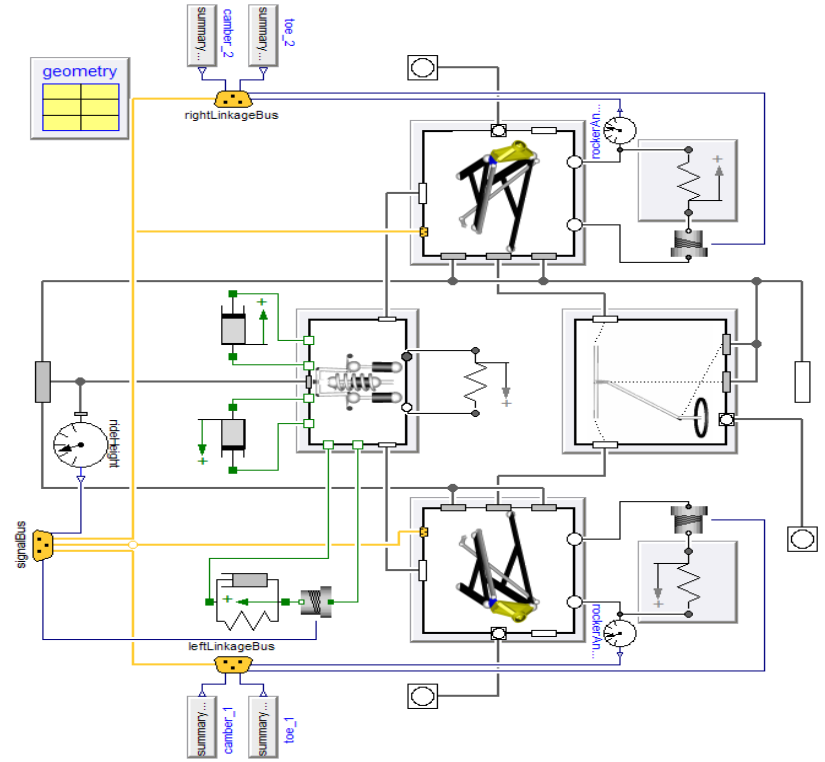
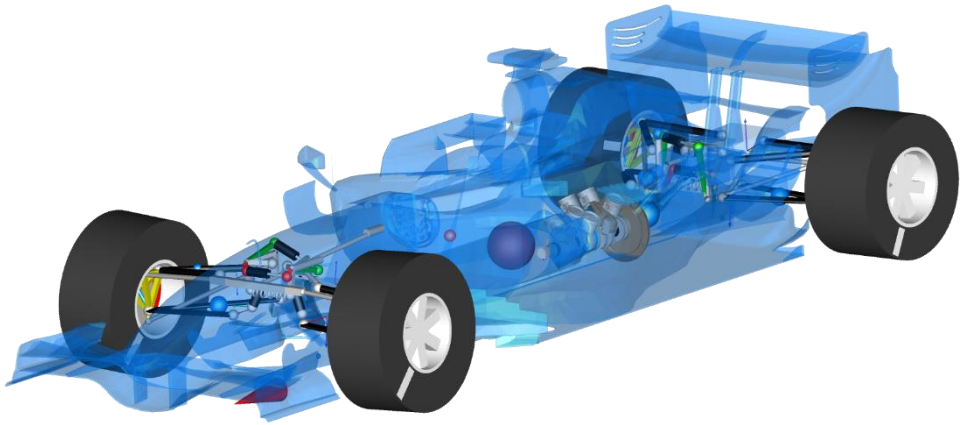
Vehicle Dynamics for Motorsports

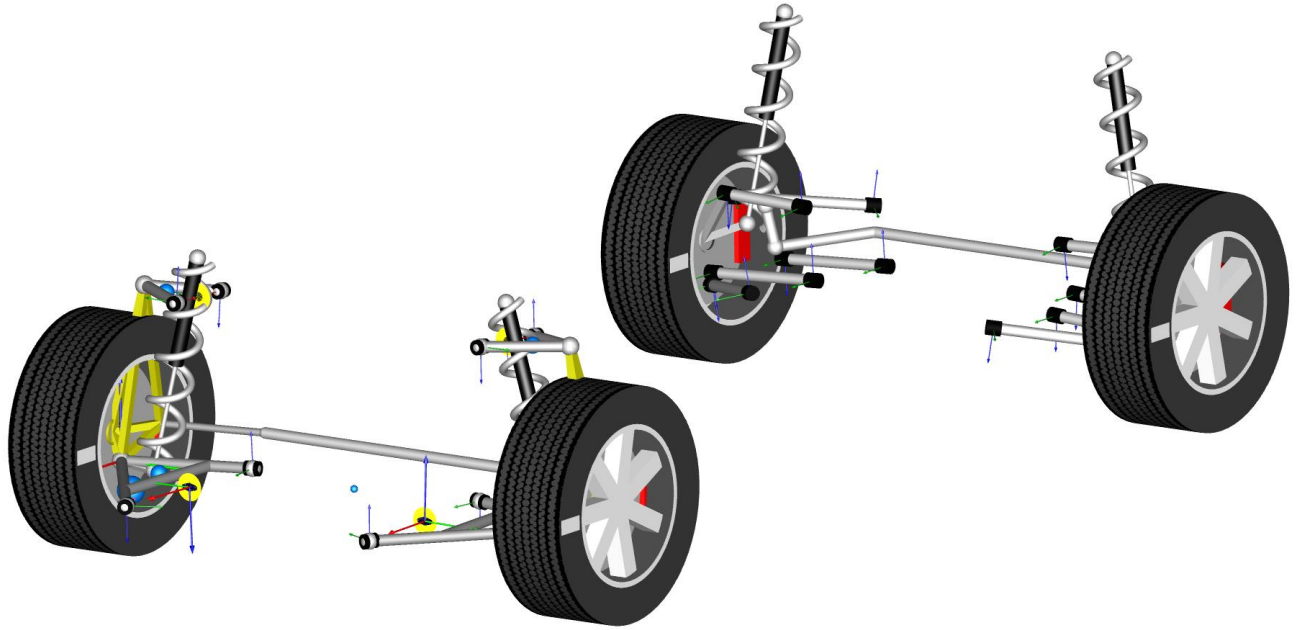
- VDLMotorsports Library
  - Add-on to Vehicle Dynamics library
  - Used in Formula 1, IndyCar, GP2, NASCAR and sports car racing
- Includes adjustable suspension
  - Specify shim thickness to adjust track rod, pushrod, etc.
- Kinematic and compliant suspension models
- Includes setup and quasi-static experiments
- Real-time capable MultiBody models
- Open and extendible
- Simulator Library provides out-of-the-box integration with rFactor Pro for DiL





Vehicle Dynamics for Road Cars

- Vehicle Dynamics Library
  - Template based approach to modelling
- Library of MultiBody suspension templates
  - McPherson, double wishbone, multi-link, trailing arm, …
  - Open and extendible to allow you to add your own templates
- Kinematic and compliant models
  - Non-linear bushes or ideal joints
  - Structural compliance effects
- Wide range of experiments
  - Quarter car, half car, whole chassis, full vehicle
  - Closed loop and open loop driver models
- Provides models for real-time simulation
- 3D Road Definition and support for rFPro Terrain Server and OpenCRG



