Using physical models for powertrain and control system development

Future Powertrain Conference
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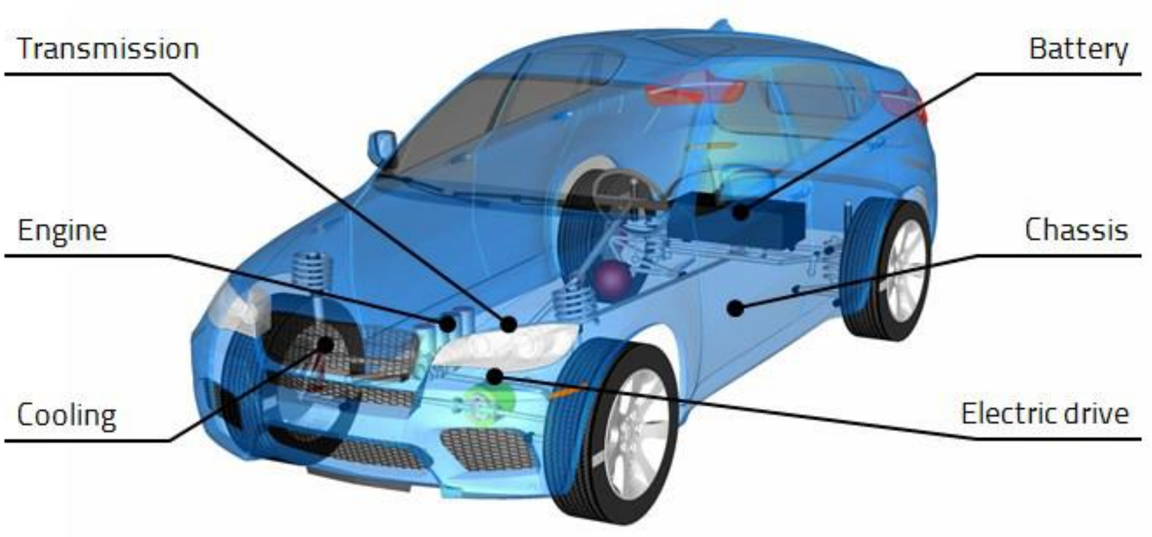
CLAYTEX

Claytex Services Limited

- Based in Leamington Spa, UK
  - Office in Cape Town, South Africa
- 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

Powertrain Challenges

- Market demands
  - Improved fuel economy
  - Lower emissions
  - Improved reliability
  - Noise quality
  - Driveability
  - Performance
- Engineering solutions
  - More active systems
    - Increases complexity
  - Better control of existing systems
    - Increasingly complex control requiring large calibration effort
  - Tighter integration of all vehicle systems
- Management demands
  - Faster time to market
  - Lower development and manufacturing cost



The need for physical modelling

- Automotive products are complex systems covering many domains
  - Mechanical, Electrical, Hydraulic, Pneumatic, Thermal, Chemical, Control, Magnetic, …
- No longer sensible to wait for prototypes to verify that all these systems interact in a good way
- It's not practical, or perhaps even possible, to fully verify and validate control systems using prototypes
- Need to use predictive models and not just functional ones to make simulation useful for control development from an early stage of the project

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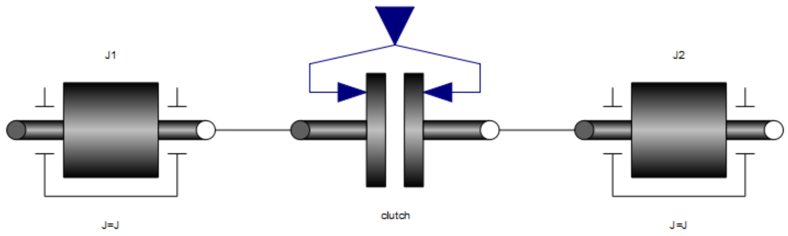
Functional and Predictive models

- 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

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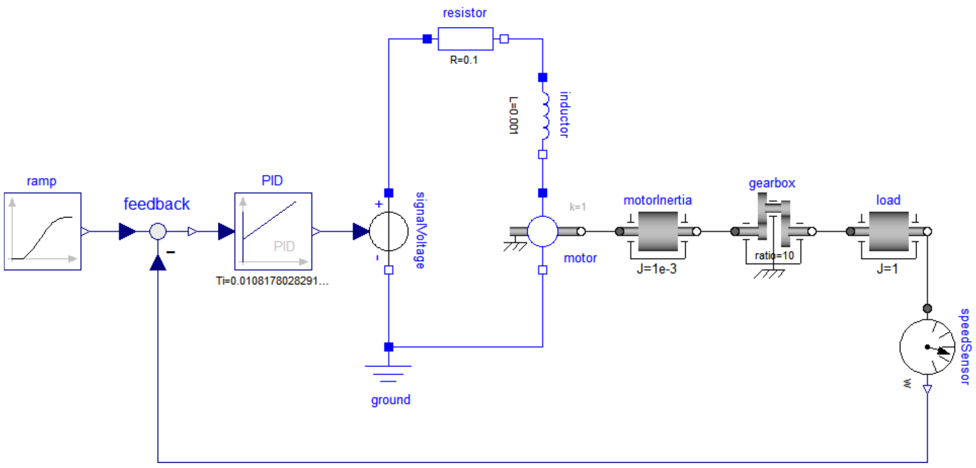
Multi-domain physical modelling

- Modelica
  - Open source, generic modelling language
  - Designed from the beginning to support a component orientated, physical modelling methodology
  - Developed by an independent, international organisation called the Modelica Association
    - Formed in 1996
- Dymola
  - Modelling and Simulation tool that uses Modelica
  - Extensive range of libraries built using Modelica covering all aspects of automotive products
  - Part of CATIA from Dassault Systemes and also available on the 3DEXPERIENCE platform



Dymola

MODELICA

CATIA

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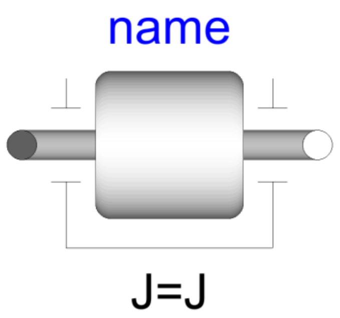
Modelling approach

- Modelica models are built from components that are defined from 1st principles
  - Modelica uses an equation based approach

```
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;
```



