Systems Engineering Specialists

Simulation of the complete race car to improve efficiency

Autosport International Show 2016

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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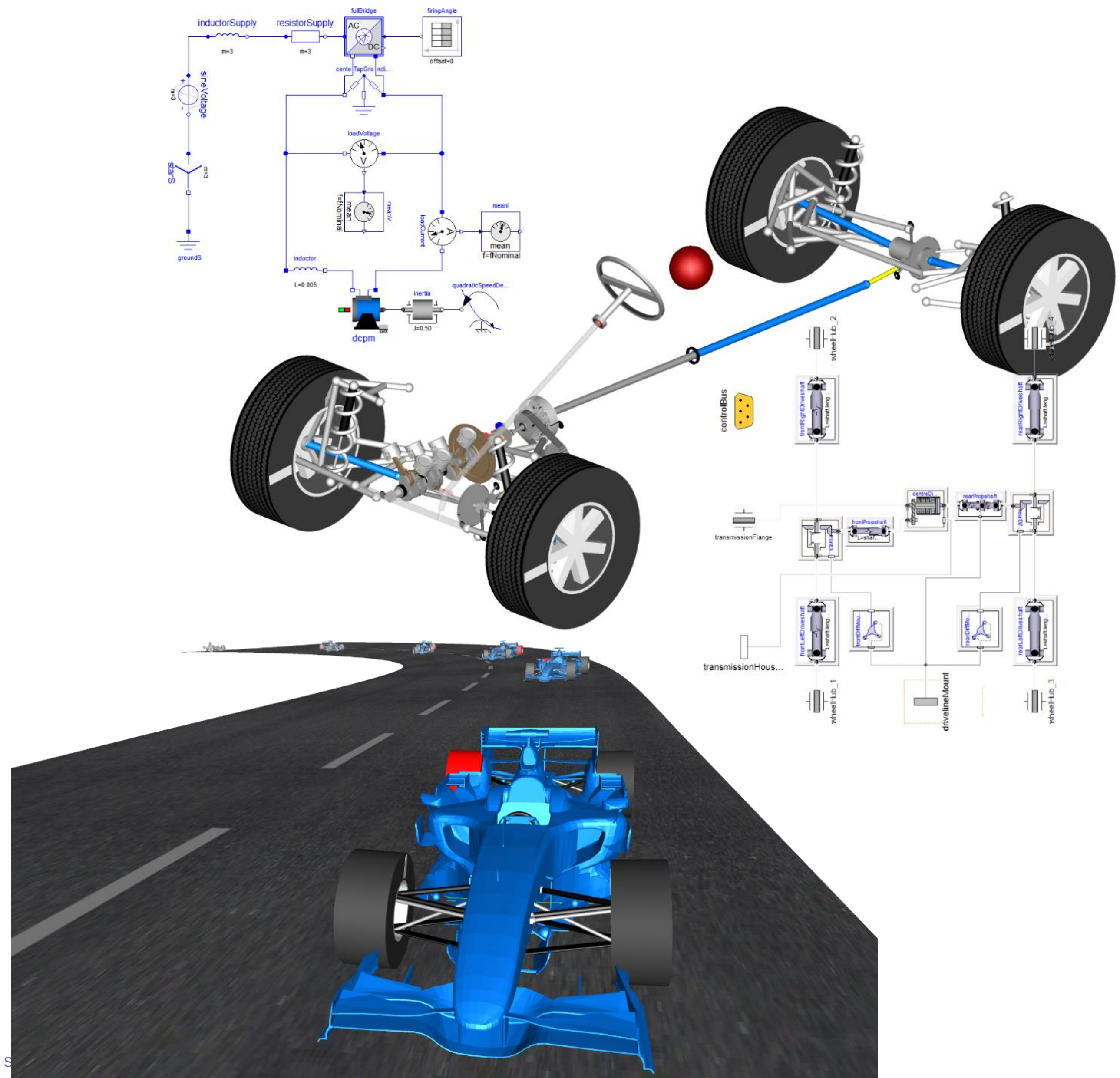
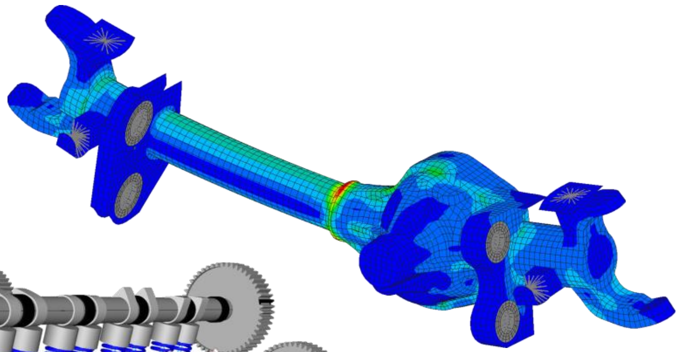
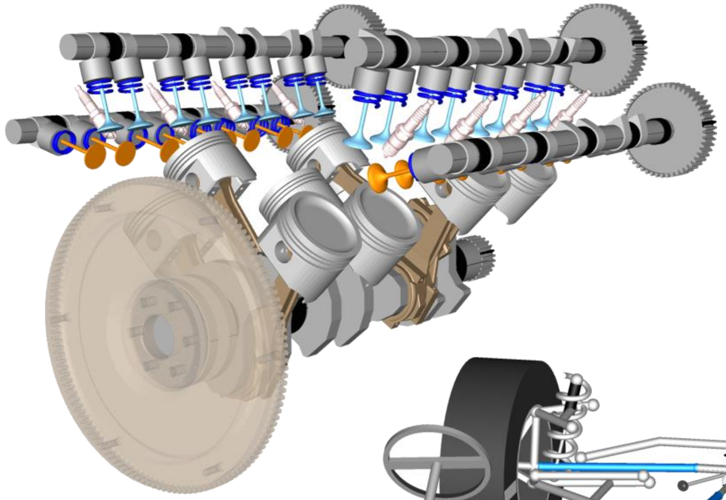
Engineering Consultancy

- Focused on Systems Engineering, Modelling and Simulation
- Active in multiple industries
- Examples:
  - Development and validation of models
  - Analysis of systems using existing tools based on Dymola, Simulink, etc.
  - Development and integration of models with driving simulators
    - From desktop simulators to high performance full-motion simulators in Formula 1 Indycar, and NASCAR
  - Development of bespoke tools to support Systems Engineering
    - Translation of models between tools/languages
    - Integration of models in to existing analysis tools and processes
  - Process development and improvement
    - Requirements Management, Model Specification, Model Management, etc.

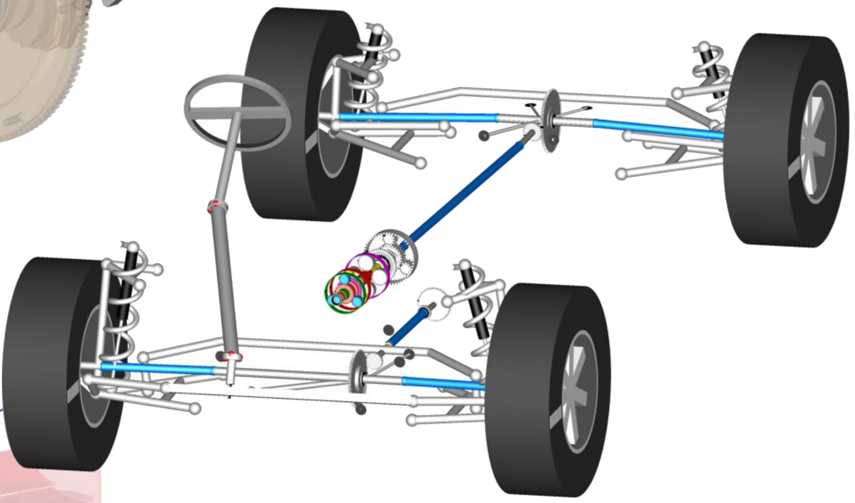


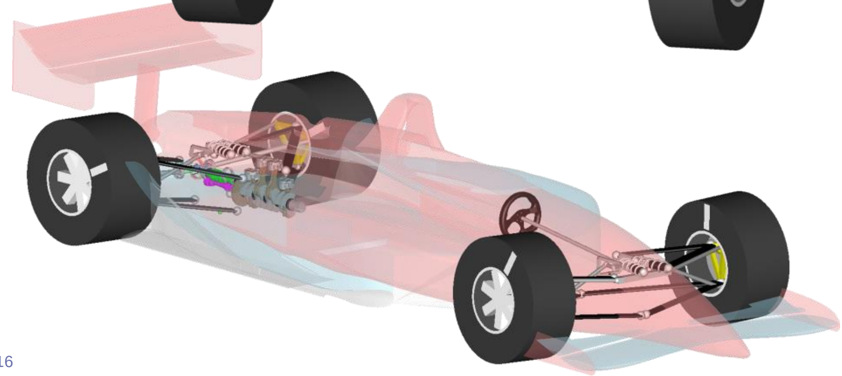
Modelica and FMI Development





- Engines Library
  - Mean value and crank angle resolved engine models
- Powertrain Dynamics Library
  - Powertrain modelling for driveability and shift quality
- Vehicle Dynamics for Motorsport
  - Used in Formula 1, NASCAR, IndyCar and Sports cars
- Simulator Integration
  - Integration of VDLMotorsports and rFactor Pro
- FlexBody Library
  - Flexible bodies from Nastran, Genesis and Abaqus
- SystemID Library
  - Neural networks for non-linear system identification of dynamic syster
- XML Reader
  - Enables the use of XML files for parameters in Modelica
- FMI Blockset for Simulink
  - Import FMI compliant models in to Simulink





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Software Portfolio

- Distributors of rFpro and Dassault Systemes solutions

Multi-domain modelling and simulation based on Modelica, supporting multiple physical domains in a single integrated simulation environment

For managing requirements traceability and impact analysis across hardware and software projects lifecycle

Design, validation and deployment of control system software using IEC 61131-3 languages for safety critical systems

A suite of design and functional tools to develop AUTOSAR compliant embedded software

Specialist products within CATIA covering every aspect of Systems Engineering including requirements, functional architecture, control design and physical modelling

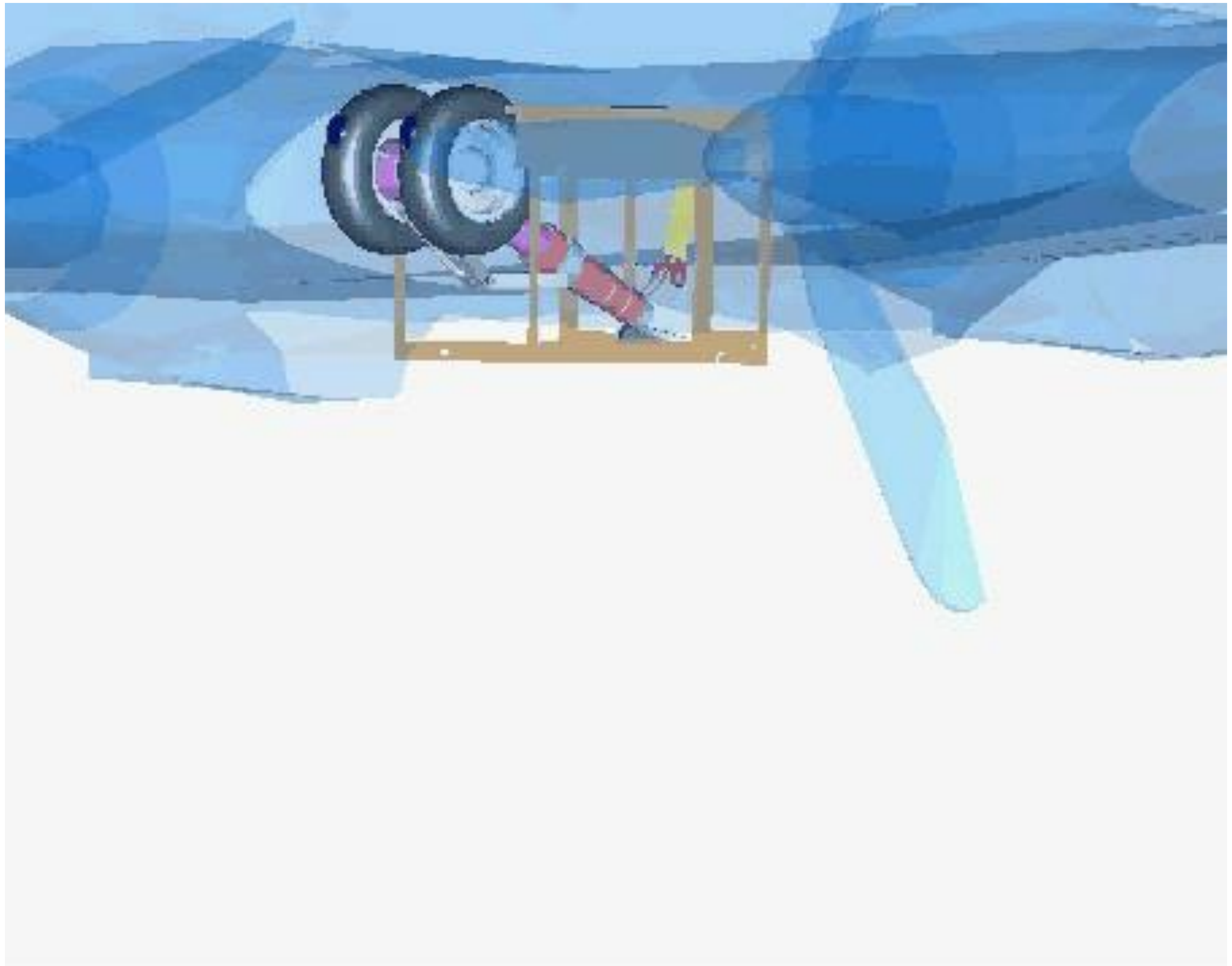
rFactor Pro focuses on simulators for engineering development of vehicle dynamics and the control systems and active safety systems that affect vehicle dynamics.