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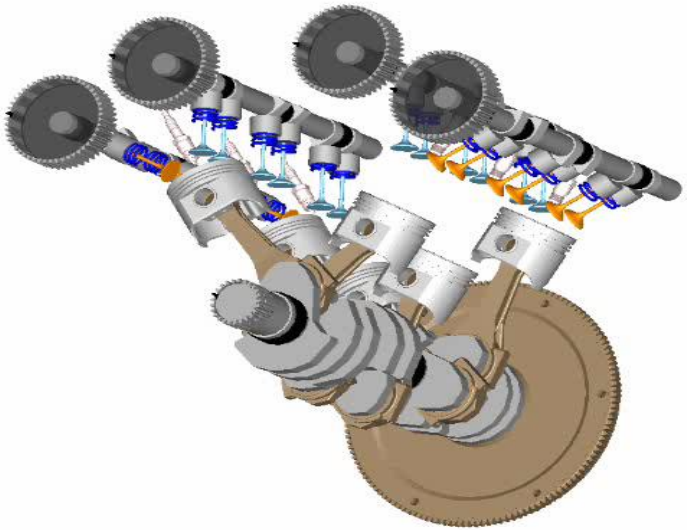
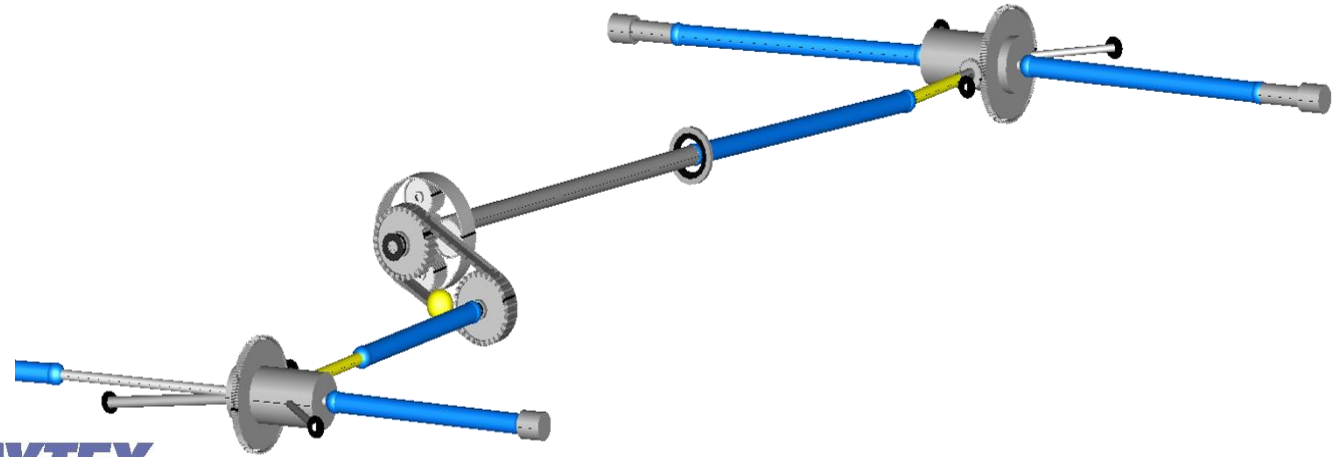
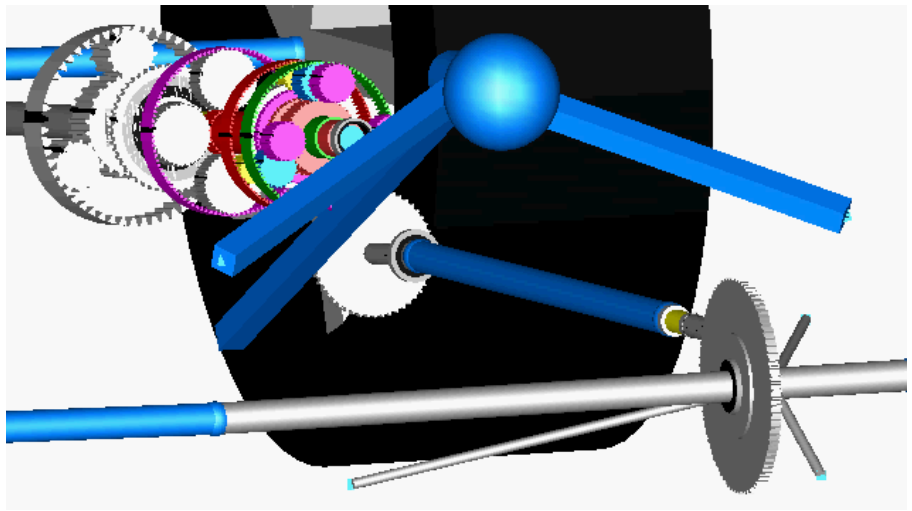
Powertrain Modelling

- Engines Library
  - Mean value and Crank angle resolved models
  - 1D thermofluids for the air-path, fuel-path, cooling, lubrication
  - MultiBody mechanics for complete engine
  - Thermal network
- Powertrain Dynamics Library
  - MultiBody mechanics for transmission and driveline
  - Thermal effects in friction
  - Variable fidelity models to support fast drive cycle simulation and detailed driveability analysis