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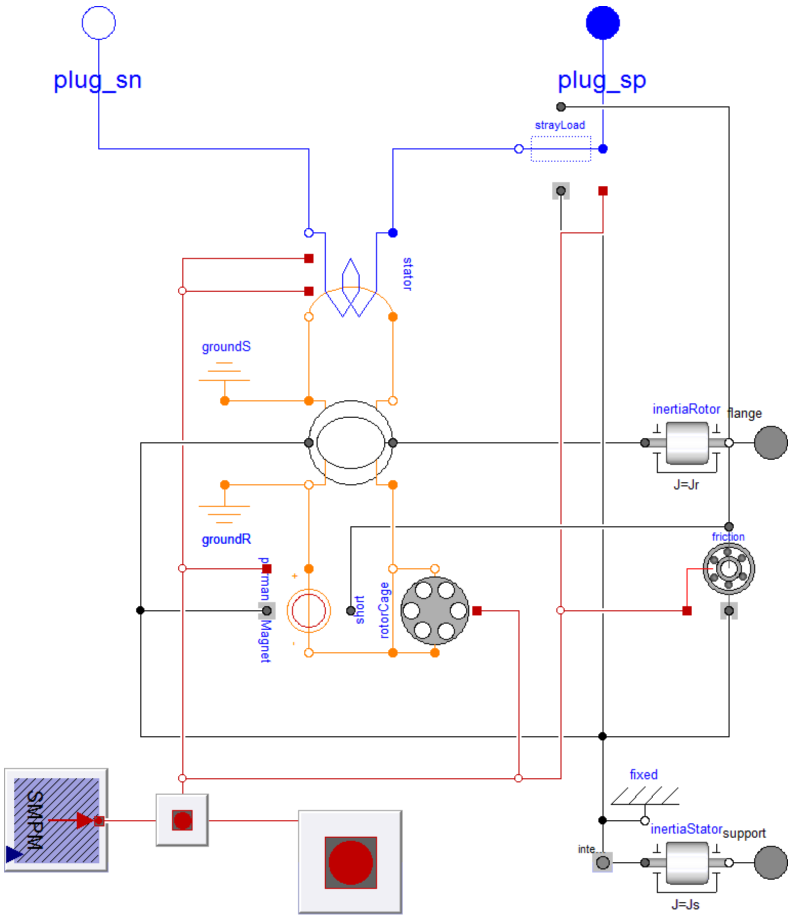
- The components are combined to define devices
  - Physical connections between components



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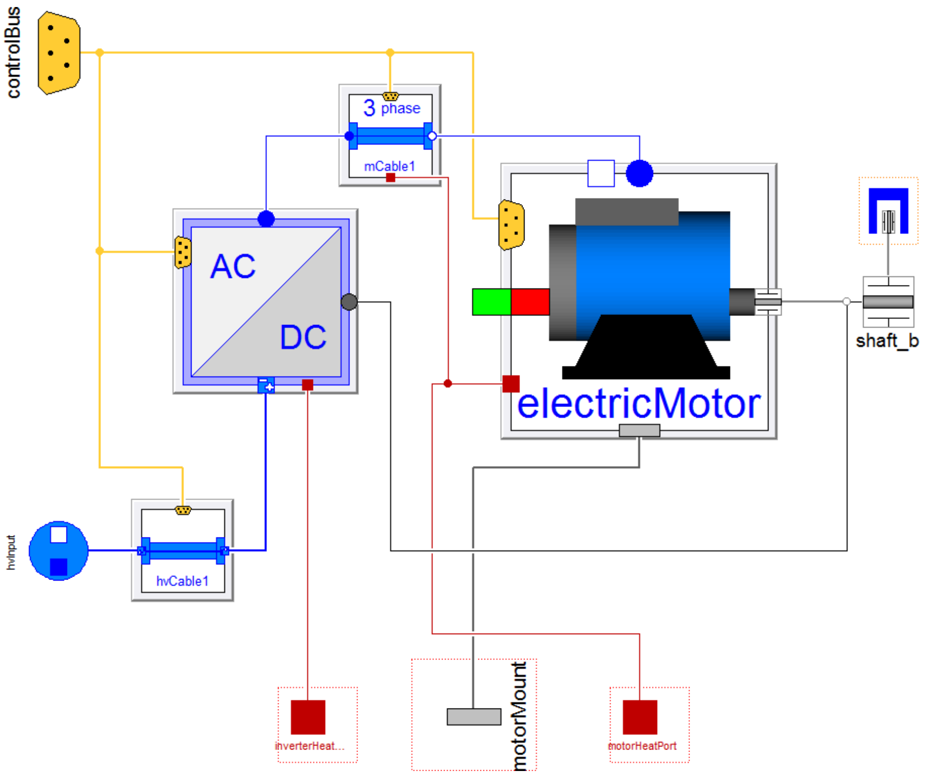
- From devices and components we create subsystems
  - Often using templates that make it easy to swap the model fidelity