Multi-domain physical modelling to enable whole vehicle simulation

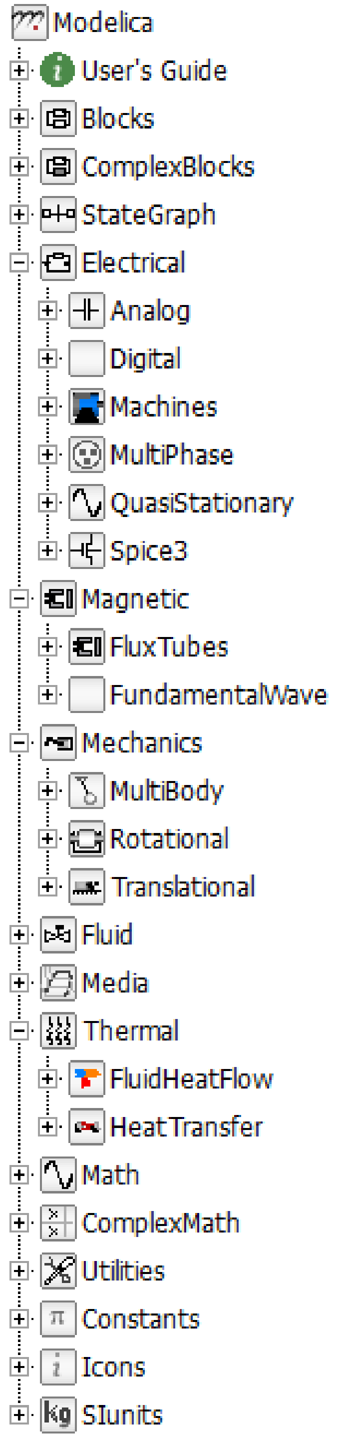
- Race cars are complex systems covering many domains
  - Mechanical, Electrical, Hydraulic, Pneumatic, Thermal, Chemical, Control, Magnetic, …
- Limited track testing in many formula means we cannot wait to verify that all these systems interact in a good way when at the track
- Consider all vehicle systems and how they interact with each other
- Need to use predictive models and not just functional ones to be able to start using simulation before a design is fixed

Dymola

- Dymola is a standalone simulation tool
- CATIA Systems is integrated into the 3DEXPERIENCE platform
  - Core functionality is the same, only the user interface changes
  - Easy to move models between the two programs
- Multi-domain modelling and simulation of complex dynamic systems
- Built on open standards
  - Modelica modelling language
  - FMI standard



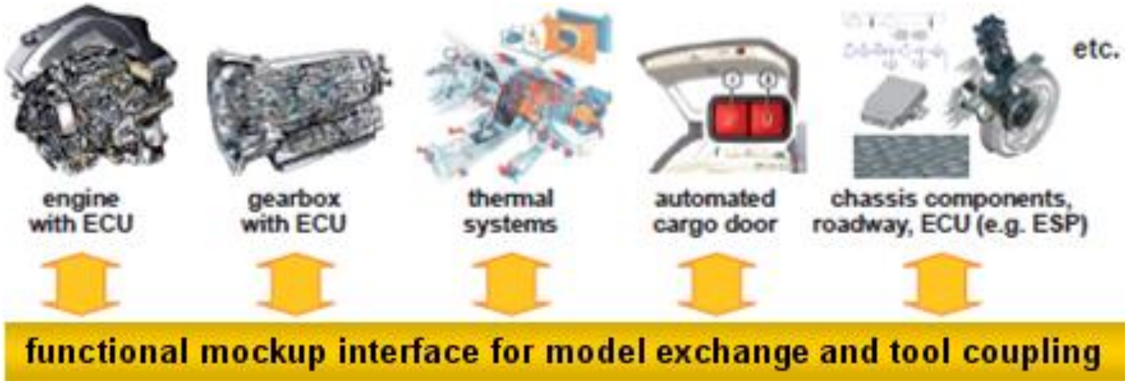
- A freely available, open source, standardised modelling language
- Developed and maintained by the Modelica Association
  - An independent, international not-for-profit organisation
  - Established in 1996
  - Currently over 120 members from academia, tool vendors and industrial end-users
    - Anyone 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
  - Control
  - Electrical
  - Mechanics
  - Thermofluids
  - Thermal



FMI Standard

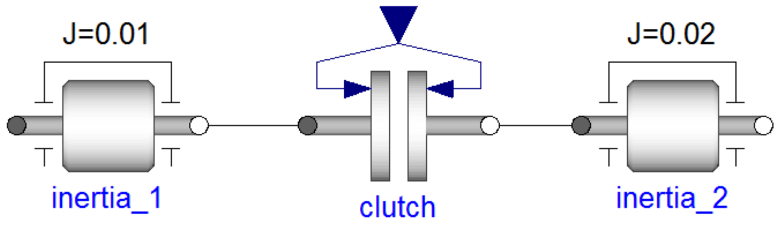
- **Functional Mock-up Interface Standard**

- Open standard for model exchange
- Goal is to improve the exchange of simulation models between partners
  - Models are exchanged in binary format to protect IP using a standard API to simplify the exchange of models
- The first version of the standard was the result of the Modelisar project, an ITEA 2 project led by Daimler
  - 29 partners, started July 2008 and finished December 2011
- FMI 1.0 and FMI 2.0 are now supported by over 70 simulation tools
  - Claytex develops the FMI Blockset which allows FMI compliant models to be run in Simulink, Excel and on Windows
- Defines two mechanisms:
  - Model exchange
  - Co-simulation



Functional and Predictive models

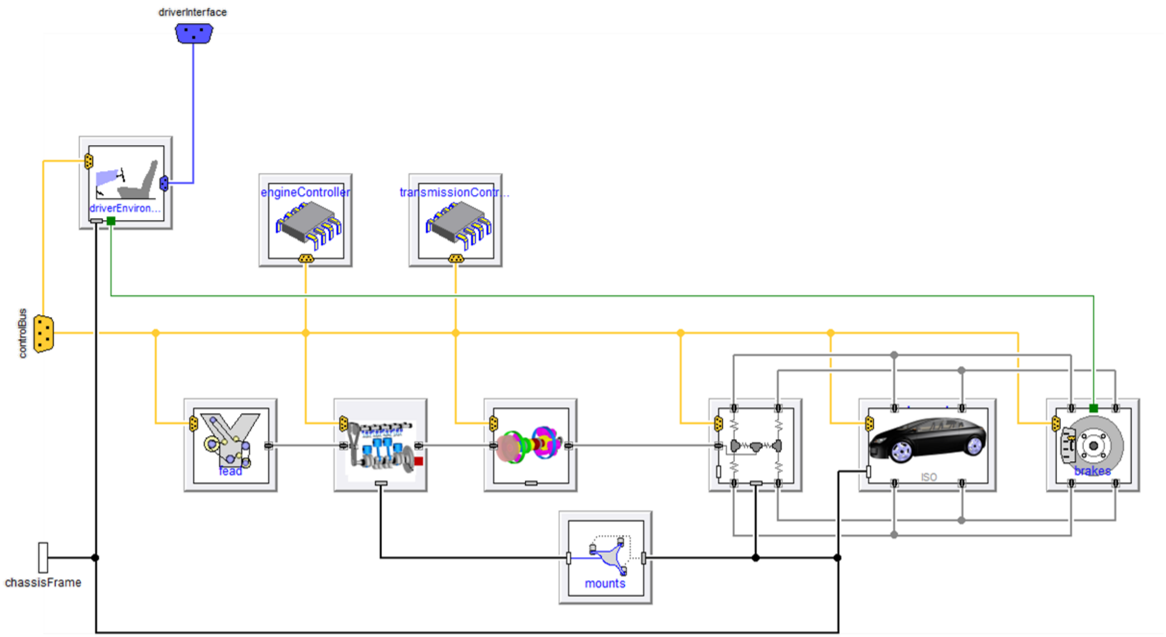
- A Functional model is one that captures the key function of the model
- A Predictive model allows us to predict the behaviour and explore it’s characteristics

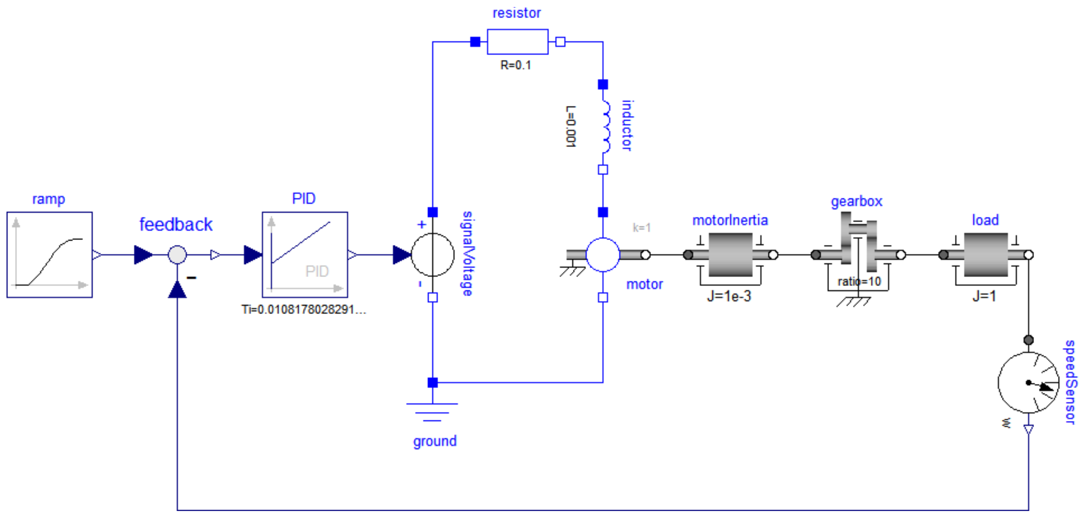


- The clutch is there to make sure the two inertias rotate at the same speed when engaged
- Functional model
  - Would reduce the relative speed across the clutch in a predefined manner
  - The controlling parameter would be the engagement time
- Predictive model
  - Would include a model for friction and the torque transfer would be a function of the clutch clamp load, relative speed, temperature, …
  - The parameters would include the geometry and friction characteristics
  - The engagement time could be predicted under different operating scenarios

Component Orientated Modelling

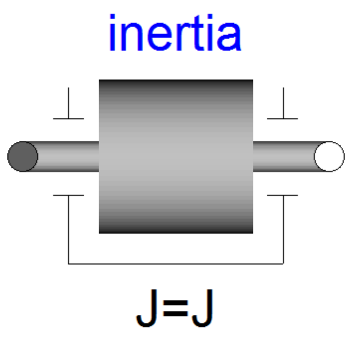
- Modelling and simulation of systems integrating multiple physical domains
  - Mechanics (1D, MultiBody), 1D Thermofluids, Control, Thermal, Electrical, Magnetics and more
- Promotes extensive model reuse at component and system level
  - Components represent physical parts: valves, gears, motor
  - 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





Model Definition

- Models are defined using the Modelica modelling language
  - Object orientated modelling language
  - Models are defined as differential algebraic equations (DAE)
  - Acausal modelling method
    - i.e. no need to rearrange the equations into a particular solution form or calculation order
- Dymola provides access to the Modelica code behind models

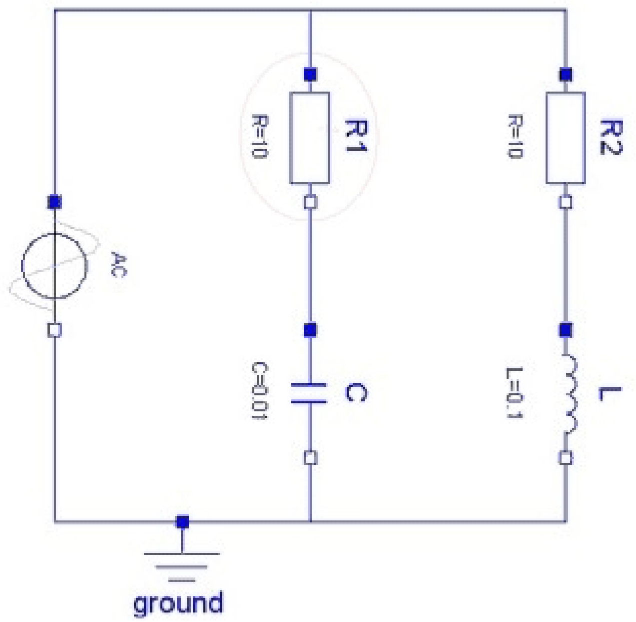



```
model Inertia
  extends Interfaces.Rigid;
  parameter SI.Inertia J=1 “Moment of Inertia”;
  SI.AngularVelocity w “Angular velocity”;
  SI.AngularAcceleration a “Angular acceleration”;
equation
  w = der(phi);
  a = der(w);
  flange_a.tau + flange_b.tau = J * a;
end Inertia;
```