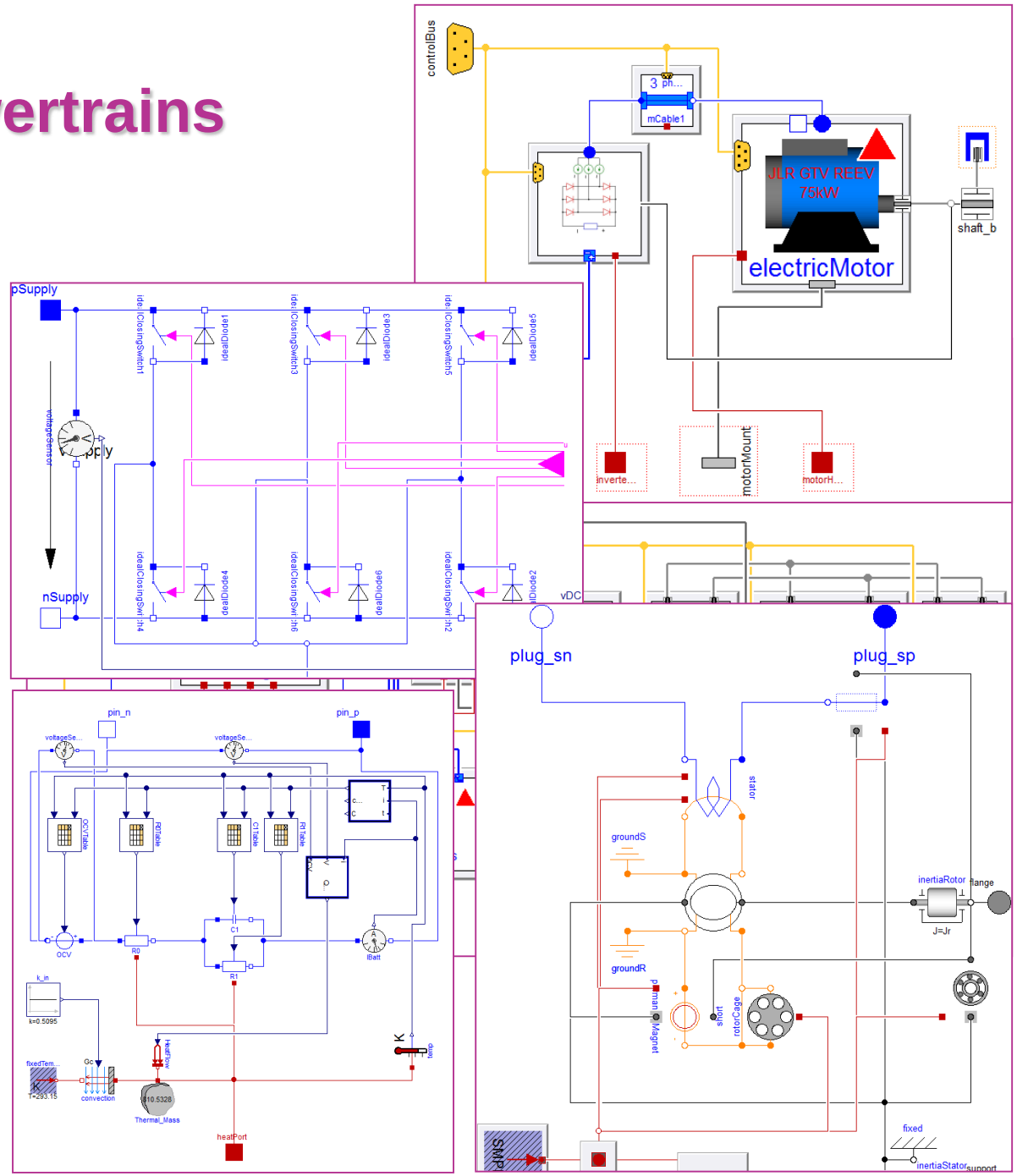






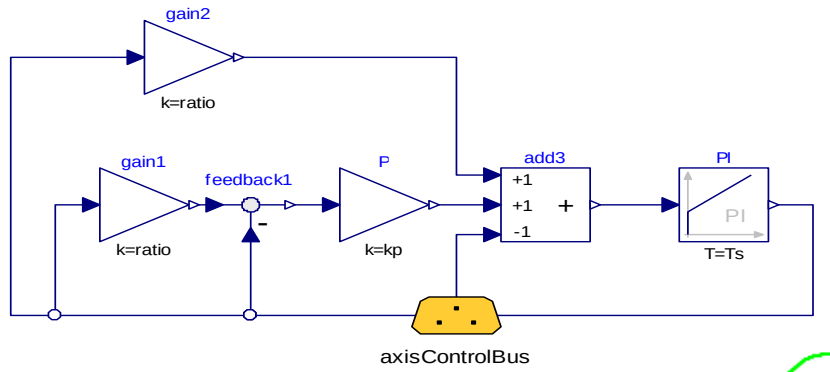
Hybrid Powertrains

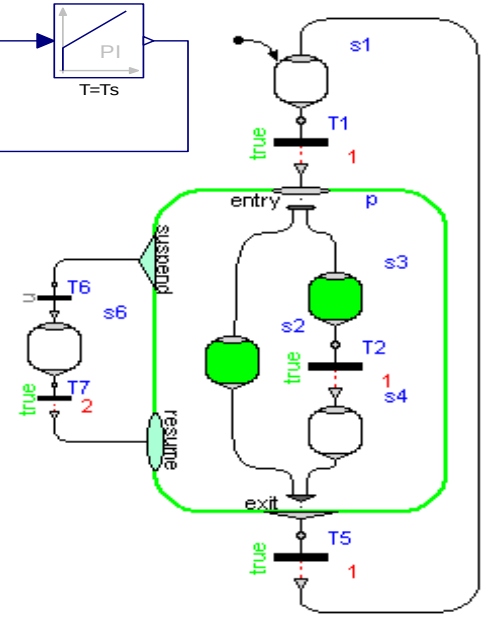
- Batteries
  - Parameter estimation functions to define the cell models from test data capturing electrical, thermal and ageing effects
  - Cell models are equivalent electrical circuit models
  - Model architecture to conveniently build the module and pack models from a validated cell model
  - 1D thermofluid approach for the cooling systems
- Electric Motors and Power Electronics
  - Motor models for fast simulation or detailed transient analysis
  - Power electronics can be ideal power balanced models or include switching effects
  - Field orientated control built into motors
  - Thermal effects in the power electronics and motors

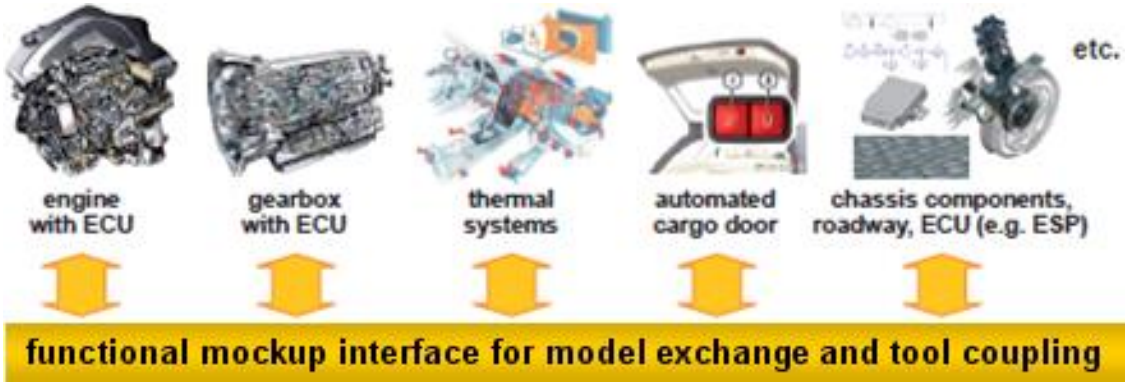


Control Systems

- Control systems in Dymola
  - Block diagrams
  - Finite state machines
  - Procedural code
- Dymola includes state of the art controller design tools
  - Model inversion to support model based control design
    - For example: use the same bicycle model as a reference model and in feed-forward design
  - Linearisation of physical models
- Integrate existing controllers
  - Import FMI compliant models
    - FMI is an open standard for model exchange supported by over 50 engineering tools
    - Simulink models can be compiled to be FMI compliant using a Simulink Coder target provided with Dymola
  - Import c-code
    - Dymola supports the use of c-code within a Modelica model
  - Export the Dymola model to be FMI compliant and use in other tools
    - e.g. FMI Blockset for Simulink, Silver, etc.