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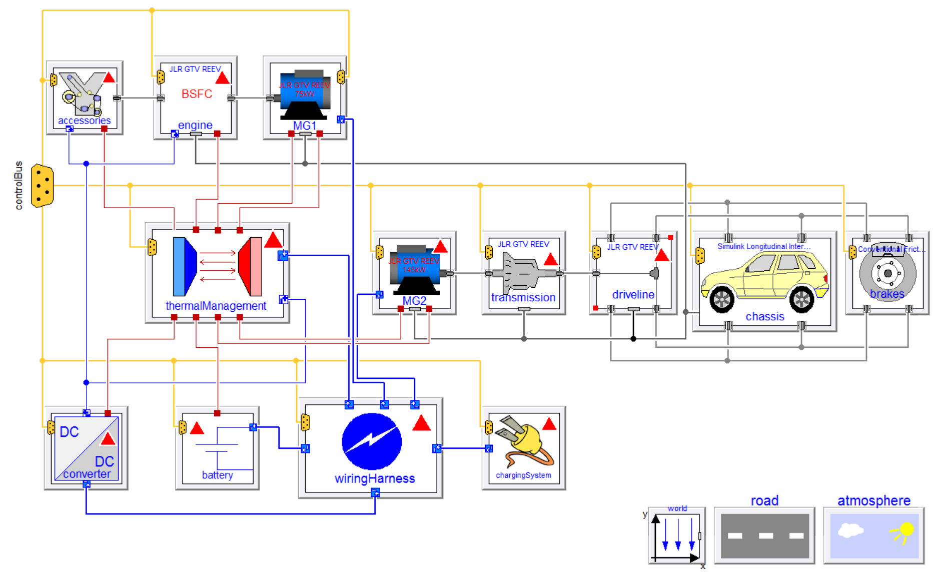
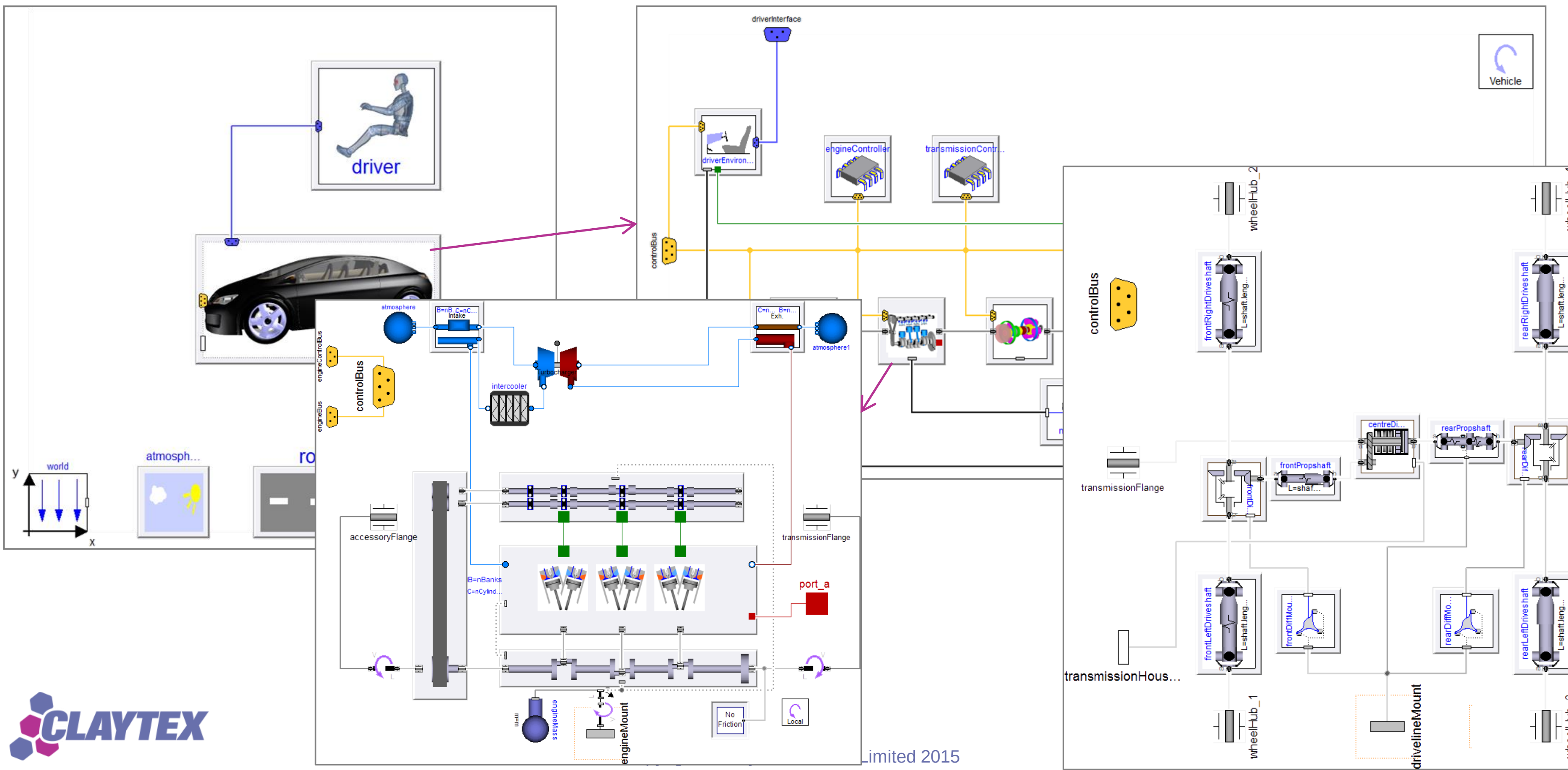
- From subsystems we create the whole vehicle model
  - Model architecture can be defined independently to promote reuse of subsystem models