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

DAE:



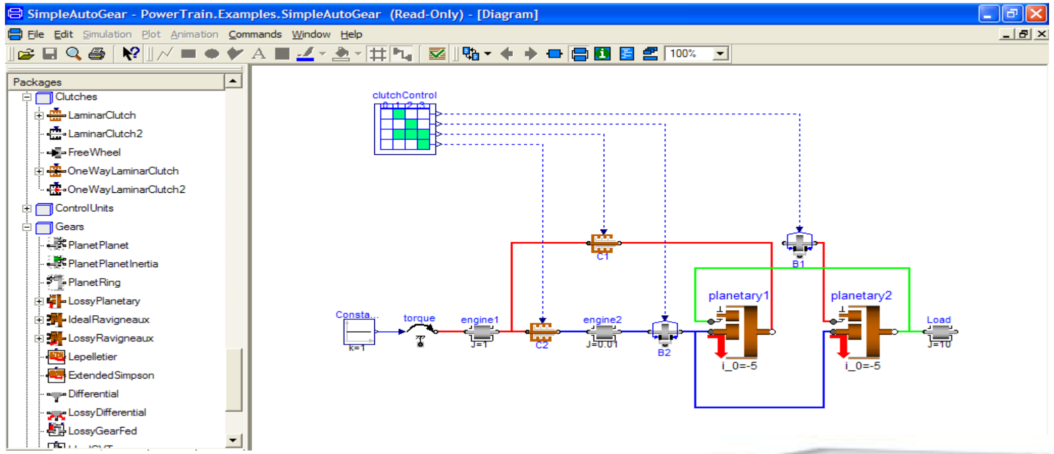
Symbolic Manipulation

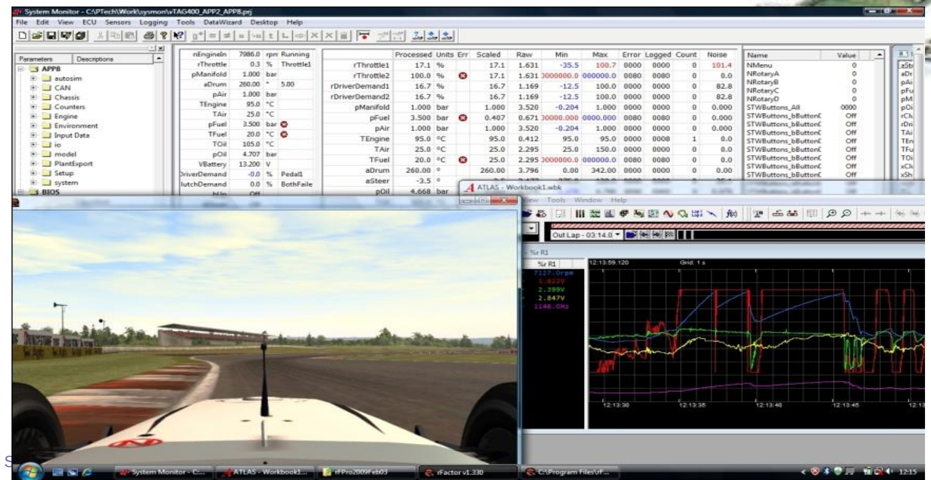
- **What does this mean in practice**

- The Inverted Pendulum contains 659 equations
  - Using the Modelica modelling approach these are formed as a DAE
- Symbolic manipulation automatically reduces this to:
  - 7 continuous time states
  - 92 other time varying quantities
    - Including 1 linear system, originally containing 14 equations but reduced to a system containing just 2 equations
  - All the other equations relate to constants or variables that are exactly equal to these 99 variables
- Advantages of Symbolic Manipulation
  - Automate the often error prone process of rearranging equations in to a solution
  - Apply advanced mathematical techniques to reduce the size of the problem
  - Can deliver real-time simulation performance of Vehicle Dynamics models with over 100,000 equations (1ms time step)

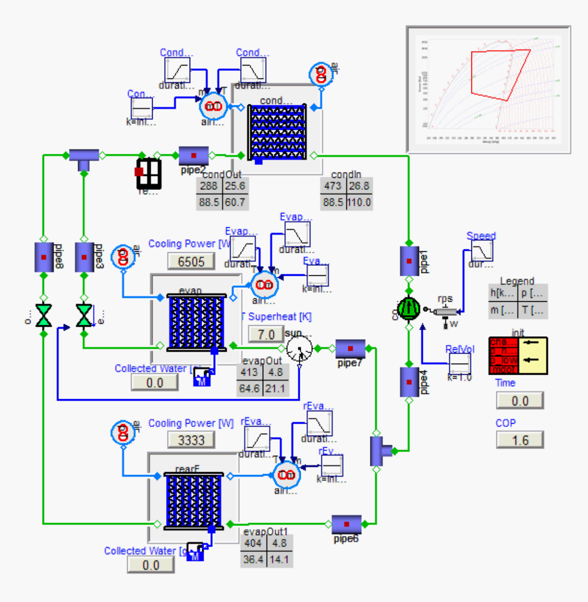
Dymola in Motorsport

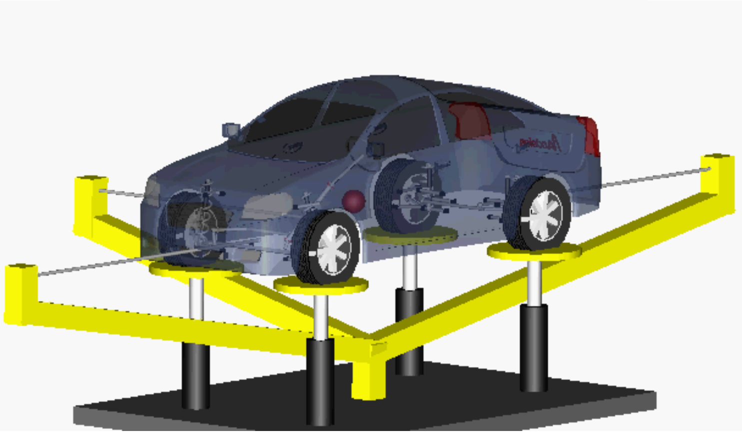
- Concept
  - Drag and drop component models to build a schematic of the system and set physical parameters to predict behaviour
- Design
  - Detailed models can be used to quickly evaluate the impact of design changes on the complete system
  - Desktop and real-time simulation
- Testing
  - Use the models to support off-track testing
  - Driver-in-the-loop and Hardware-in-the-loop simulators
- Race
  - Use the models trackside for setup optimisation and with the telemetry system
  - Integrate into trackside tools



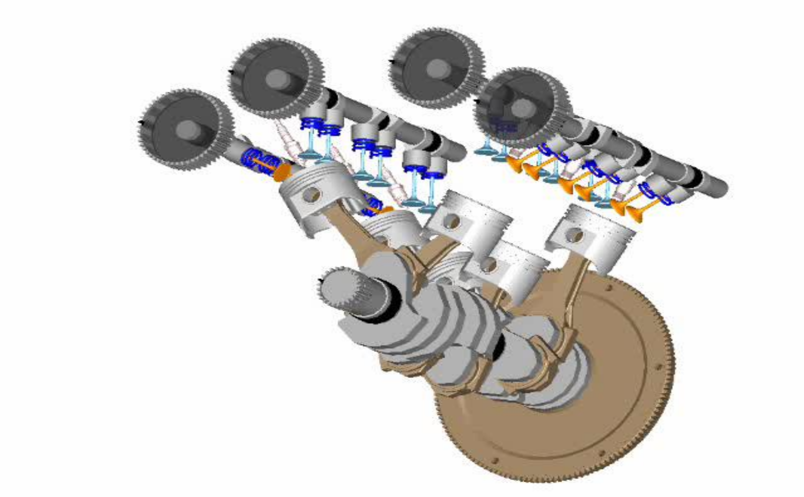


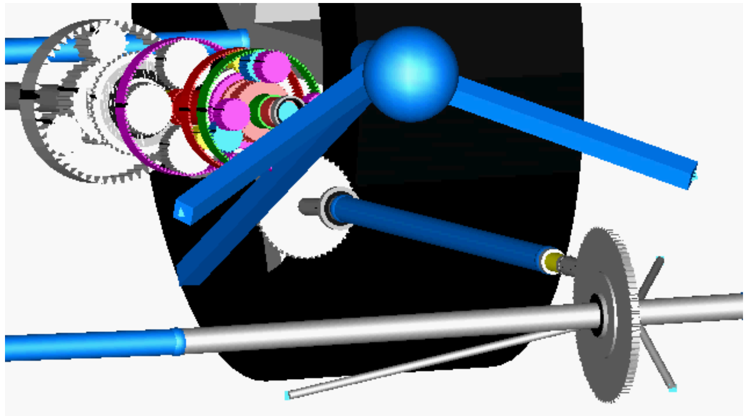
Modelica Application Libraries for Motorsport





- Battery
- Belts
- Build Tools
- eDrives
- Engines
- FlexBody
- Fuel Cell
- Heat Exchanger
- Hydraulics
- Liquid Cooling
- Pneumatics
- Powertrain Dynamics
- Simulator
- Smart Electric Drives
- SystemID
- Terrain Server
- Vapor Cycle
- VDLMotorsports





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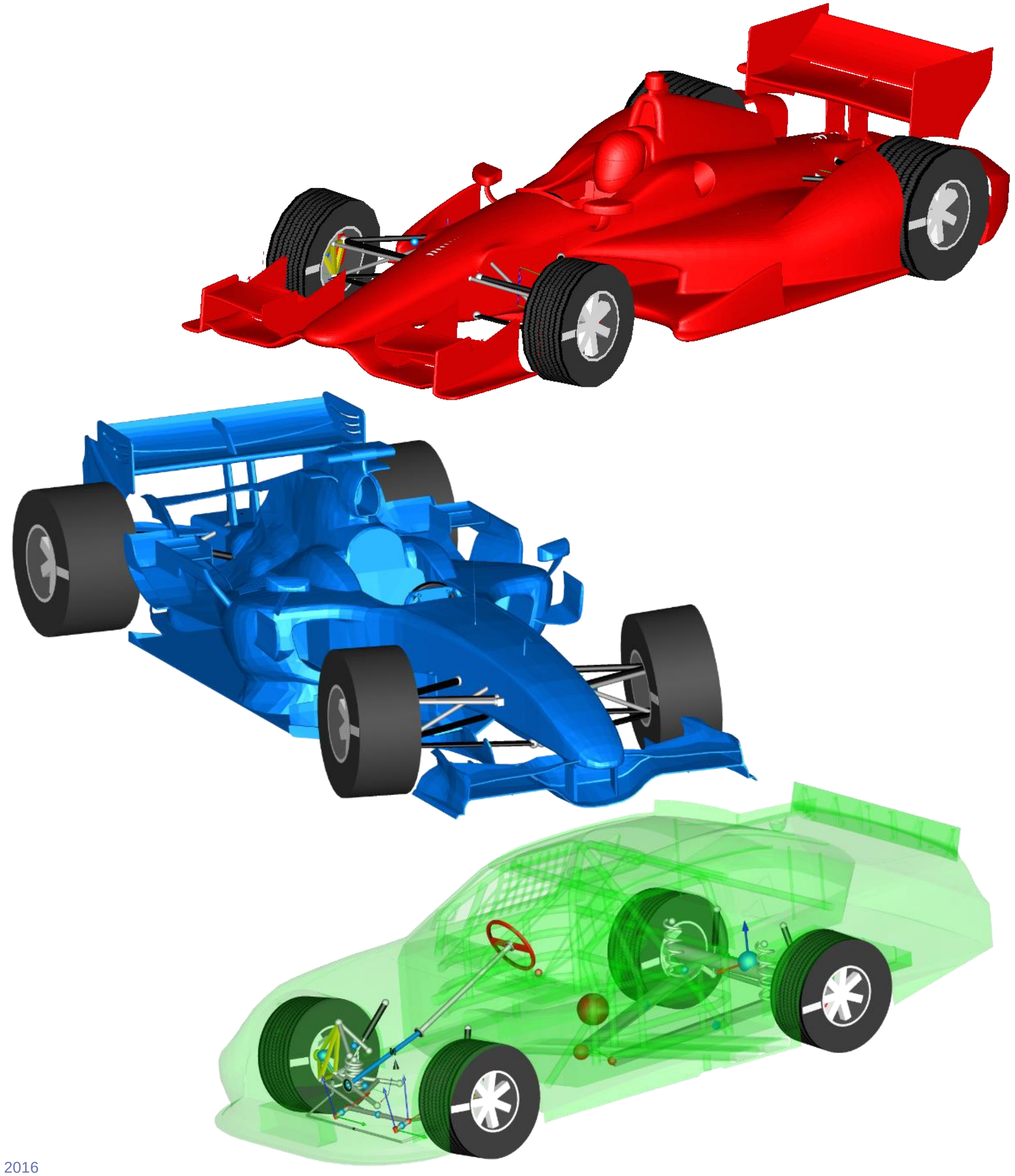
Vehicle Dynamics for Motorsport