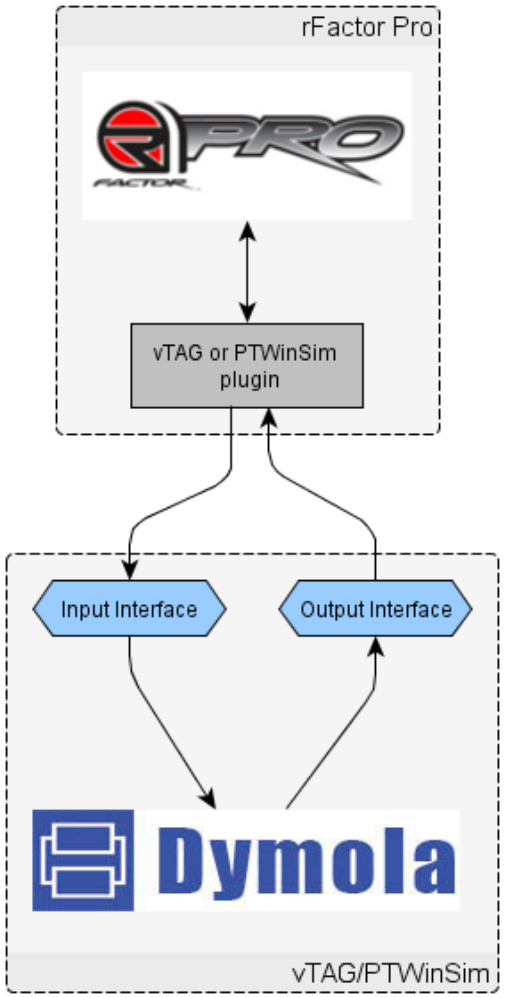






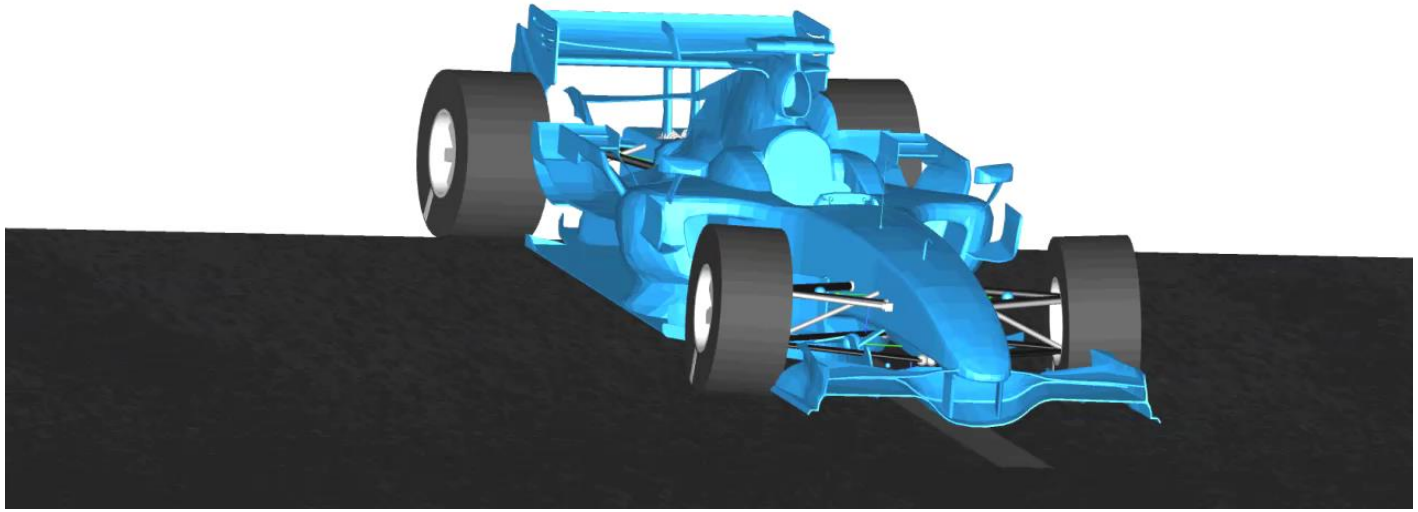
Driver-in-the-Loop Simulators

- Claytex have developed a set of solutions that enable Vehicle Dynamics models to be used with rFactor Pro
  - Simply plug the vehicle model in to a template and execute the build function
- Compiles model to work with McLaren Electronics vTAG and PTWinSim environments
  - Soft real-time environments
- Compatible with the HiL environments using the Dymola tools (dSpace, xPC, etc.)
- Solution proven on several motion platforms
  - Ansible Motion, McLaren Electronics, MOOG
- Also used for static simulation environments
- Supports full range of rFactor Pro features
  - High Definition Terrain Server and multiple tyre contact points
  - Collisions



Formula 1 2014 Powertrains

- Dymola is used by F1 teams, NASCAR and IndyCar
- Using Dymola it was possible for the teams to simulate the 2014 powertrain as part of a complete vehicle model
  - Engine performance and efficiency
  - MGU-H and MGU-K strategies
  - Thermal management of all systems
  - Impact on vehicle dynamics of higher torque output and delivery



- Why is Dymola popular in Motorsport?
  - Extensive range of application libraries
  - Based on Modelica which means the models are open and extendible
  - Powerful modelling language to implement new ideas from first principles and explore the behaviour
  - The same model can be shared across the team and deployed for different applications
    - Desktop, HiL, SiL, DiL, trackside, …