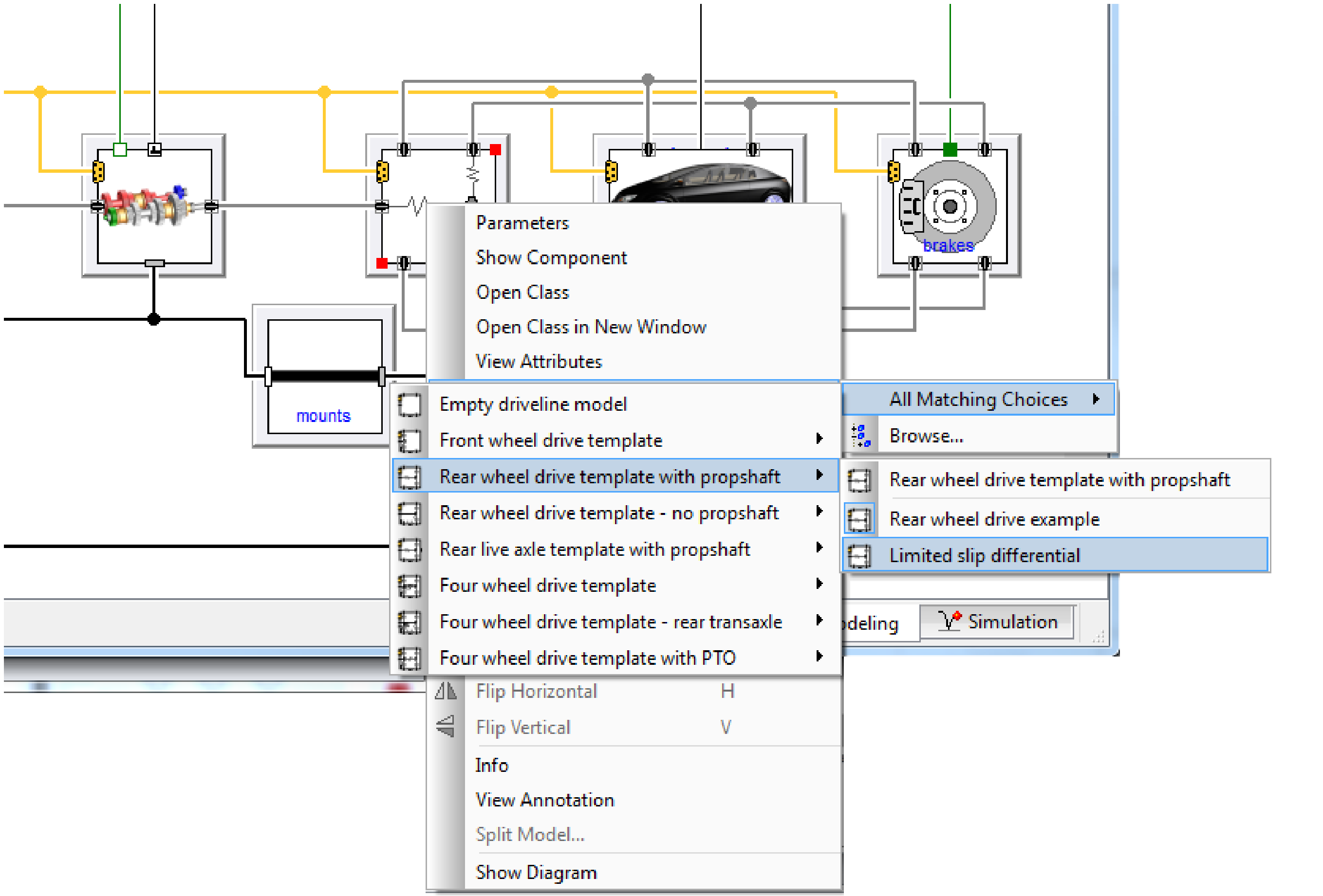
Automotive Model Architecture

- VehicleInterfaces is an open standard from Modelica Association
  - Designed to promote the easy coupling of libraries from different vendors
  - Supports 1D and MultiBody modelling and any combination of these



Automotive Model Architecture

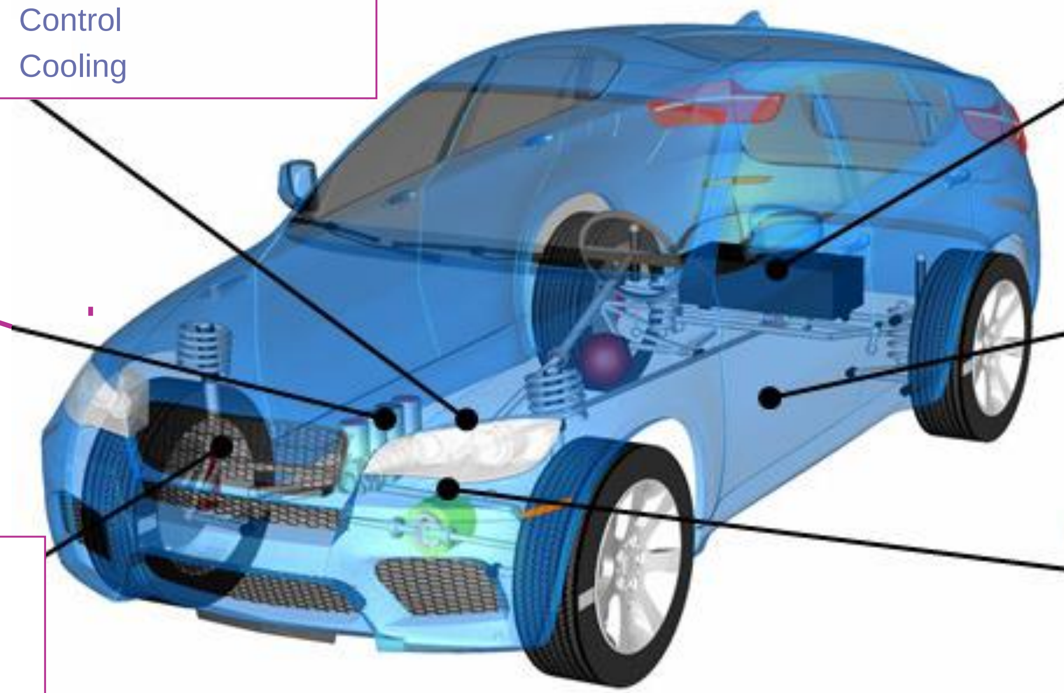
- Right click on subsystems to find compatible options to plug-in
  - Lists expand as you add your own models



Powertrain Modelling

- Gearbox and Driveline
  - Mechanics
  - Thermal
  - Hydraulics
  - Electrification
  - Control
  - Cooling

- Engine
  - Air flow
  - Mechanics
  - Cooling system
  - Fuel system
  - Control system
  - Electrification
  - Hydraulics



- Battery
  - Electrical
  - Thermal
  - Cooling
  - Control

- Chassis
  - Mechanics
  - Control

- Thermal Management
  - Engine Cooling
  - HVAC
  - Battery Cooling
  - Power Electronics Cooling

- Electric Drive
  - Electrical
  - Thermal
  - Control

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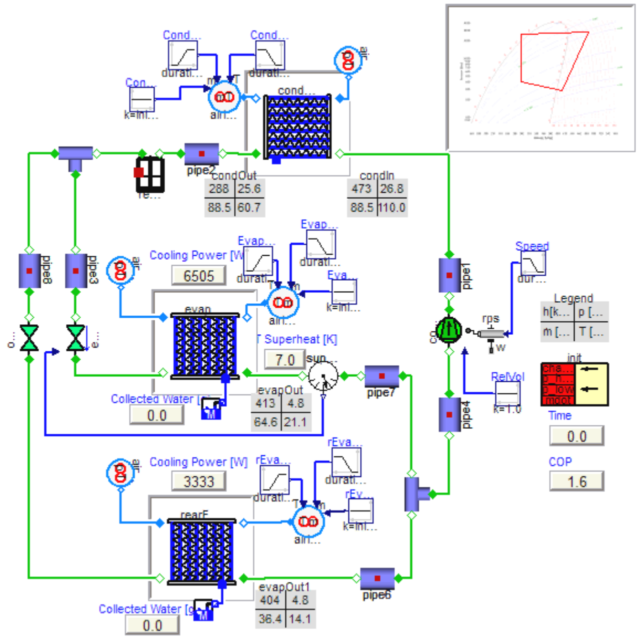
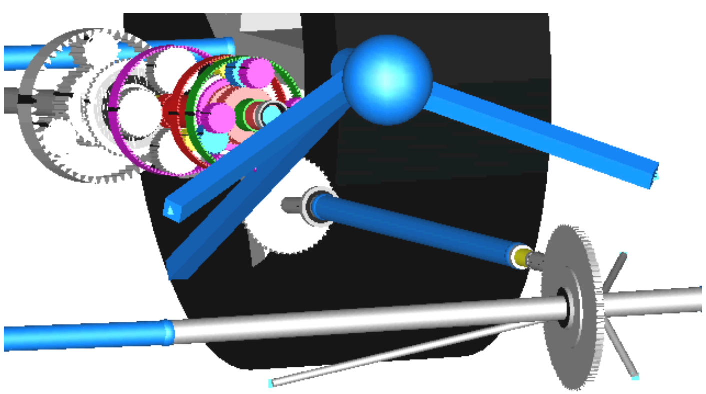
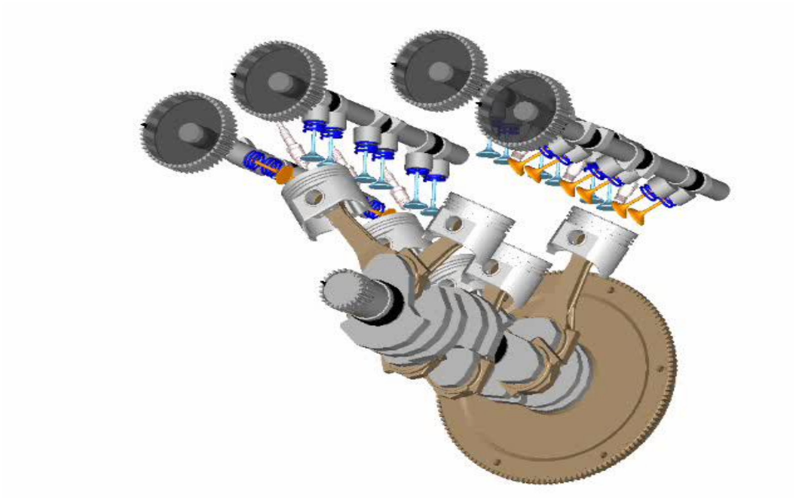
Automotive Application Libraries