- VDLMotorsports 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
- Pacejka tyre model
- Wide range of experiments for K&C and dynamics plus setup and quasi-static tests
- Real-time capable MultiBody models
- Open and extendible



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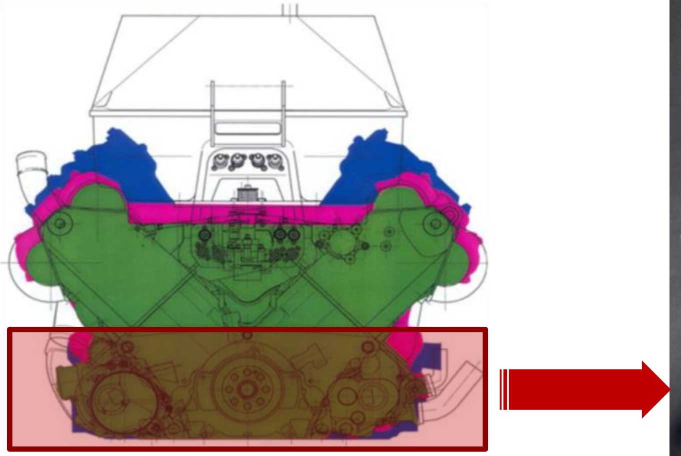
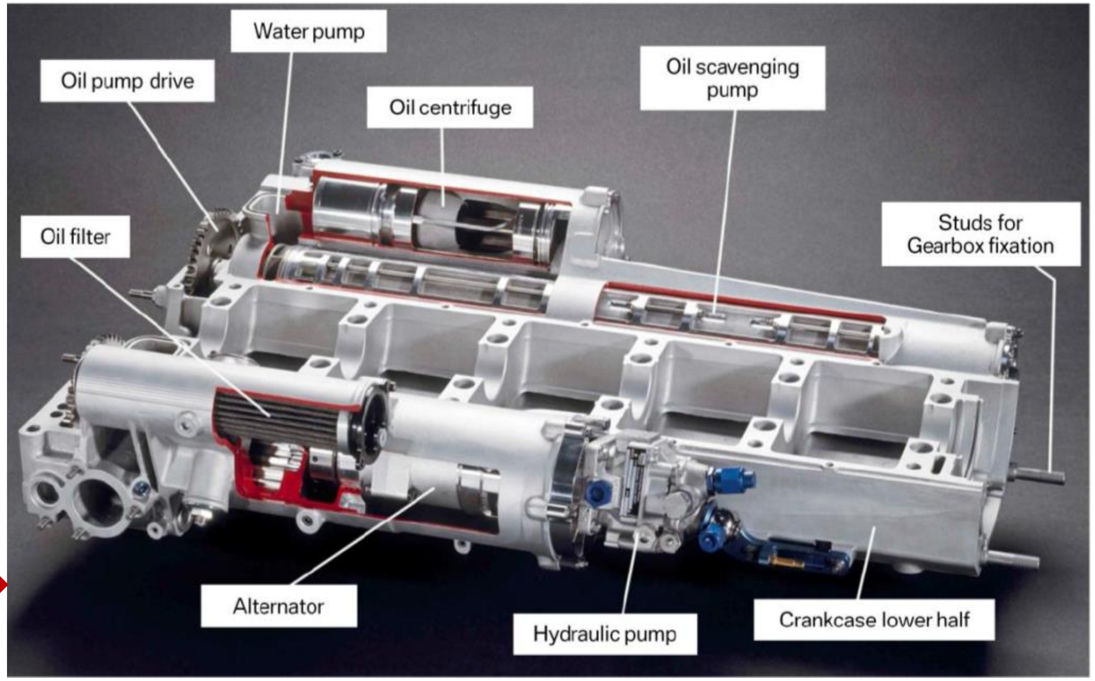
Sports Prototype Examples

1. Daytona Prototype model in Dymola
2. LMP Project completed at Oxford Brookes University

Motorsport Engine Ancillary Power Consumption Optimization

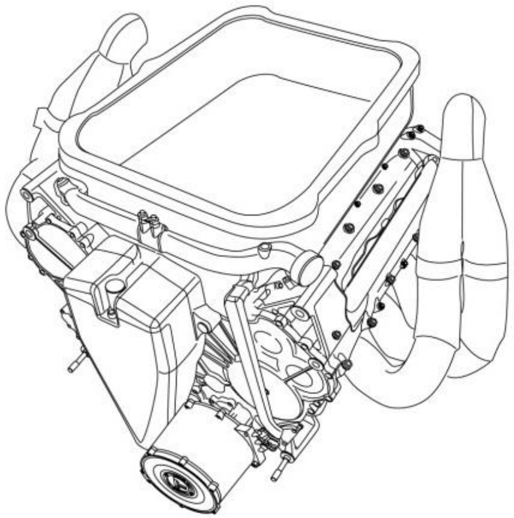
- Oxford Brookes MSc Dissertation Project
  - Student: Gabriel Elias, Supervisor: Stephen Samuels
  - Published at SAE, 2015-01-1163
- Objective
  - To optimize the power consumed by engine ancillaries on high performance racing cars
- What are ancillaries?
  - Supporting objects attached to an IC engine which provide a function vital to proper operation.
- Which ancillaries are targeted?
  - Oil Pressure & Scavenge Pumps
  - Water Pump
  - GDI Fuel Pump





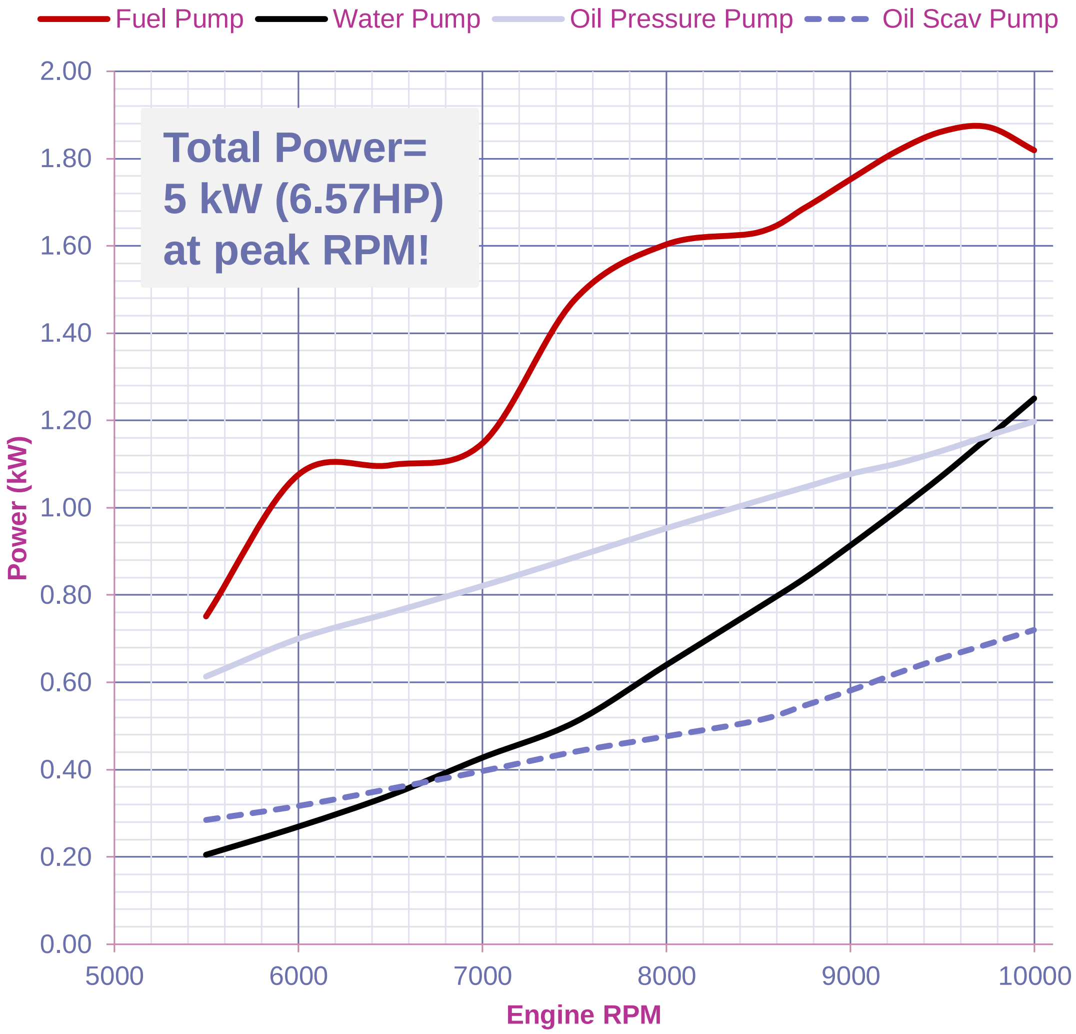
Why Optimize? What's the benefit?

- The ancillaries for a V8 use over 6.5 HP at Peak RPM!
- Reducing Engine Losses
- More Efficient Energy Sources
- Fuel Savings



- Solution?
  - Create Mechanical/Electrical Hybrid Drive for engine ancillaries
  - Use KERS recovered energy to power
  - Actuated by throttle position

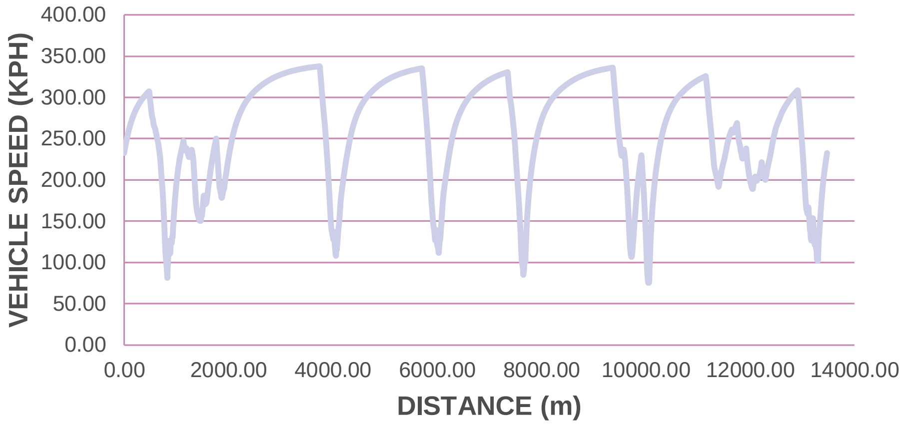
Engine Ancillaries Power Consumption vs Engine RPM

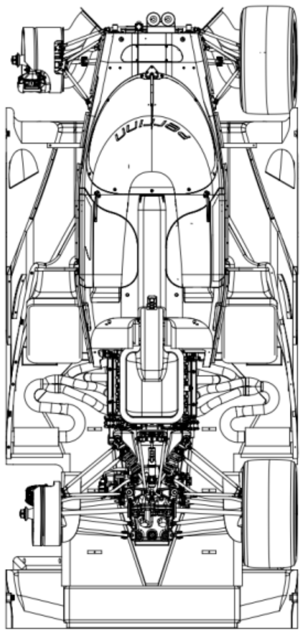


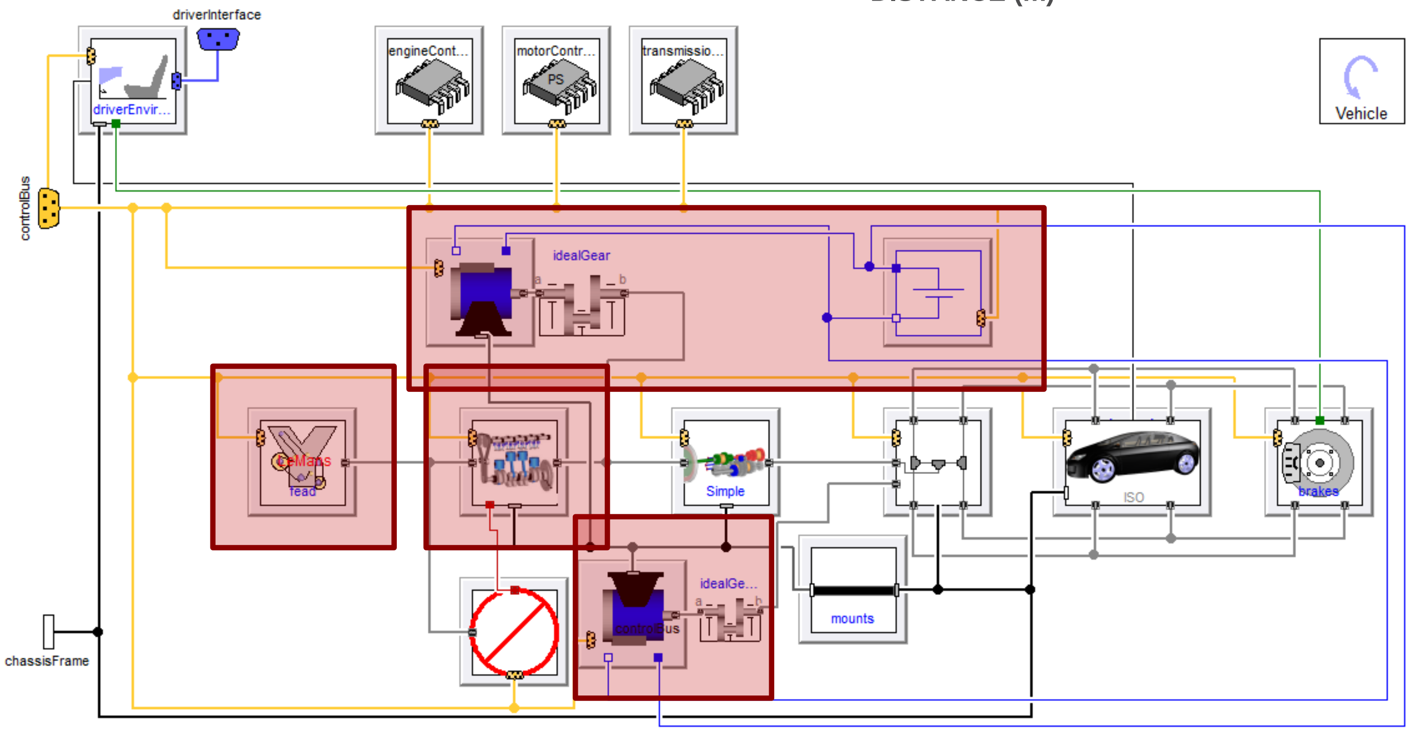
Vehicle model

- Dymola 1D linear vehicle model
  - 3.7L V8 Engine
  - Front and rear axle MGUs (313kW)
  - 7-Spd DCT Transmission
  - Engine Ancillaries
- KERS Power AND Recovery