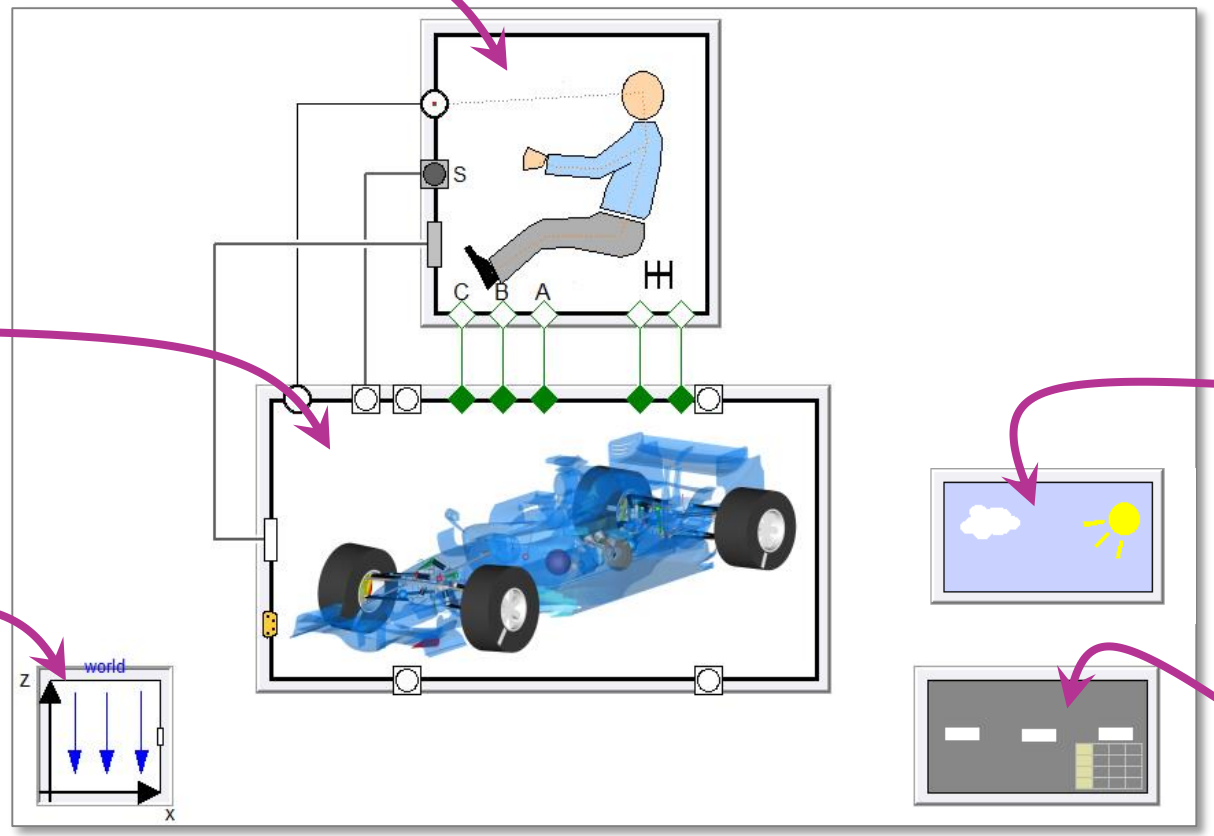
CLAYTEX

Simulation experiment

Driver model
- Throttle
- Brake
- Steering
- Gears

Vehicle model
- Powertrain
- Chassis
- Brakes
- Tyres

World
- Coordinate system
- Gravity
- Animation settings

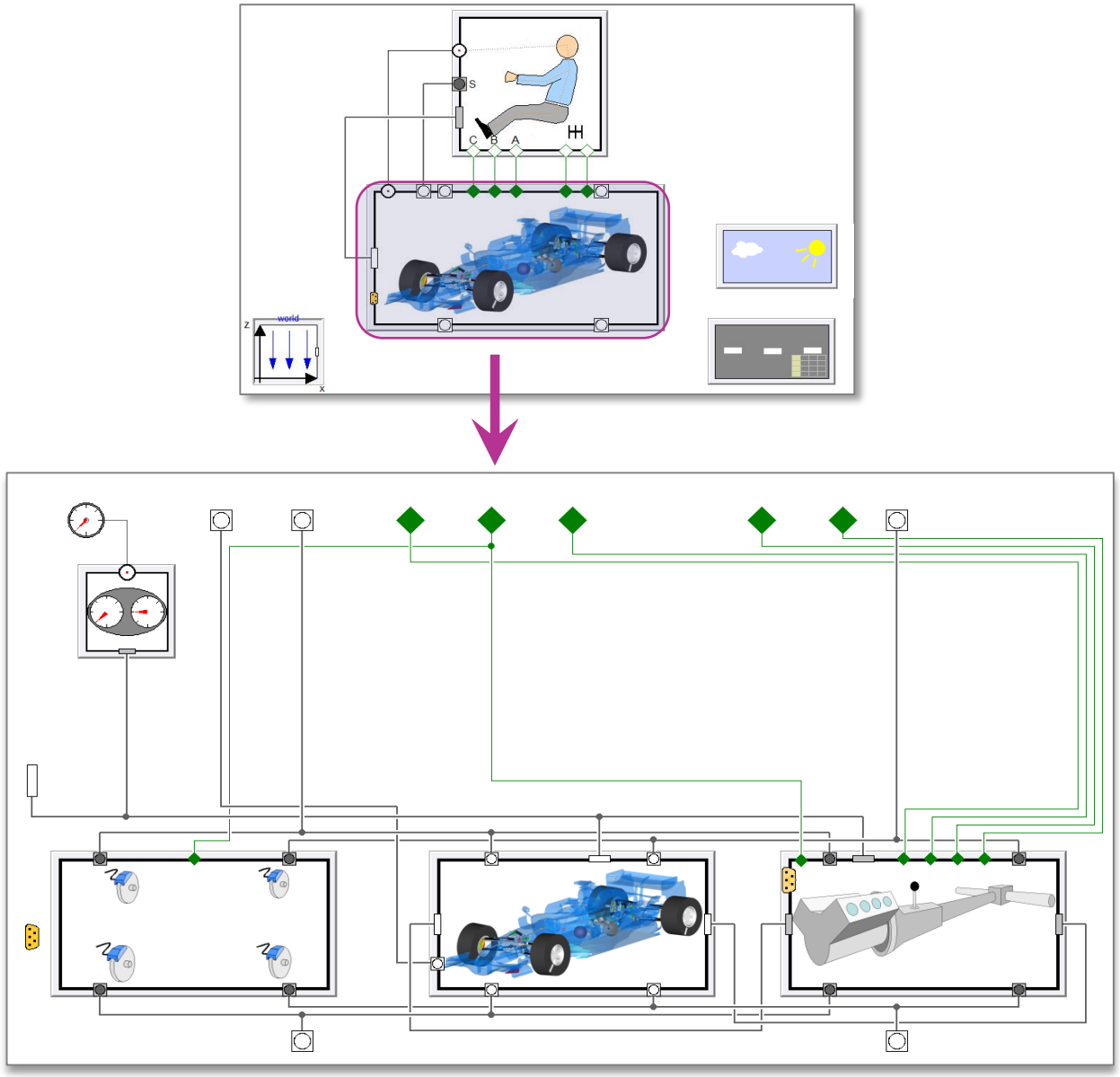


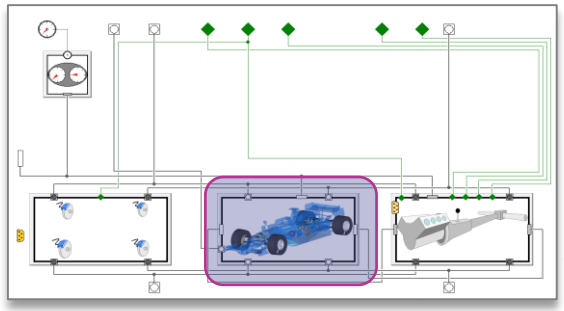
Atmosphere
- Pressure
- Density
- Wind speed and direction

Road model
- 3D road surface model
- Inclination
- Friction coefficient of surface