- Air Conditioning
- Belts
- Batteries
- Engines
- E-Drives
- FlexBody
- Fuel Cell
- Heat Exchanger
- Human Comfort
- Hydraulics
- Liquid Cooling
- Pneumatics
- Powertrain Dynamics
- Simulator
- Smart Electric Drives
- SystemID
- TIL Suite
- Vapor Cycle
- Vehicle Dynamics
- VDLMotorsports
- XMLReader



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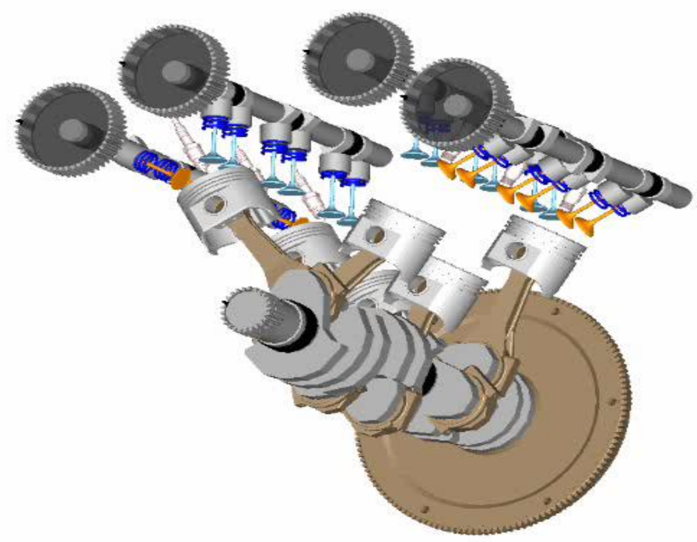
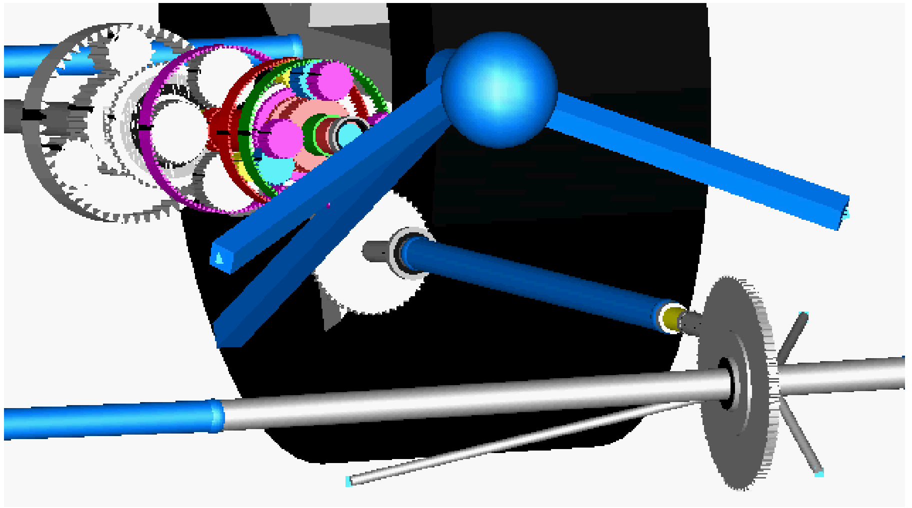
Powertrain Modelling

- Engines Library
  - Mean value and Crank angle resolved models
  - 1D thermofluid models of intake and exhaust
  - Multibody mechanics models
  - Include the cooling and lubrication ciruits
- Powertrain Dynamics Library
  - Map based engine models
  - Model fidelity ranges from simple drive cycle (1D models) to driveability, shift quality and launch feel (MultiBody models)
  - Include torsional compliance, backlash, joint dynamics, bearing effects, mesh stiffness
- Electric Drives Library
  - Batteries, Super Capacitor, PEM fuel cell
  - Power electronics, ideal power balance and detailed switching models
  - Quasi stationary models for fast simulation
  - Transient models for studying the detailed dynamics
  - Thermal effects in power electronics and machine models