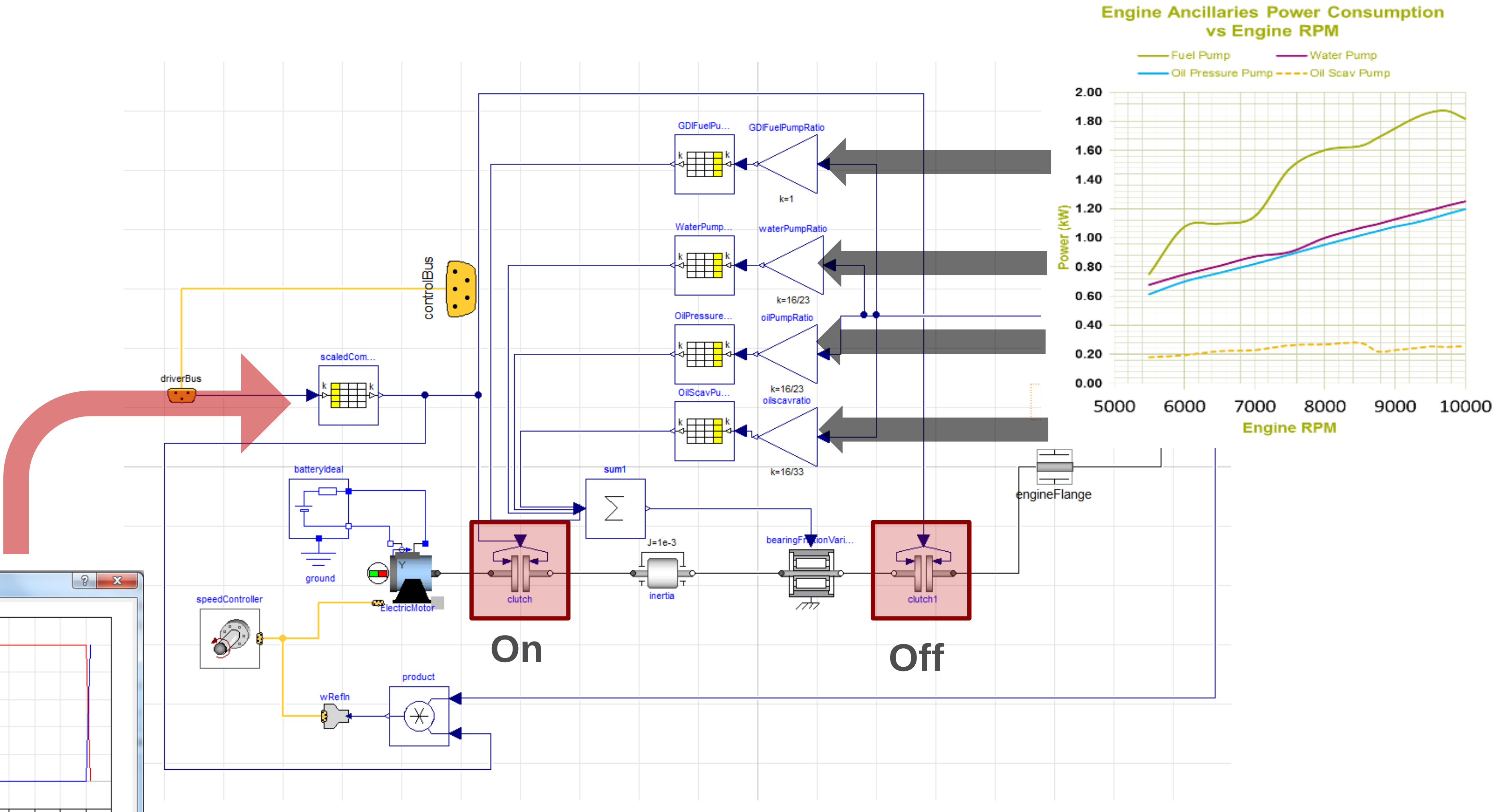
LeMansLMP1-H 8MJ Simulated Speed Trace



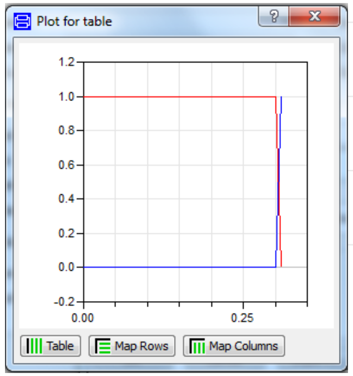




Modelling of ancillaries in Dymola



Throttle Pos. Actuated clutches



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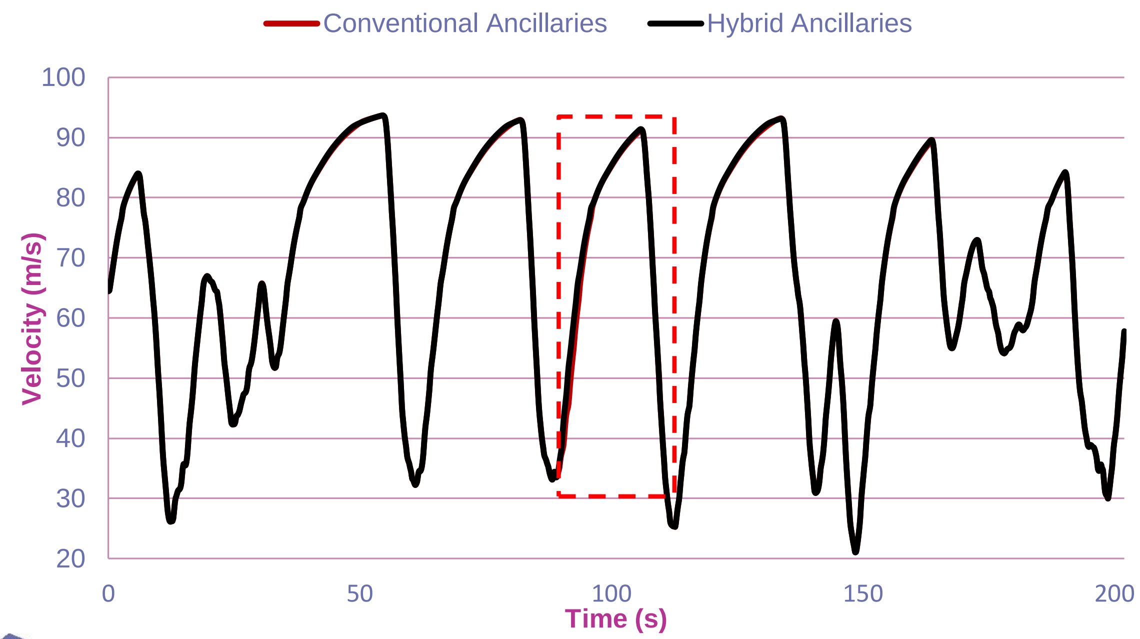
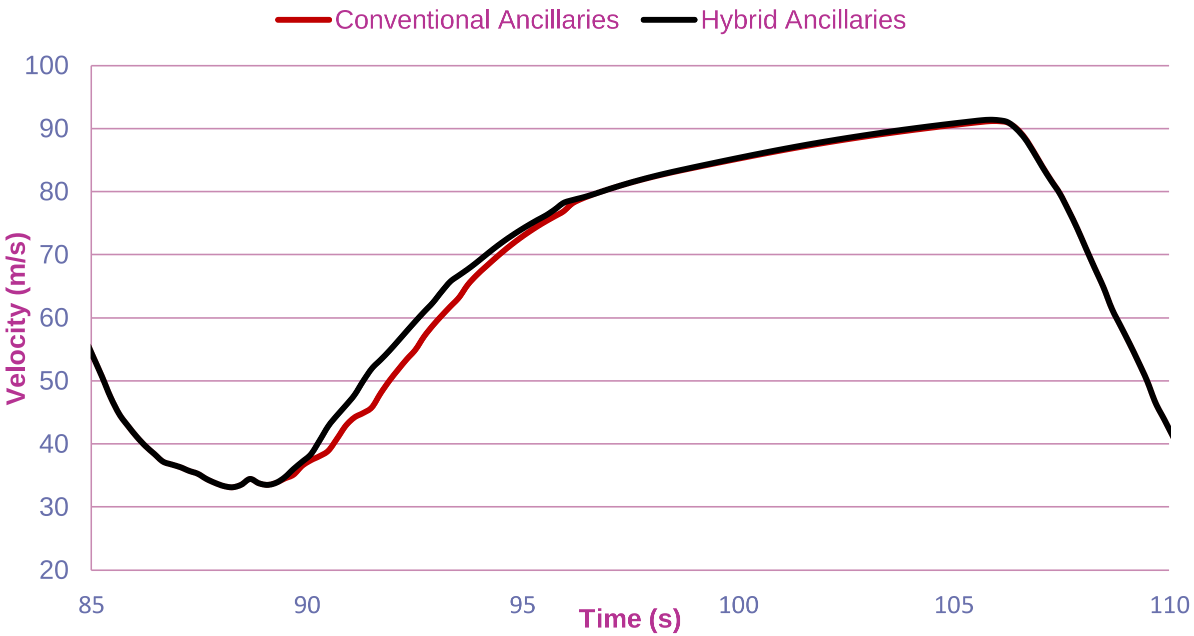
Results of speed-matching experiment

- Improved acceleration out of corners due to reduced load on engine
- Following the same speed-time profile achieve a fuel saving of 70cc per lap

	Conventional Ancillaries	Hybrid Ancillaries
Fuel Burned	4.23	4.16
Difference (cc)		-70cc