Vehicle model

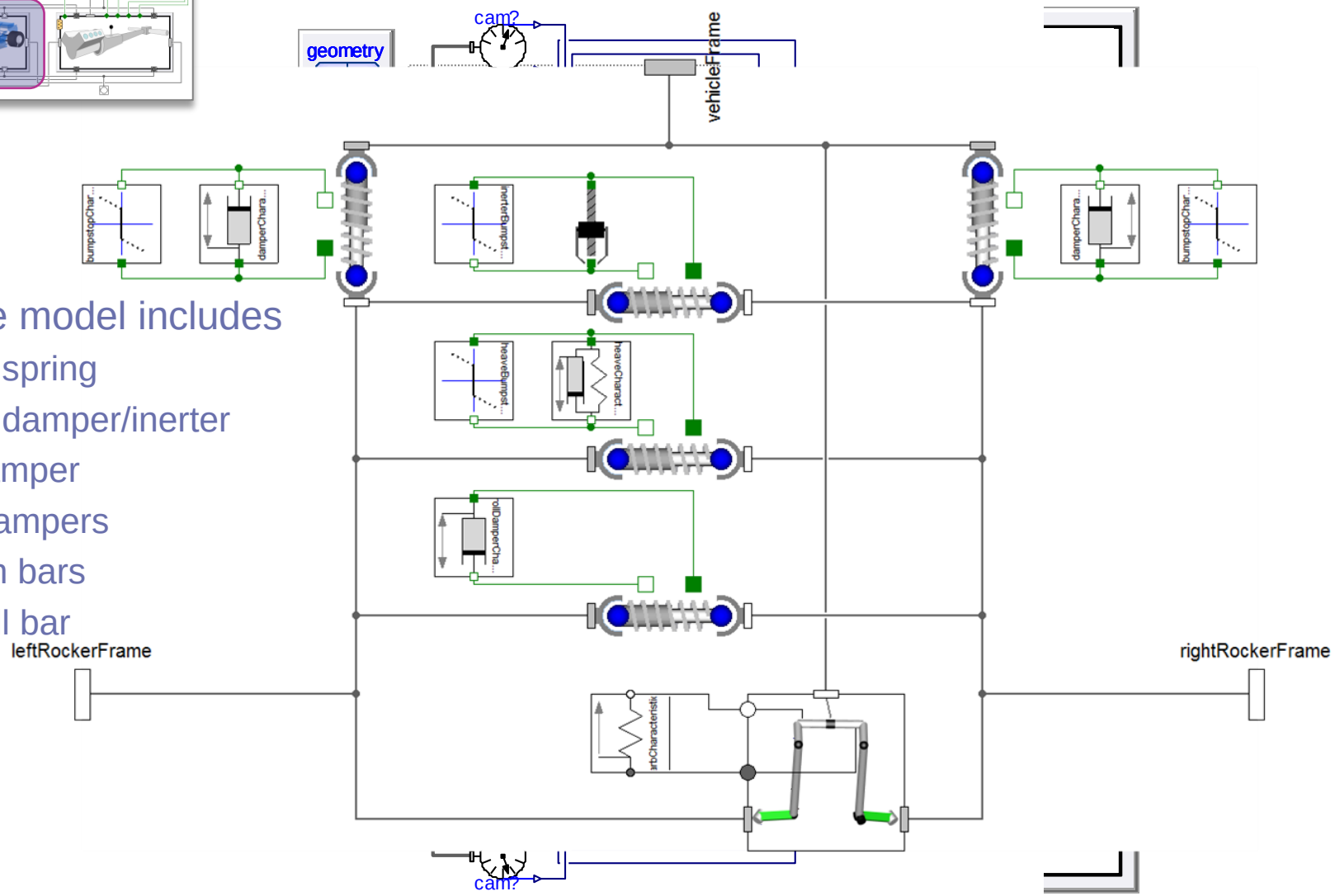
- Vehicle Dynamics
  - Multibody chassis
  - Pacejka tyre models
  - Aerodynamics
  - Ground impact
- Brakes
- Powertrain
  - Engines
    - Power unit ICE and cooling
  - Electrical libraries
    - MGU-K
    - MGU-H
    - Energy Storage
  - Driveline
  - Gearbox



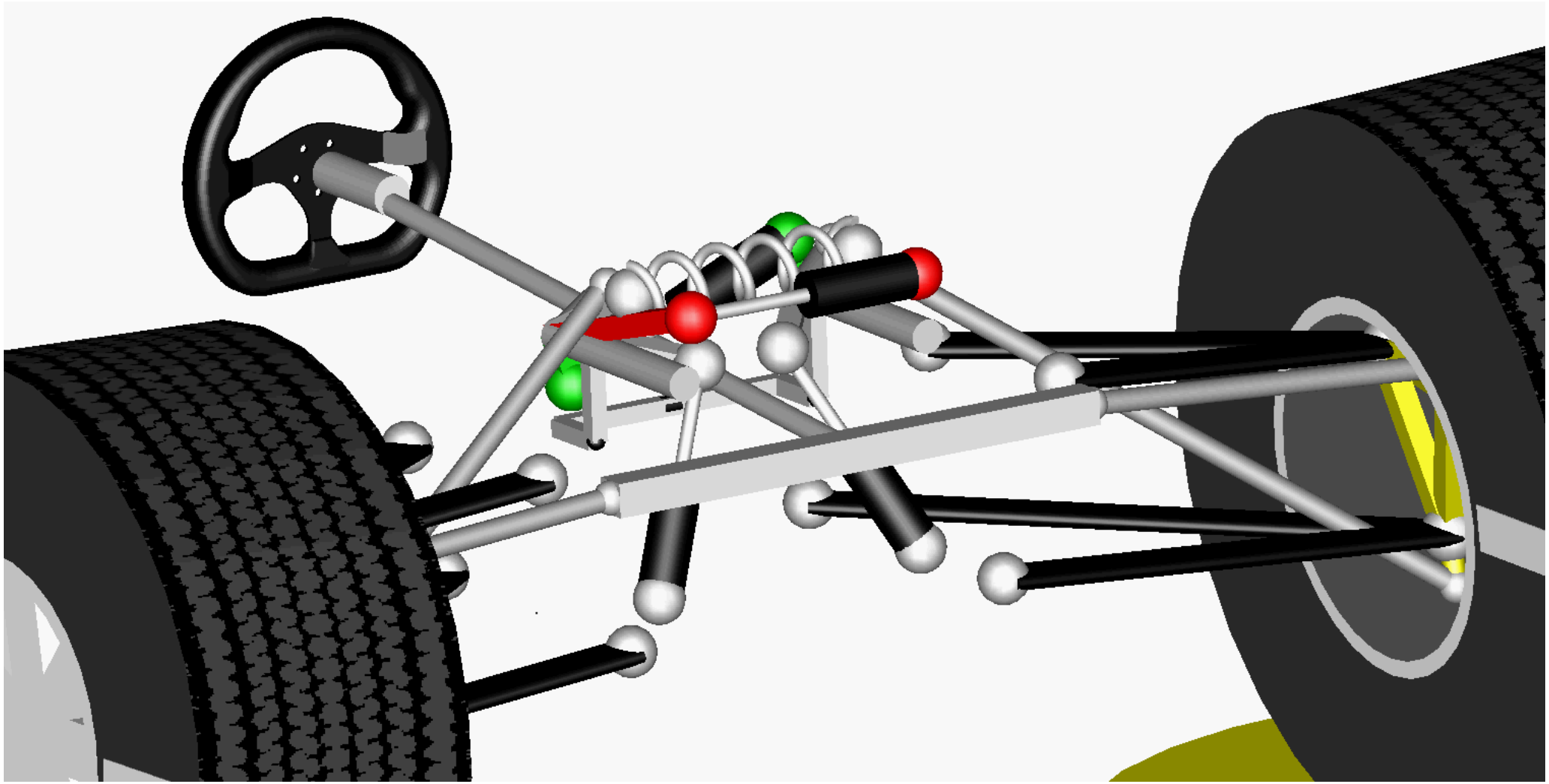


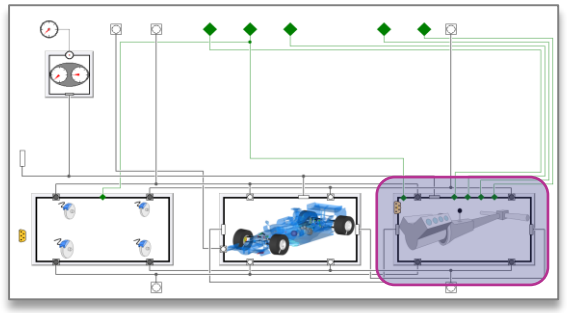
Chassis and suspension

- Real-time model includes
  - Heave spring
  - Heave damper/inerter
  - Roll damper
  - Ride dampers
  - Torsion bars
  - Anti-roll bar