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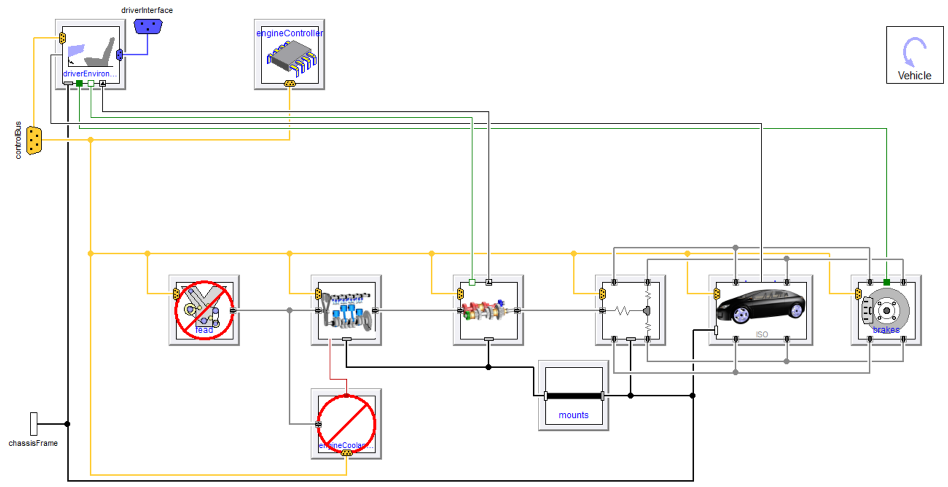
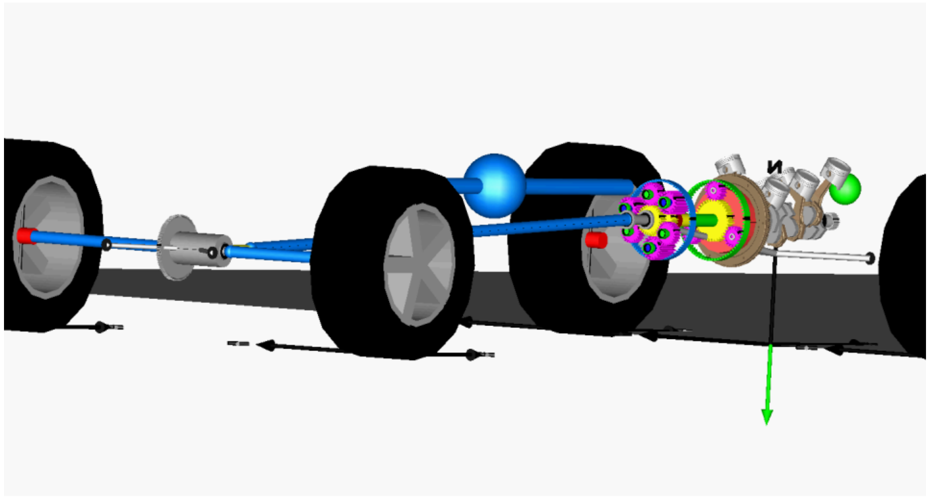
Concept Definition

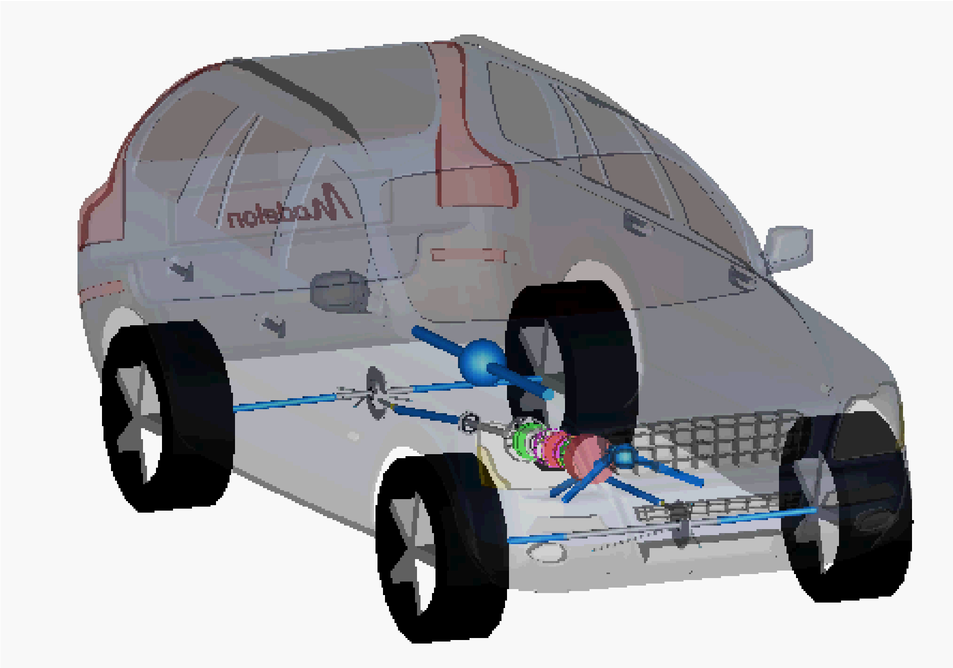
- Define the model architecture
- Powertrain Dynamics library includes animation while still modelling effects as 1D
  - More detailed effects can be turned on later
  - Minimal data requirements suitable for concept studies
- From an early stage understand the interaction of different systems
- Verify that targets are compatible and refine the hardware specification
  - Run performance tests, drive cycle tests, etc.
- Typically uses a mixture of functional and predictive models