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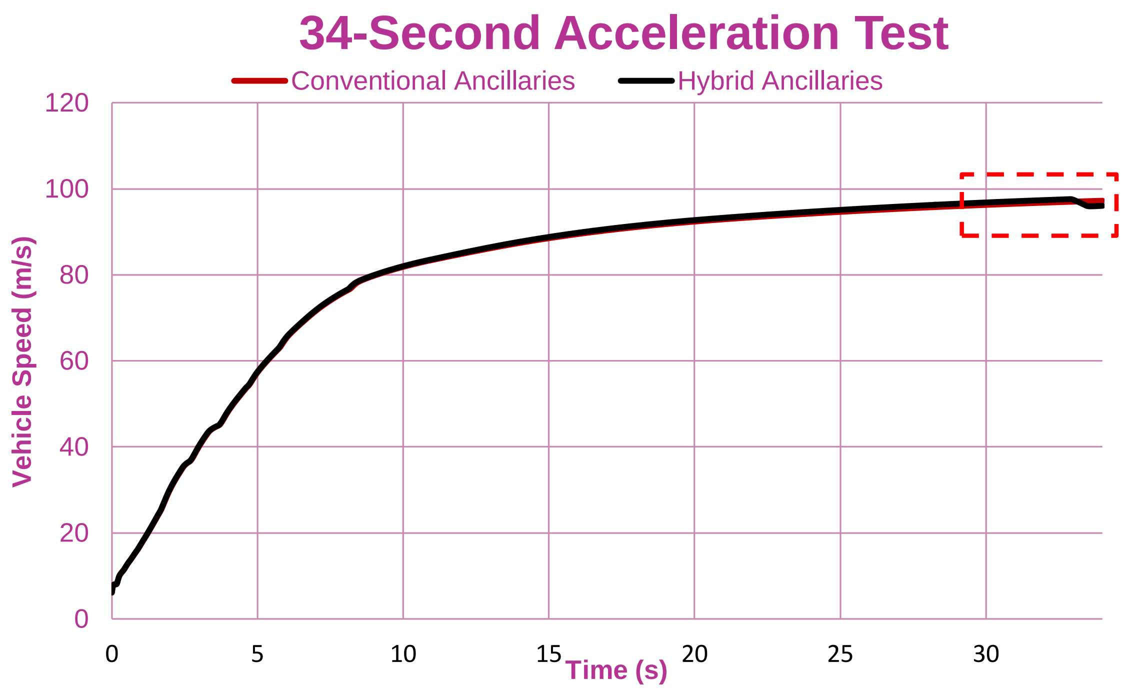
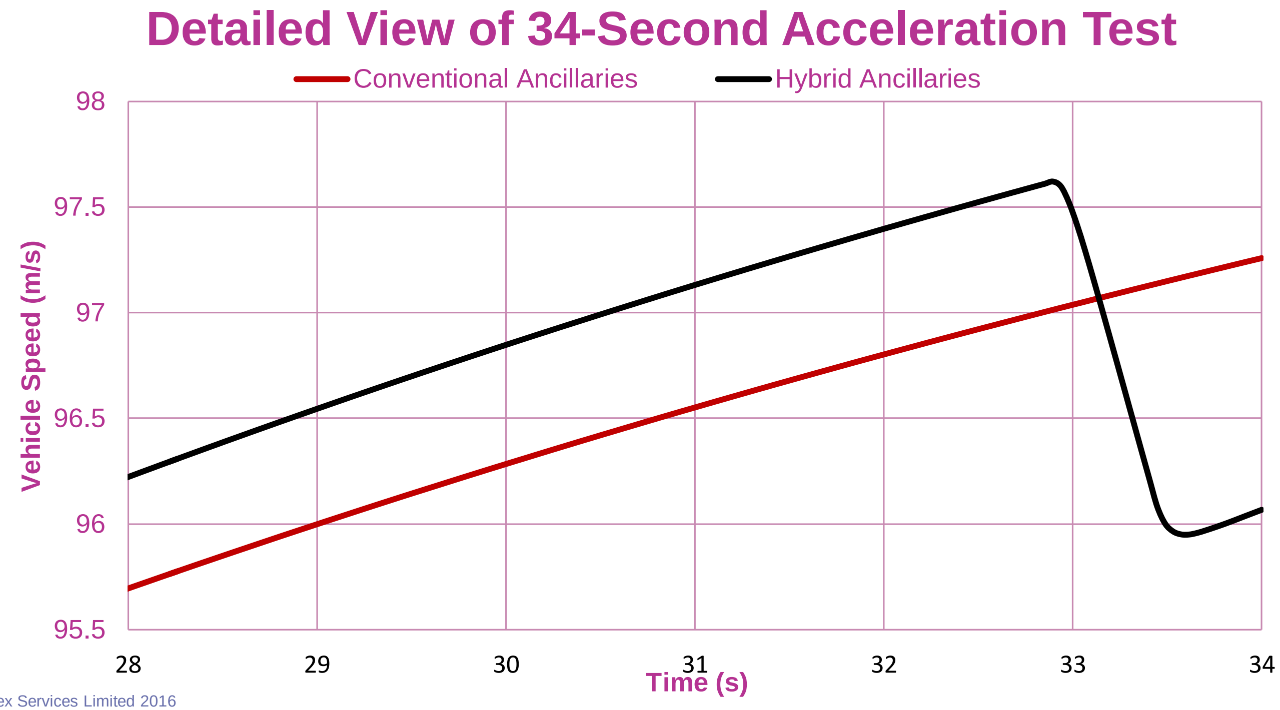
Results of acceleration experiment

- Straight line acceleration test
  - Top speed increases by 0.37m/s
  - Time taken to reach top speed is reduced by 1.11s

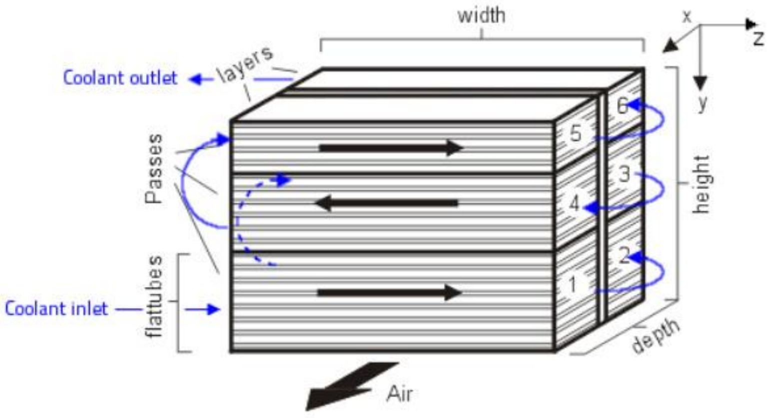
	Top Speed (m/s)	Time Top Speed Achieved (s)
Conventional Ancillaries	97.25	34.0
Hybrid Ancillaries	97.62	32.89
Performance Delta	+0.37 m/s	-1.11 s

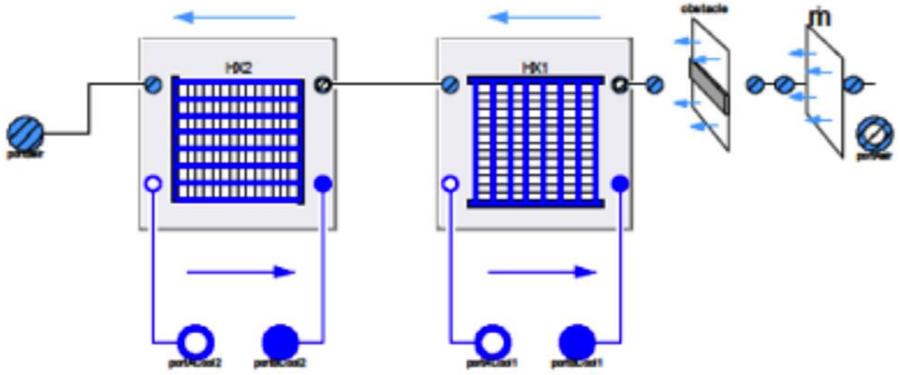




Possible extensions to this work

- Thermal Management
  - Add the cooling and lubrication circuits for the engine, ancillaries and KERS
  - Use the Heat Exchanger Libraries to build detailed simulation of cooling systems
    - Supports different types of heat exchanger
    - Consider heat exchanger stacks with obstructions
- Battery Management
  - Characterise the cell model for electrical, thermal and ageing
  - Easily scale to the module and pack
  - Couple to the thermal management simulation
- Detailed modelling of the ancillaries
  - Implement physical models of the lubrication, cooling and hydraulic circuits
  - Variable speed control of pumps to minimise energy use whilst maintaining necessary system performance

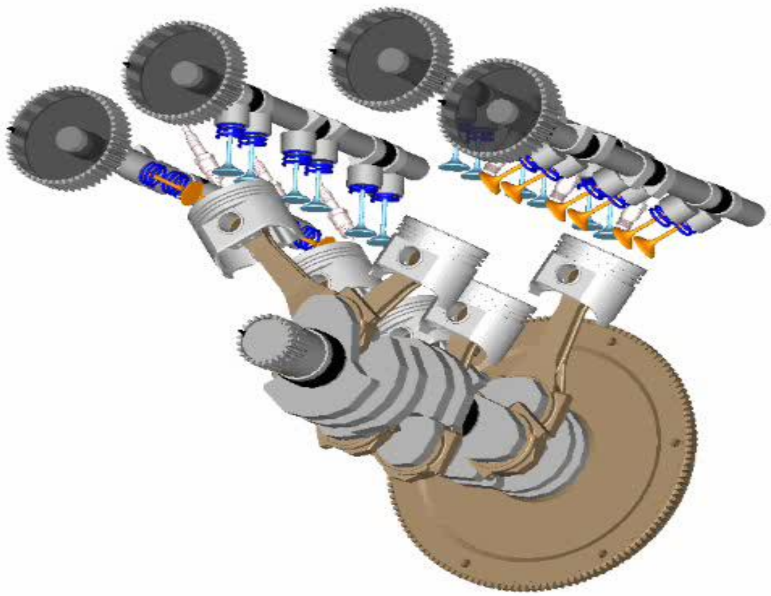


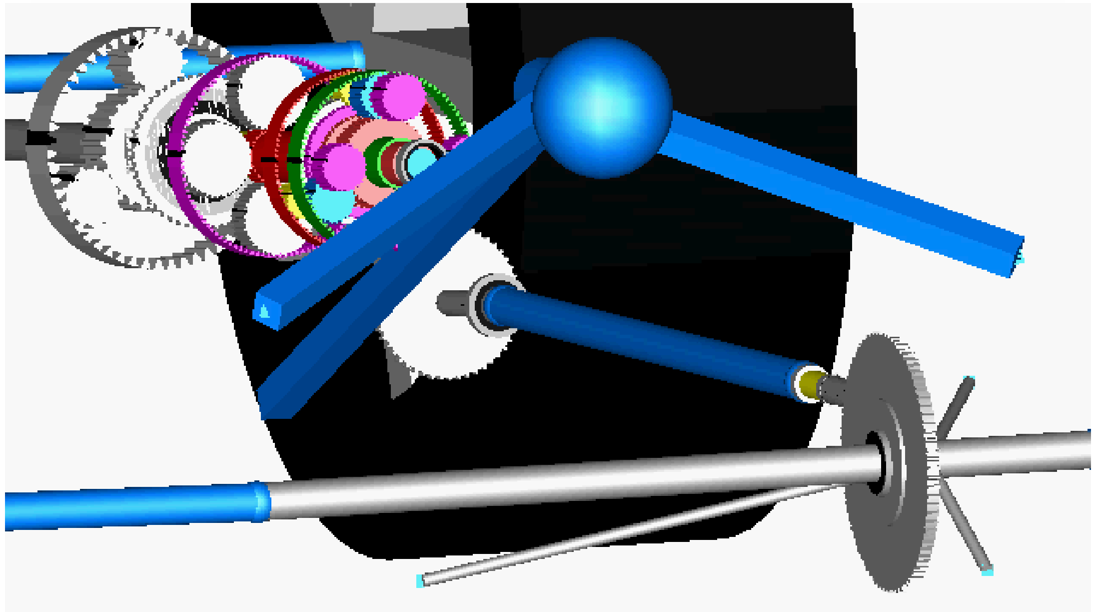


Detailed Powertrain Modelling

- Engines Library
  - Spark Ignition and Compression Ignition engines
  - Supports Naturally Aspirated and Forced Induction (turbochargers and superchargers)
  - Mean value and Crank angle resolved models

- Powertrain Dynamics Library
  - Detailed transmission and driveline modelling
  - From drive cycle to detailed driveability simulation
  - Determine all forces in gear mesh, include dynamic effects of joints, elastically mount the powertrain in the chassis





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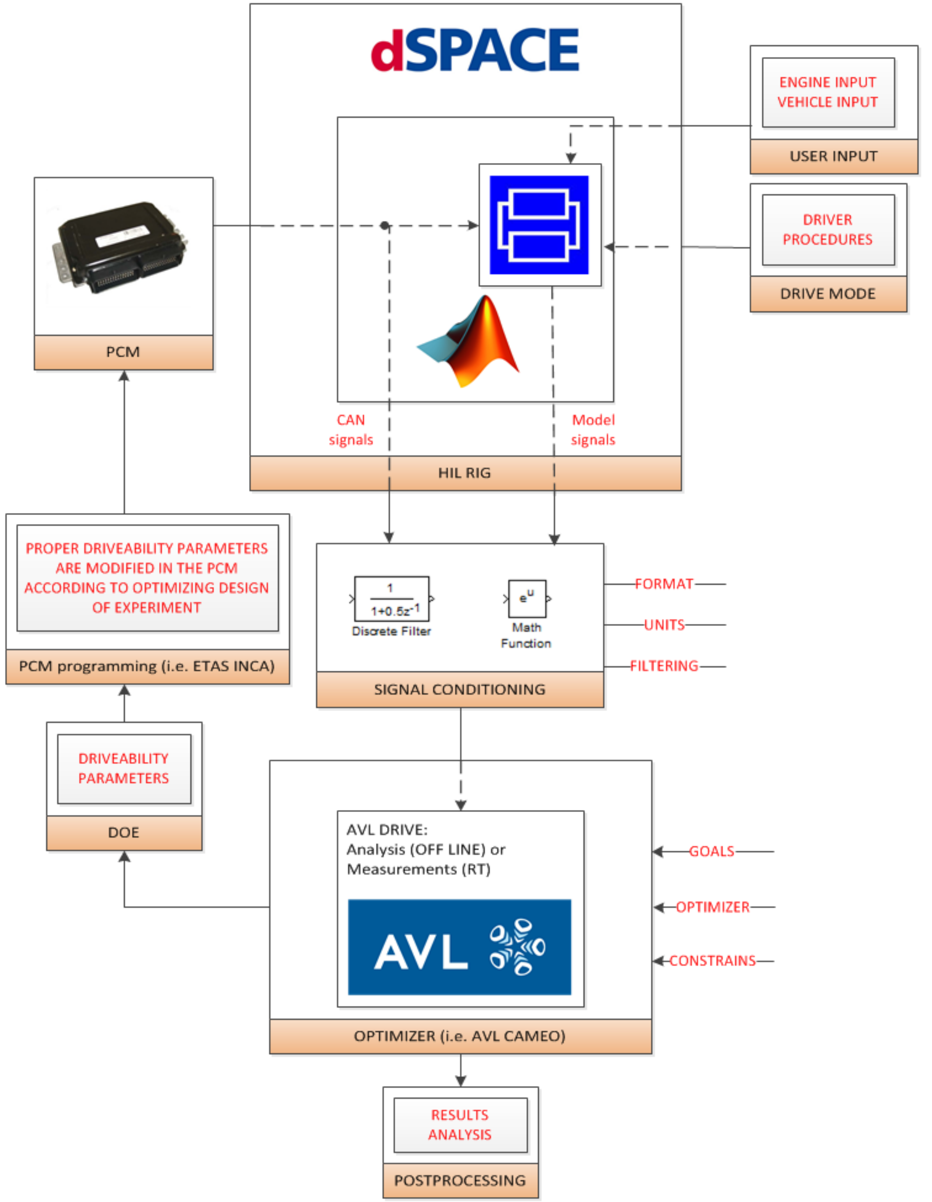
MORSE project