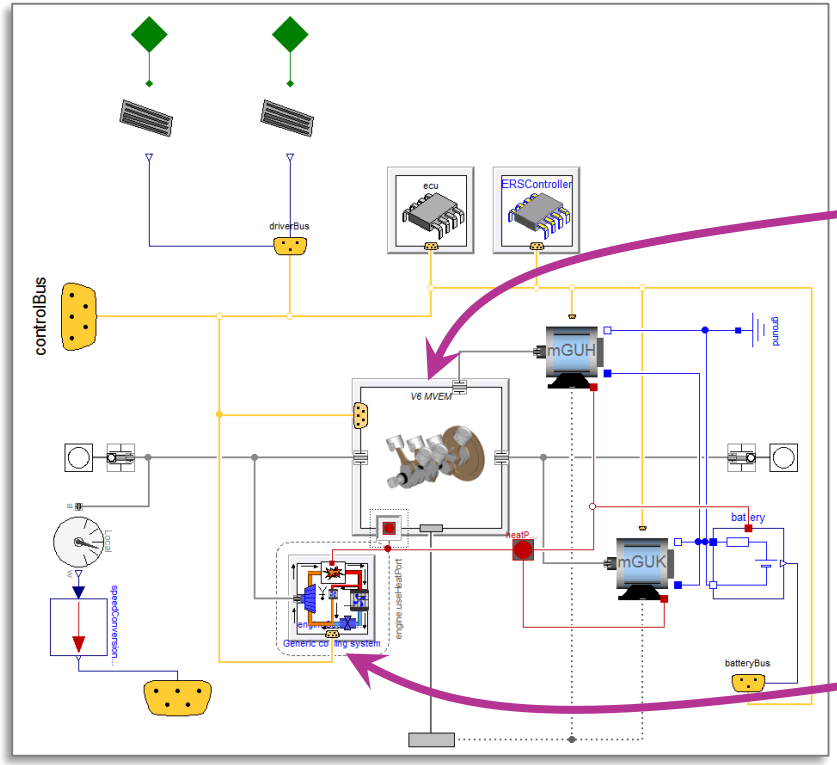
Animation of front suspension

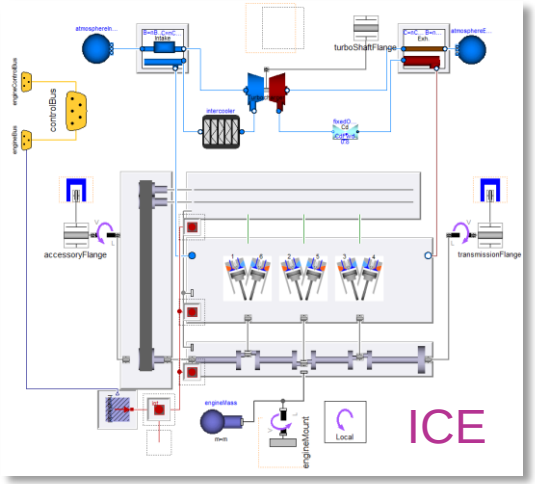


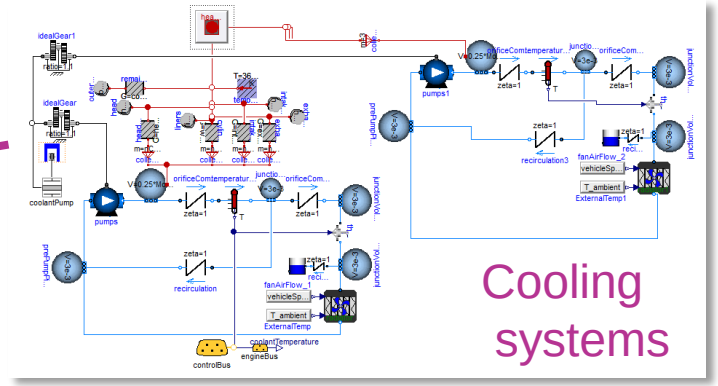


ICE, MGU and Coolant System integration

- Parameterised mean value engine model is pressure charged by means of a mapped turbocharger and integrated with the MGU-H and MGU-K in the power unit model below:



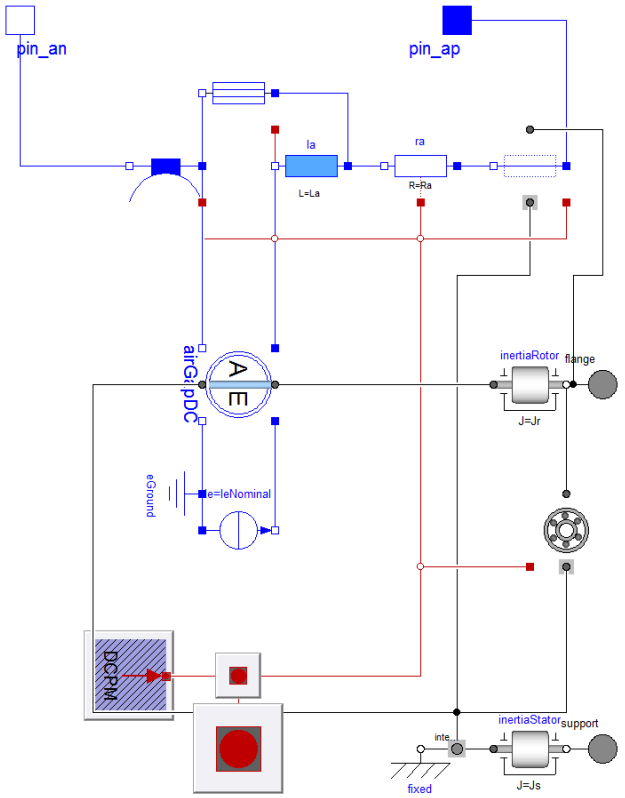




MGU and Energy Storage representation

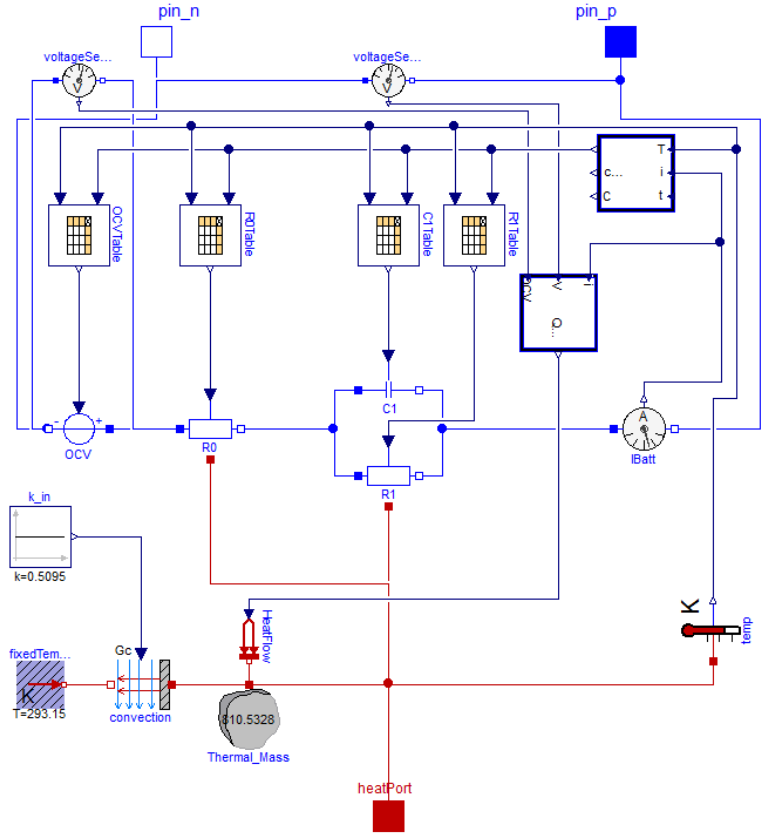
MGU-K and MGU-H

- Electrical effects
  - Internal resistance
  - Heat losses
  - Inductance
- Mechanical effects:
  - Inertia
  - Frictional losses
  - Heat rejection
  - Torque reaction into MGU support



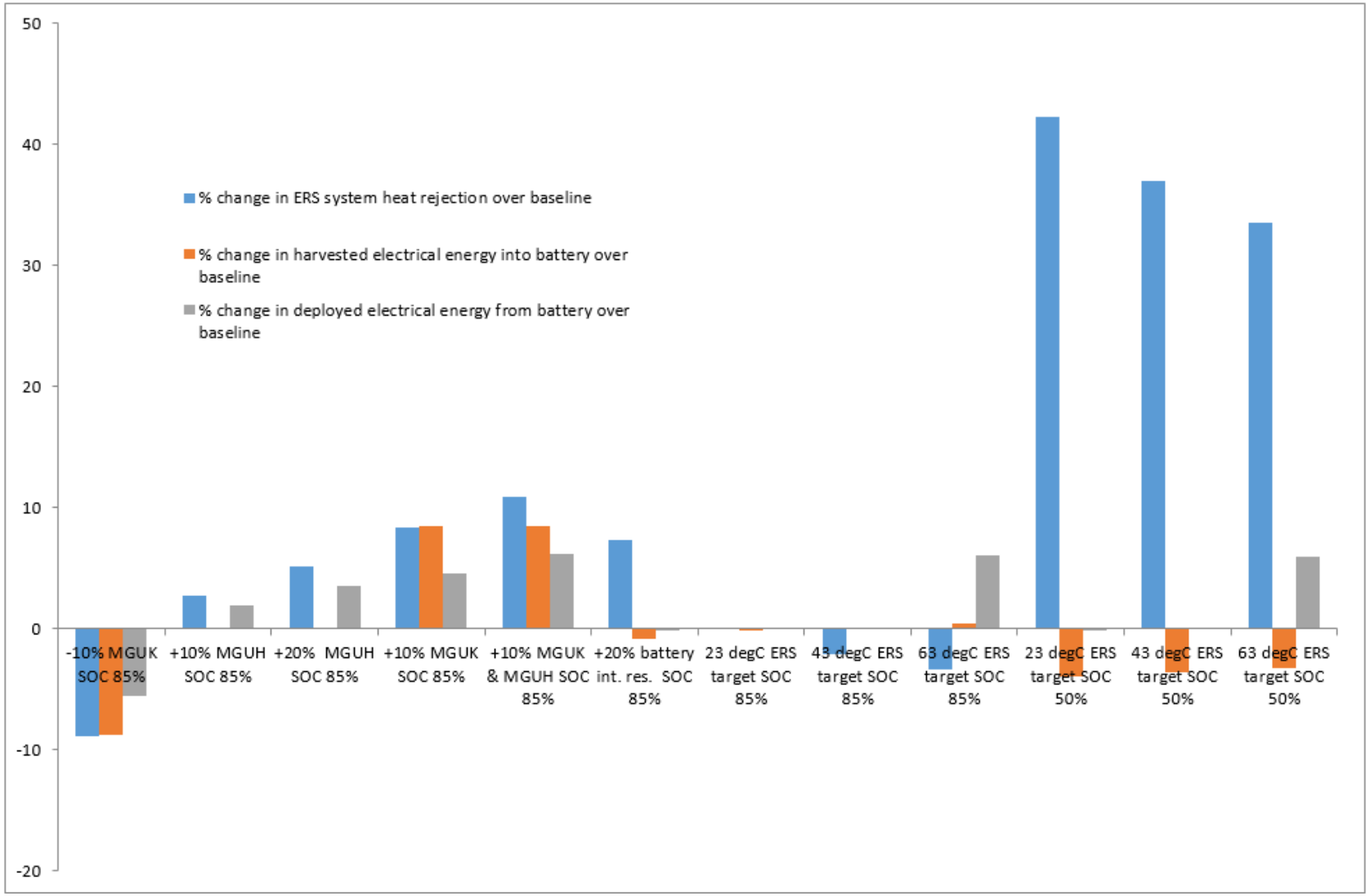
Energy Storage

- Equivalent Circuit model
  - Internal resistance
  - Diffusion limitation
  - Thermal losses
  - Resistance
  - Capacitance
  - OCV with temperature & SOC dependency



Simulation results

- Ability to interface multiple domains to understand the whole system dynamics
- Multiple ERS control strategies were evaluated using physical system models
- Models are real-time capable and can be used within a driver simulator



Driver-in-the-loop

- Dymola models can then be exported to run as part of a driving simulator
  - Run the model directly within rFPro
    - McLaren Electronics vTAG or Podium Technologies PTWinSim
  - Run the model on a HiL system
    - Concurrent, dSpace, etc.
- Technology also supports road car applications
  - Same motion platform with different cockpit
  - Urban environments and proving ground rather than race tracks to drive on

Videos from Ansible Motion and rFPro

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Summary

- Modelica and Dymola can be used to create multi-domain vehicle models suitable for use in Driver-in-the-Loop applications
  - MultiBody vehicle dynamics models
  - Mean value engine models
  - Electrical and thermal models
  - Control systems
- Using Dymola, new design ideas and concepts can be quickly modelled and compiled for use in the simulator
  - Enables real drivers to start evaluating these ideas at a very early stage in the development process
  - The simulator usage increases and is brought earlier in to the development process
- Supports HiL integration to enable calibration and validation of real controllers

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