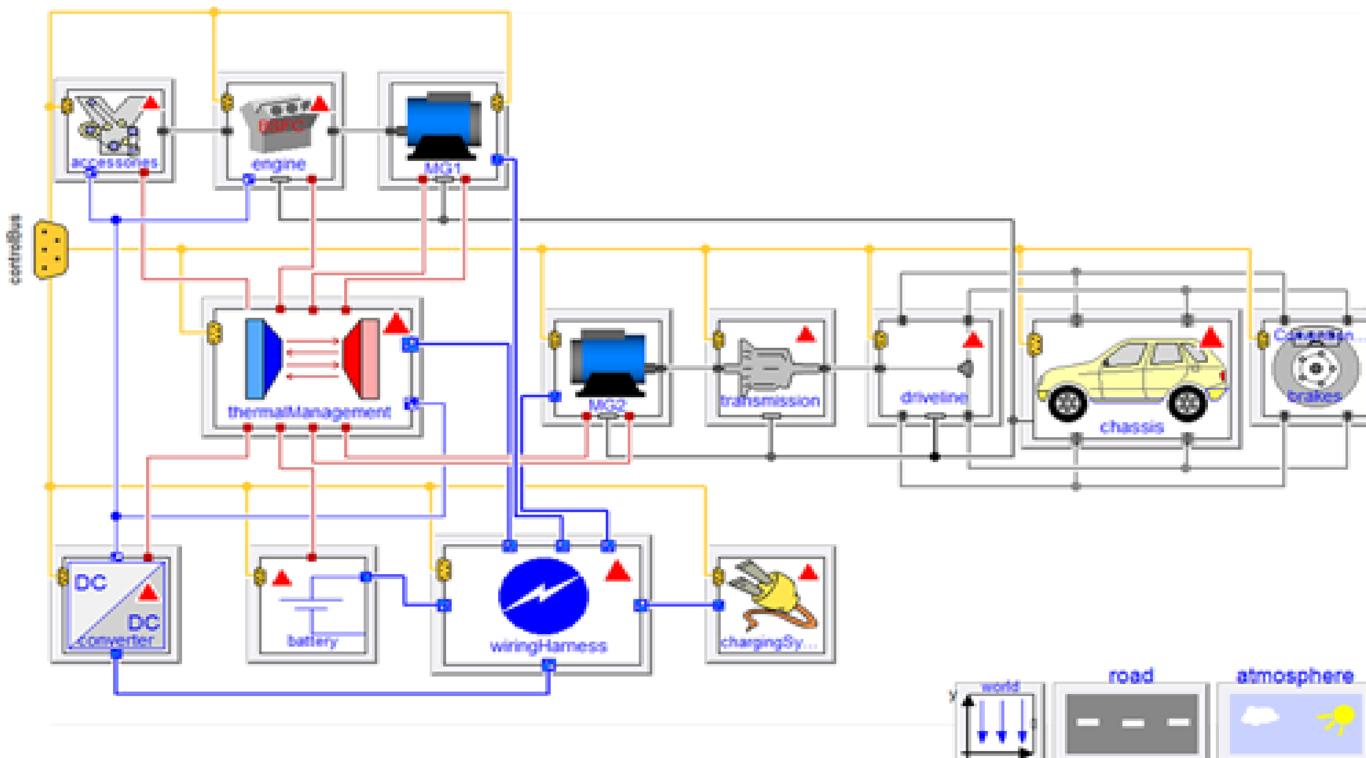
Driveability

- Predict the vehicle level response to tip-in and tip-out manoeuvres
- Same model architecture as used in the concept study but now using only predictive models
- Gearbox, Driveline and Chassis are now MultiBody system
- All powertrain systems are elastically mounted
- Enables the development of the control strategy
  - Develop the torque demand strategy by applying the controller demand to the flywheel and assessing the vehicle response
  - Later, introduce an engine model to validate the complete control strategy



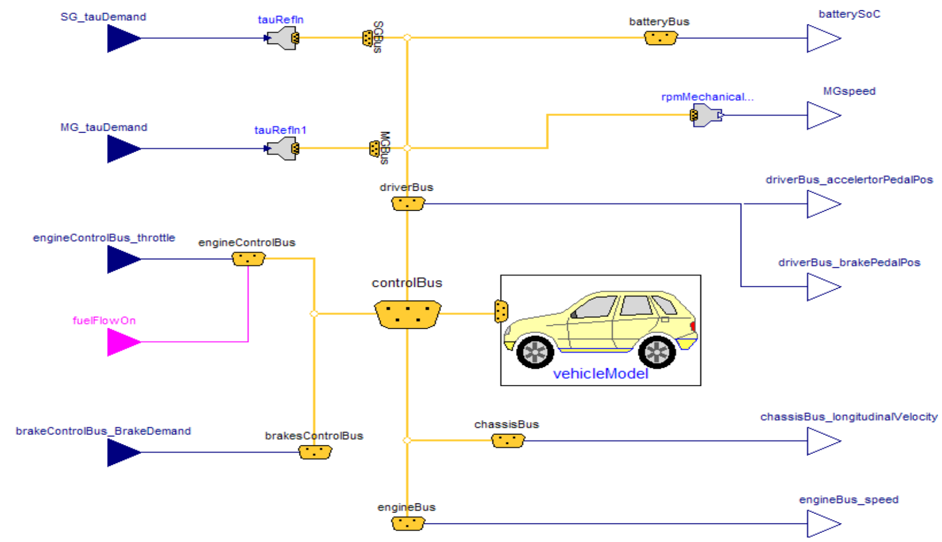
Whole vehicle efficiency

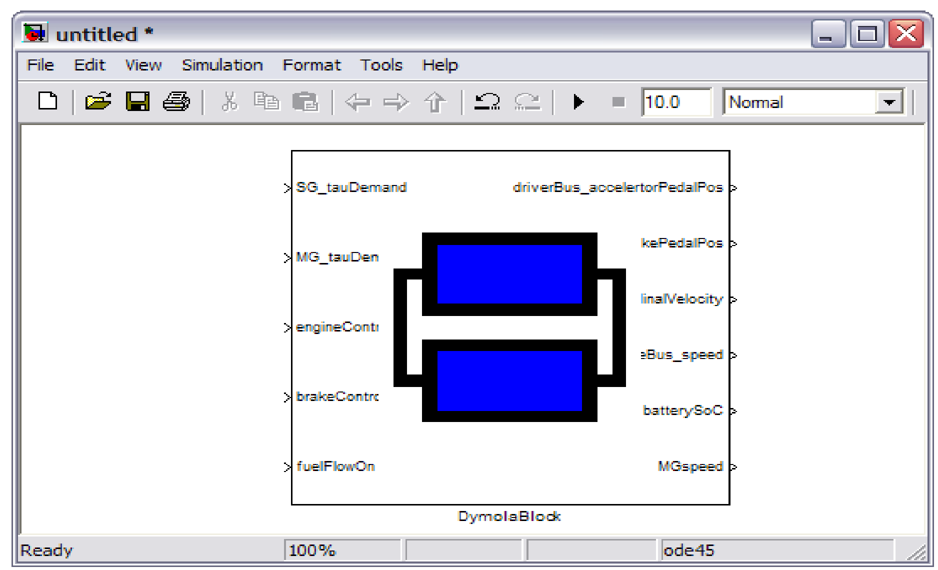
- The complete Hybrid vehicle powertrain can be modelled including the mechanical, electrical and thermal aspects of the whole system
  - Ancillary systems such as the AC system can all be included
- Enables the interaction of the whole system to be predicted
- Investigate overall vehicle efficiency and investigate ways to reduce energy consumption