- MOdel-based Real-time Systems Engineering (MORSE)
  - Collaborative research project with Ford and AVL Powertrain
  - Co-funded by Innovate UK as part of the “Towards zero prototyping” competition
    - UK government organisation
  - 2 year project
- The project is aiming to address some of the challenges of validating the functional requirements of electronic control systems using real-time simulation of multi-domain physical models created in Dymola
  - Models are being developed using the Engines and Powertrain Dynamics Libraries from Claytex

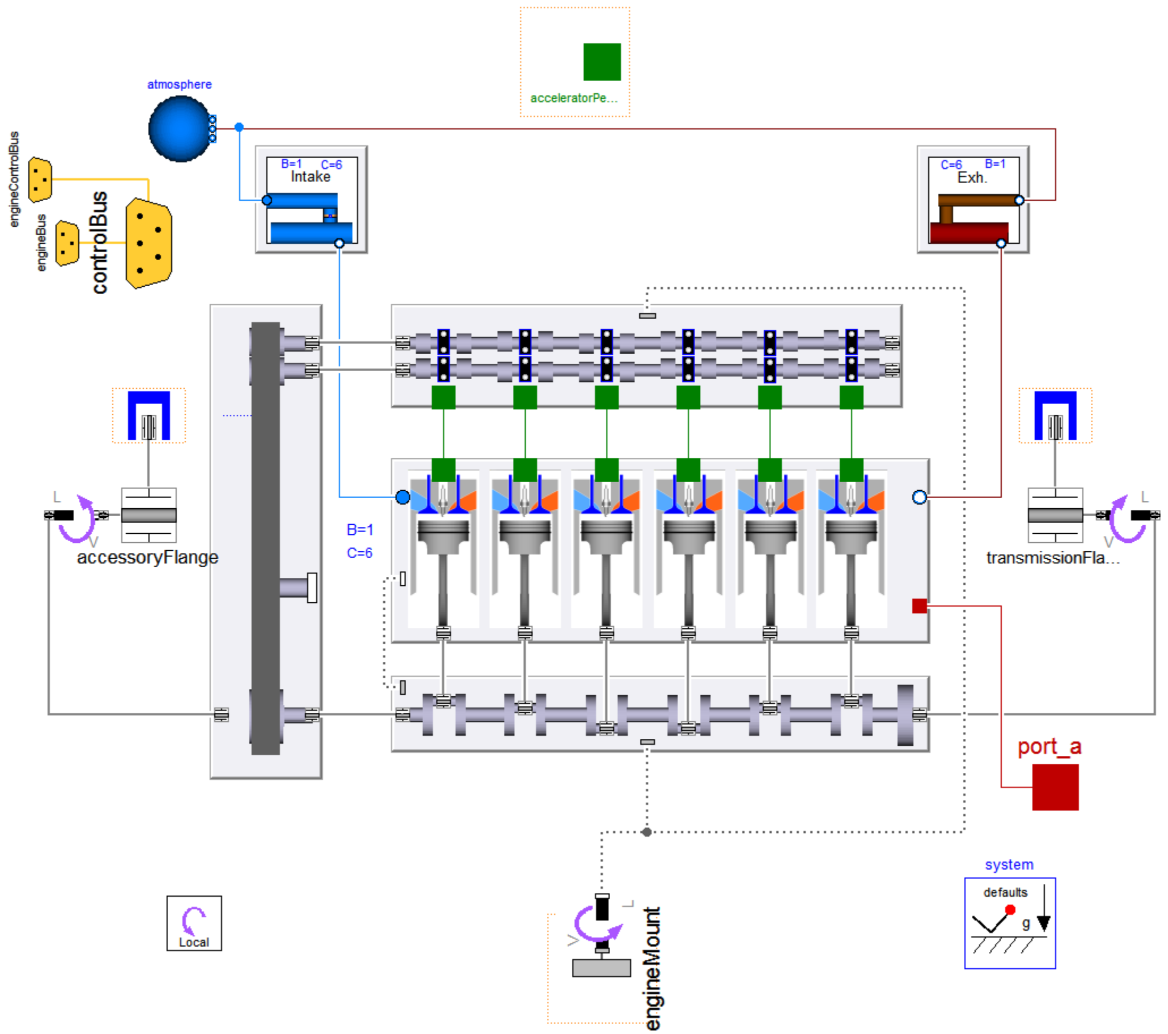


Go Further

Innovate UK
Technology Strategy Board

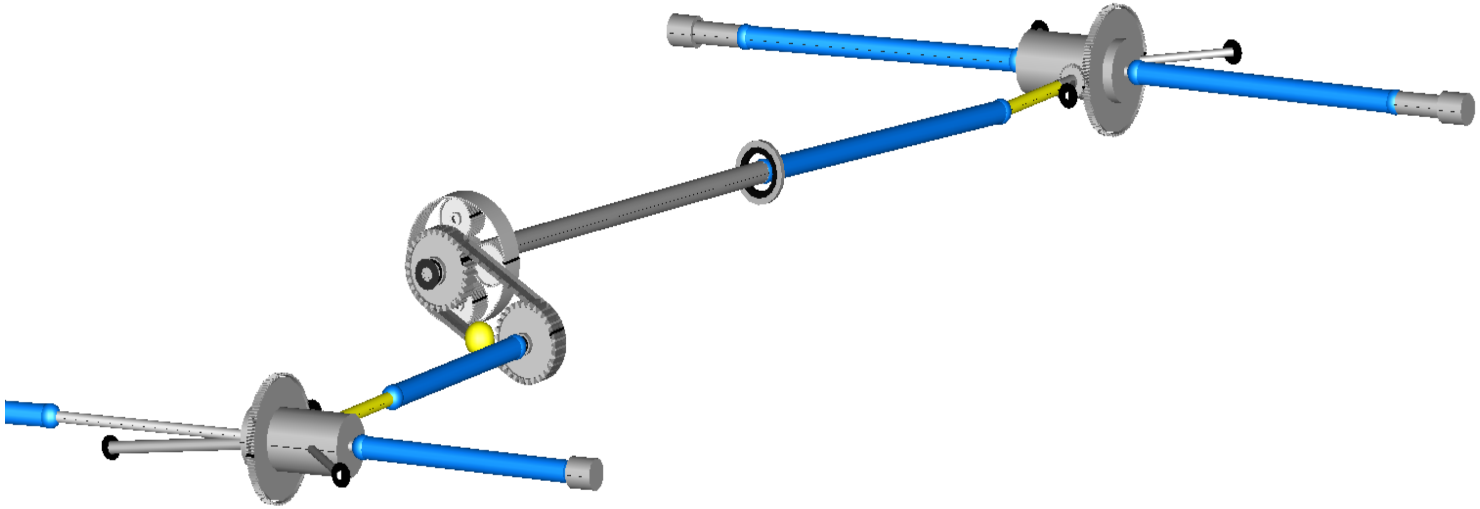
Engines Library

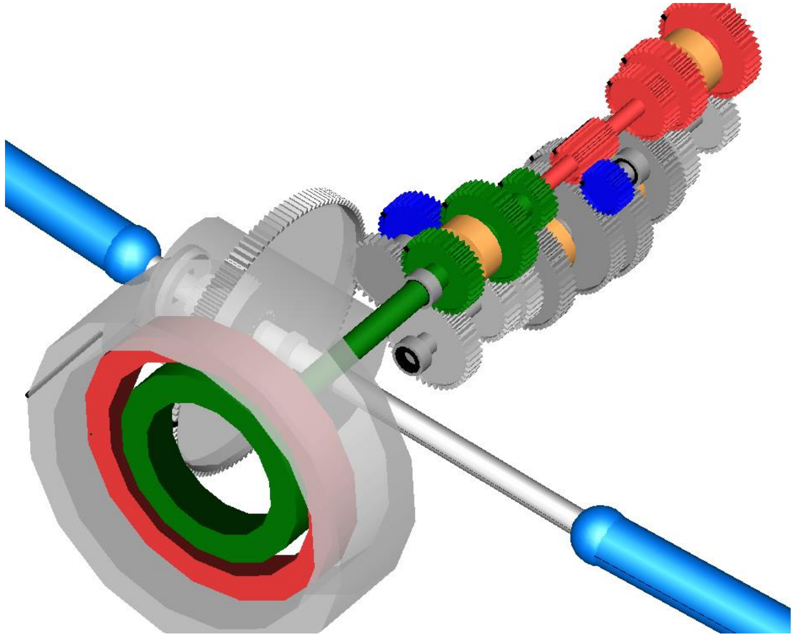
- Mean value and Crank angle resolved engine models
  - Wiebe model for crank angle resolved models
  - Open and expandable making it easy to add your own combustion models
- 1D thermofluid models of intake and exhaust
  - Models for emissions control, turbochargers, superchargers, egr, ...
- Mechanics modelled using 1D/MultiBody hybrid approach
  - Detailed mechanical models possible including all bearings effects, torsional compliance, etc.
- Thermal network to model heat transfer through engine and 1D thermofluid coolant system models
- Engine architecture with templates for various engine configurations (i3 to V8)
  - Open and extendible to easily plugin new ideas



Powertrain Dynamics Library

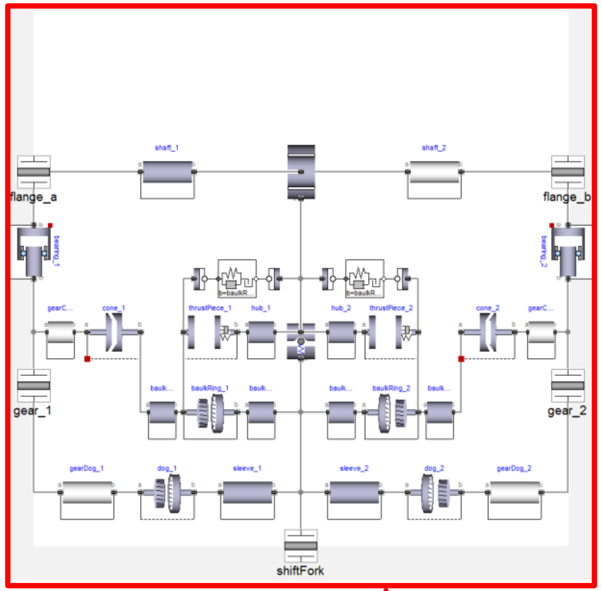
- Convenient modelling approach for complex powertrains
- Wide range of components available for modelling powertrain systems
  - Bearings, gear meshes, losses, compliance and backlash, clutches, torque converters (steady state and dynamic models), dog clutches, and more
- Model fidelity ranges from simple drive cycle (1D models) to driveability, shift quality and launch feel (MultiBody models)

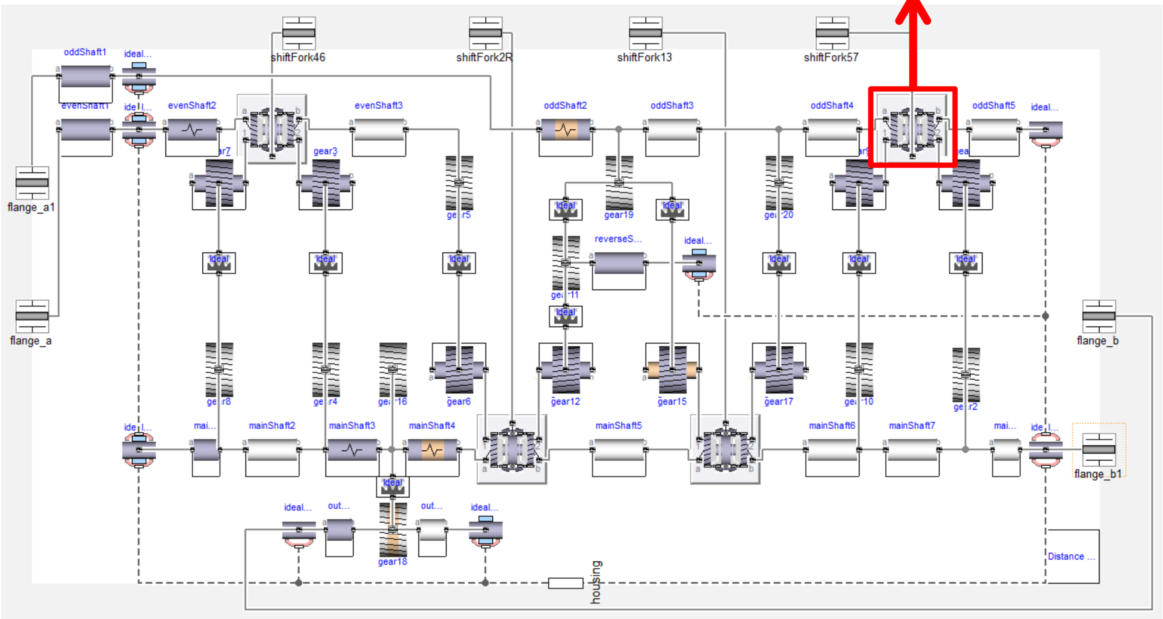




Transmission modelling

- Gearsets
  - All use shafts, bearings, gears and mesh models
  - Manual / AMT / DCT use synchronizer models
  - AT / CVT use clutches and brakes to the housing
  - Synchronizer models use shafts, splined sleeves, dog and cone clutches to model sleeve axial dynamics
- Transmission
- Combine with Torque converter, Retarders and shift actuation with Barrel cams, shift forks and detents