Coupling to the control system models

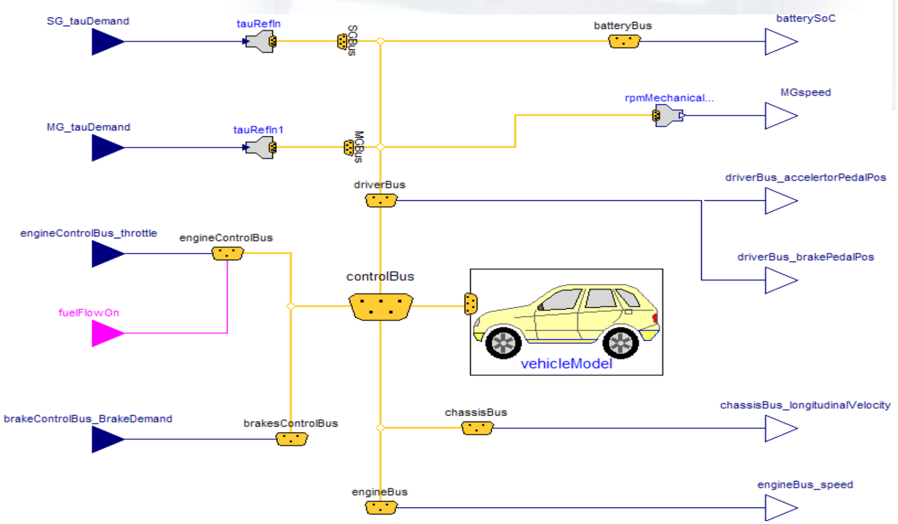
- Dymola supports the FMI standard
  - Allows the import and export of FMI compliant models
- FMI is an open standard for model exchange supported by over 50 different simulation tools
- Dymola models can be compiled and used in Simulink using the FMI Blockset for Simulink
- Simulink models can be compiled with Simulink Coder to be FMI compliant and imported into Dymola
- Dymola also supports the use of c-code





Hardware-in-the-Loop

- Dymola models can be compiled and run in real-time
  - Official support for dSpace, xPC, vTAG, PTWinSim
  - Also proved to work on Opal-RT, ADX, Concurrent and many more systems
- Special methods are used during the symbolic manipulation process to achieve real-time simulation of complex models
  - Inline integration
    - Combine the model equations with explicit or implicit Euler and Runge Kutta methods
  - Event handling during real-time simulation
    - Minimise the increase in turn around time at an event
- Specialised models are also available to achieve real-time performance of models with over 100,000 equations



Driver-in-the-Loop

- Dymola is now used by a number of Formula 1, NASCAR and IndyCar teams and organisations
- Provides the vehicle dynamics models that run in real-time on the new bread of engineering class simulators
  - For example: Ansible Motion platform
  - 6 dof platforms with fast response times matched to high quality vision systems
- Developed in Motorsport to enable detailed vehicle dynamics development with a human driver
- Dymola is able to generate MultiBody vehicle dynamics models that run in real-time

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For the future…

- We can already
  - build complex physical models of the complete vehicle
  - couple these models to other tools that support the FMI standard
    - Simulink via the FMI Blockset for Simulink,Simpack, Silver, ETAS, dSpace, etc.
  - run some of these models in real-time
    - E.g. Vehicle Dynamics for DiL, simple powertrain models
- What we are working on now is
  - expanding the range of model libraries to increase the level of fidelity available in some crucial areas
    - Batteries and Engines are the main focus
  - increasing the complexity of models that can be run in real-time to support increasing HiL and DiL usage
  - helping customers benefit from the modelling capabilities already available

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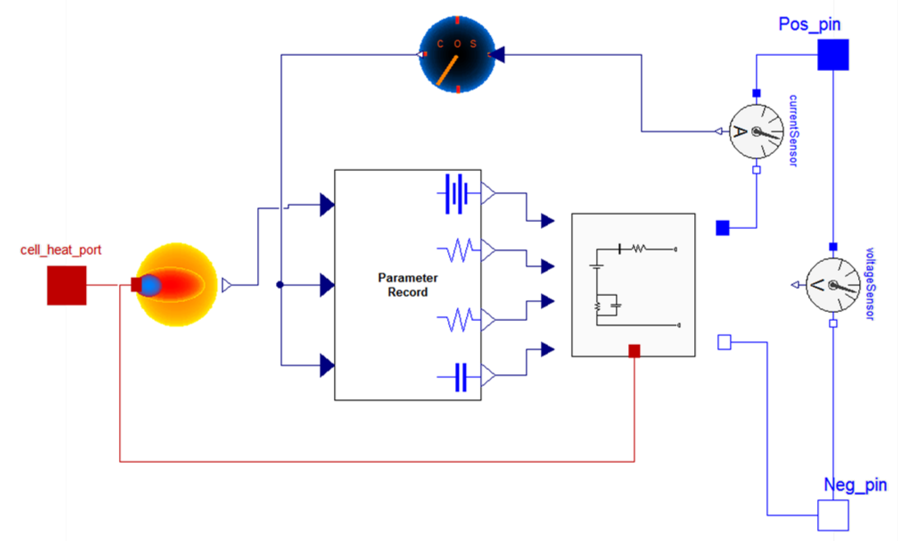
For the future – Battery Modelling

- Collaborative research project as part of the HVM Catapult with WMG and Jaguar Land Rover
  - 3 year project
- Aims to develop a Modelica library for modelling batteries from the cell level through to the complete battery pack based on research published by WMG and Jaguar Land Rover
- The solution will feature
  - Parameter estimation functions to define the cell models from test data capturing electrical, thermal and ageing effects
  - Cell models are, initially, 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
  - Easy integration with other Modelica libraries to define the complete electrical and thermal management system



The research described is supported by Innovate UK through the WMG Centre High Value Manufacturing (HVM) Catapult in collaboration with Jaguar Land Rover

For the future – Detailed models in Real-time

- MOdel-based Real-time Systems Engineering (MORSE)
  - Collaborative research project with Ford and AVL Powertrain UK
  - Co-funded by Innovate UK as part of the "Towards zero prototyping" competition
  - 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
- The focus for Claytex
  - Enhancement of the Engines and Powertrain Dynamics Libraries for real-time simulation
  - Addition of a more predictive model for combustion
  - Introduction of warm-up throughout the driveline system
  - Extend the range of applicability for the libraries to include a wider range of driving scenarios
    - Vehicle launch at any temperature, Tip-in, Tip-out, Start-stop, etc.
  - Bring powertrain simulation to the same level as our existing real-time vehicle dynamics solutions and support HiL and DiL

Go Further

Innovate UK
Technology Strategy Board

Summary

- Modelica is a powerful modelling language well suited to Model Based Design of Automotive products
  - Multi-domain, component orientated modelling
- Allows us to easily create complex multi-domain physical models of powertrains to predict their behaviour
  - Extensive range of application libraries for Automotive Powertrain
- Dymola enables the same model to be used for desktop simulation and XiL simulation including providing support for real-time simulation
- Significant development projects to continually increase the sophistication of the model libraries and enable more detailed models to be run in real-time

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