Approach:

1. Layout of shafts and bearings (shafts define the sections between the gears/ synchronizer centre point)
2. Add gears and simple synchronizers
3. Add mesh models
4. Verify behaviour

Formula 1 Powerunit

- The Formula 1 power unit introduction in 2014 is a complex system
  - 1.6l V6 turbocharged engine
    - Fuel flow rate limits
    - Overall race fuel of 100kg
  - 2 motor-generators
  - 8 speed gearbox
  - The energy recovery limit is 2MJ per lap from the crankshaft motor
  - The energy discharge limit from the battery is 4MJ per lap
- Many different aspects of the system needed to be optimised
- Thermal management of the ERS to reduce weight and improve aerodynamic losses:
  - Intercooler sizing
  - Reduce coolant volume throughout the cooling system
- Therefore necessary to:
  - gain a better understanding of the thermal performance of the ERS devices, focussing on the ES device for this particular task

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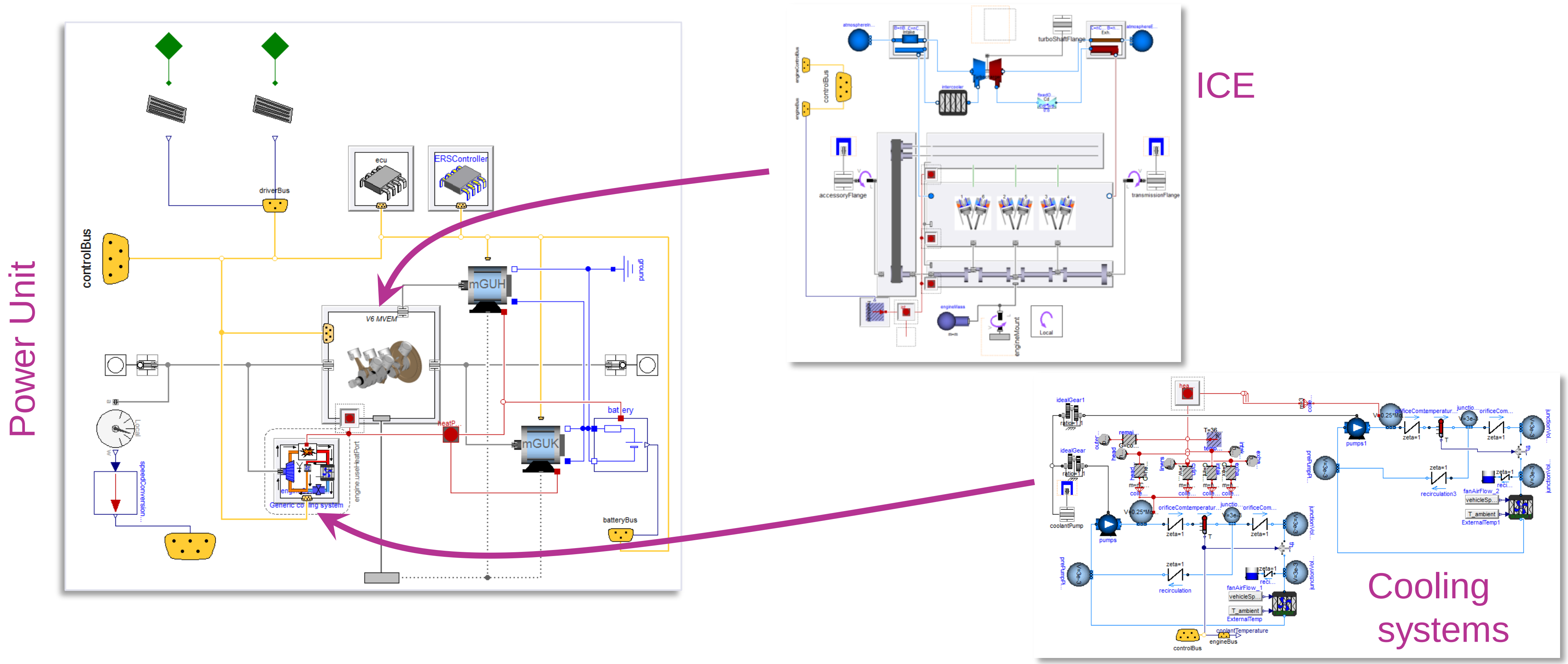
ICE, MGU and Coolant System integration

- Turbocharged mean value engine includes integrated MGUH
- MGUK connected to the crankshaft
- Cooling system for ICE, MGUH, MGUK and battery pack



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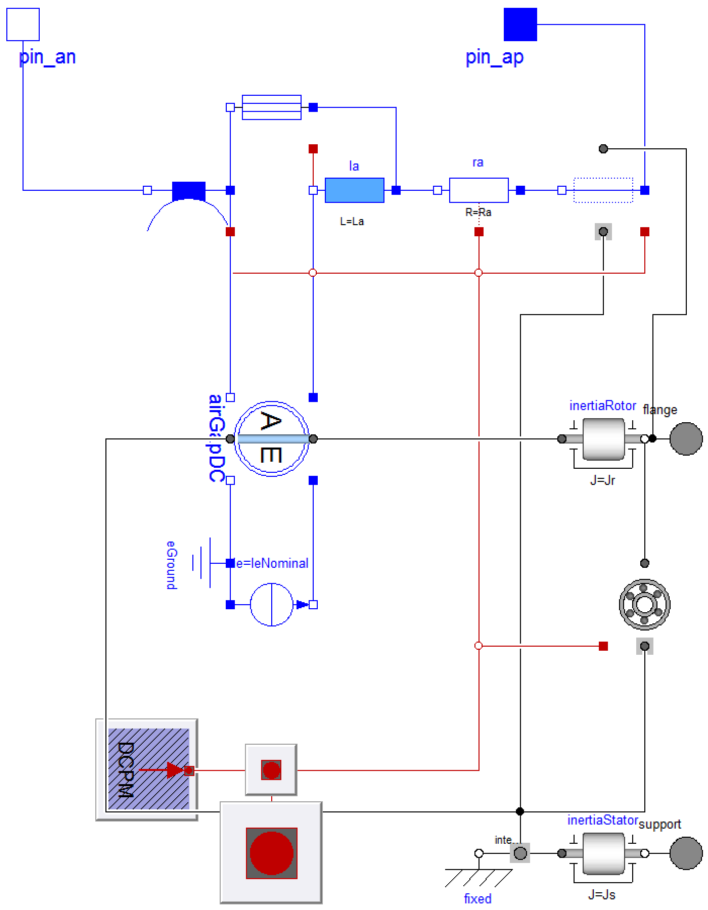
MGU and ES representation

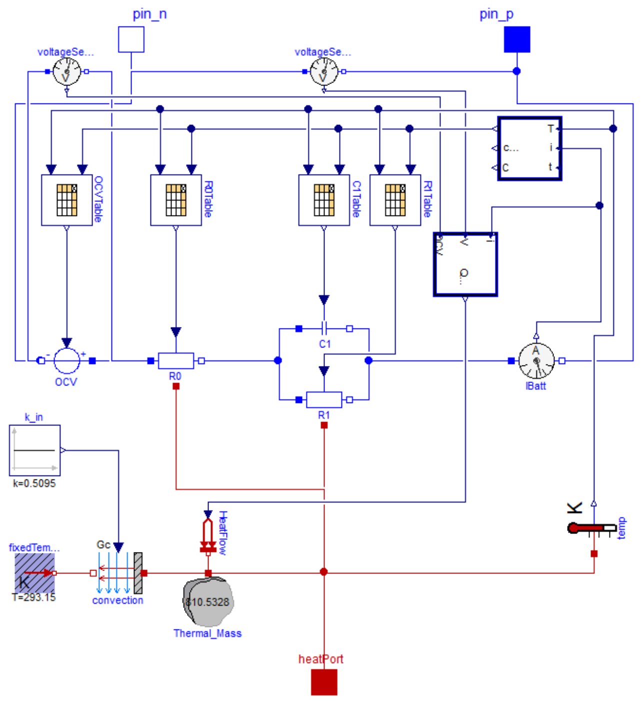
MGUH and MGUK

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



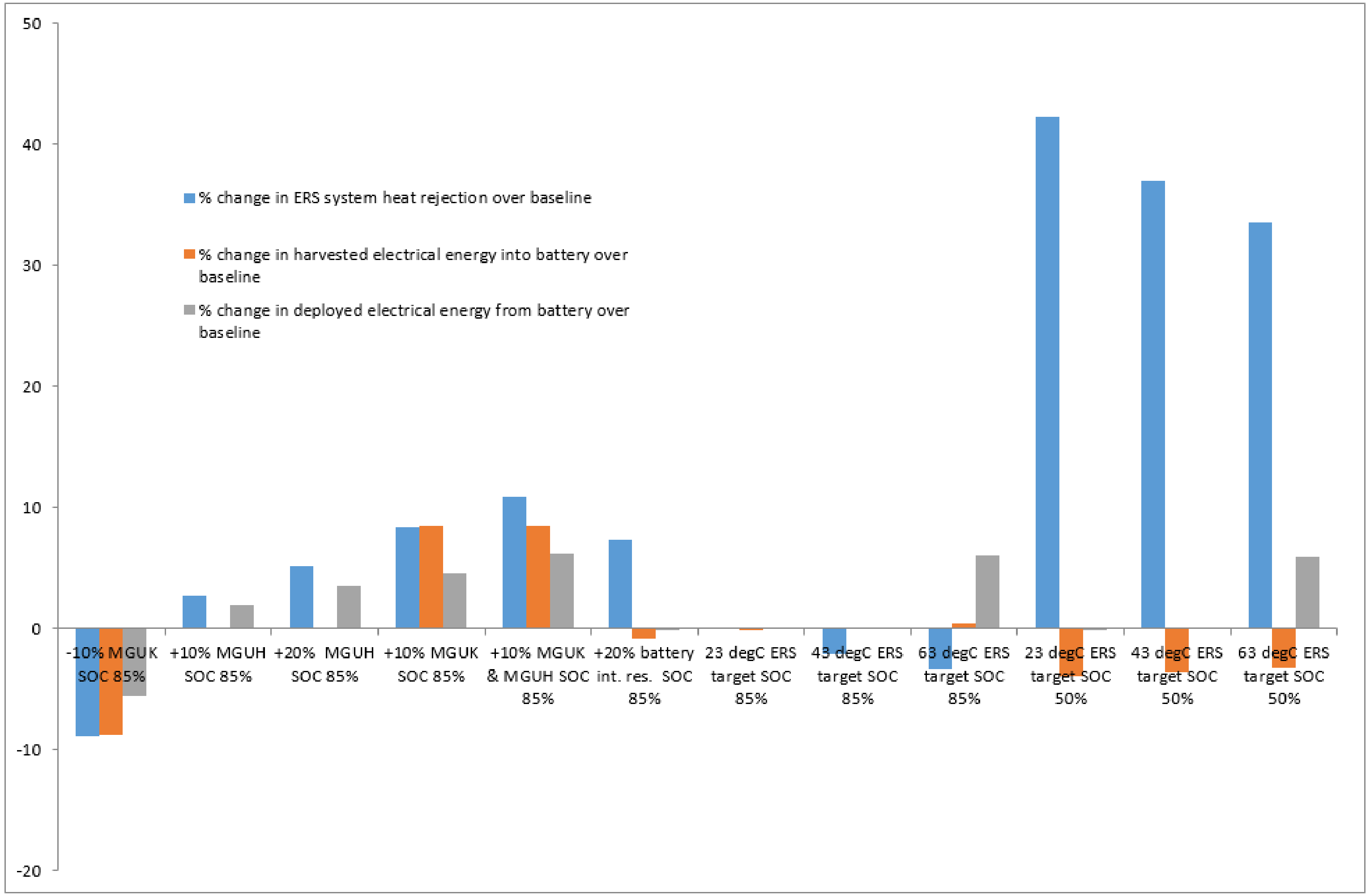
Battery Pack

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



Some results from this study

- 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



Summary

- Dymola can be used to create models of the complete vehicle
  - Engines, electric motors, battery, thermal management, suspension, etc.
- Using Dymola, new design ideas and concepts can be quickly modelled and evaluated
- Models can be easily reused for different types of analysis
- Supports optimisation of the system as a whole
- Models can be deployed to non-experts using FMI standard
  - Embed in existing trackside tools
  - Provide models to control engineers working in other tools such as Simulink
  - Distribute models with Excel as the user interface

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Contact

For further information please contact:

Mike Dempsey
Claytex Services Ltd.
Edmund House
Rugby Road
Leamington Spa
CV32 6EL
UK

Tel +44 1926 885900
Fax +44 1926 885910
mike.dempsey@claytex.com