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Real-time simulation of the 2014 Formula 1 car

Abstract

In 2014 a new powertrain specification will be introduced in to Formula 1. This new specification will change the internal combustion engine to be a 1.6 litre V6 turbocharged spark ignition engine with increased use of Energy Recovery Systems (ERS).

Dymola is already used by several Formula 1 teams for many different applications. The aim here is to show how it can be used to model the 2014 specification car to start optimising the whole car at an early stage. The model presented includes the new powertrain specification together with a complete multibody vehicle dynamics model that can run in real-time. This model is suitable for use in many applications including use in a driving simulator.

Introduction

The 2014 Formula 1 Technical Regulations [1], published in July 2011, mark a significant change in the Formula 1 powertrain design for the 2014 season. Both the capacity and engine speed will be reduced compared to 2012. Turbochargers will be reintroduced for the first time since the late 1980's in an effort to maintain the power when produced by smaller engines.

The ERS will replace the previous Kinetic Energy Recovery System (KERS), delivering increased power. ERS will incorporate two motor generator units, connected to the engine crankshaft and turbocharger respectively. In addition to providing power boost, the ERS will be used to propel the car when in the pit lane. The gearbox will contain 8 forward gears plus reverse gear.

For 2014 the engine will be a 90 degree V6 arrangement with a 1.6 litre capacity and maximum speed of 15000rpm. The engine will have 2 inlet and 2 exhaust valves per cylinder, no variable valve timing or variable valve lift. The fuel mass flow rate must not exceed 100kg/h and below an engine speed of 10500rpm the fuel flow rate is limited according to the following formula:

$$Q\left(\frac{kg}{h}\right) = 0.009N(rpm) + 5$$

A single stage turbocharger will be permitted, but it must not use variable geometry or variable nozzle turbines.

The car will operate in Electric Mode in the pit lane, the engine fuel supply and ignition source will be stopped and the ERS will propel the car. The driver will therefore require an on-board starter device for restarting the engine when exiting the pit lane.

The ERS will consist of:

- Motor Generator Unit – Kinetic (MGUK),
- Motor Generator Unit – Heat (MGUH),
- Energy Storage (ES).

The MGUK is comparable to KERS. The motor generator will be mechanically linked to the drivetrain with a fixed speed ratio to the crankshaft, which could be clutched. The maximum power delivered by the MGUK to propel or brake the car will be no greater than 120kW. The energy stored from MGUK to the ES will not exceed 2MJ per lap and the energy used by MGUK from the ES will not exceed 4MJ per lap. The electrical output of the MGUK will be measured.

The MGUH will be mechanically linked to the exhaust turbine of the turbocharger with a fixed speed ratio, which could be clutched.

The ES stores energy from the ERS. The form of storage is not specified by the regulations; however its total weight will be between 20 and 25kg. When the car is on track the delta between the maximum and minimum states of charge will not exceed 4MJ. Measurements will be taken at the input and output of the ES.

These changes in the powertrain specification introduce a number of challenges for the teams. The overall control strategy of the powertrain will need to be optimised to deliver the performance, fuel economy and driveability targets to enable the drivers to achieve the best lap time. At the same time the systems place an increased demand on the engine and electronics cooling systems.

Dymola Model Overview

Model Architecture

A complete model of the 2014 Formula 1 car including the engine, gearbox, energy recovery systems and chassis has been created in Dymola. This model is based on a number of the commercial Modelica libraries: Engines [2], VDLMotorsports [3], Alternative Vehicles [4] and uses the Vehicle Dynamics Library [5] model architecture as the framework to integrate the systems.

The top level of the vehicle model is shown in Figure 1 and consists of the driver, car, track and environmental conditions. The car model is broken down in to the major subsystems: engine, transmission, driveline, chassis and brakes. The ERS is included within the engine model.

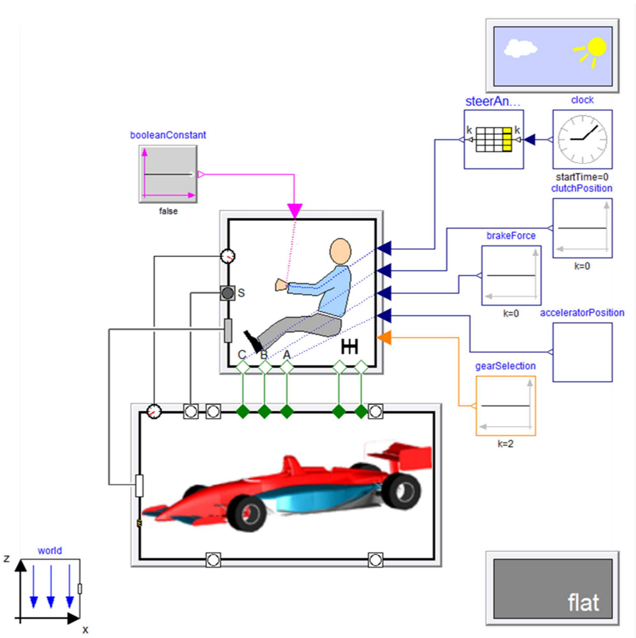

Figure 1: Complete vehicle model with open loop driver model

The model architecture makes use of the Modelica replaceable classes concept which makes it very easy to plug-in different fidelity models in to each part of the model. For instance, a simple ideal gearbox can be replaced with a high fidelity model including all of the shift mechanism details without requiring changes to the other surrounding models.

Engine Model

The Engines Library [6], [7], has been used to create a model of the 1600cc V6 turbocharged engine to be used in 2014. This model includes all the major features of the engine formula including the motor generators attached to the turbocharger and crankshaft, the intercooler and the cooling systems.

A mean-value engine model has been used to enable us to achieve real-time simulation whilst still capturing the major transient effects that influence the performance and driveability of a turbocharged engine. The model includes air-flow through the intake, turbocharger, intercooler and exhaust systems capturing the pressure and temperature transients. The mean-value combustion model takes in to account these effects together with the afr, spark timing and other factors to determine the torque output and exhaust gas temperature.

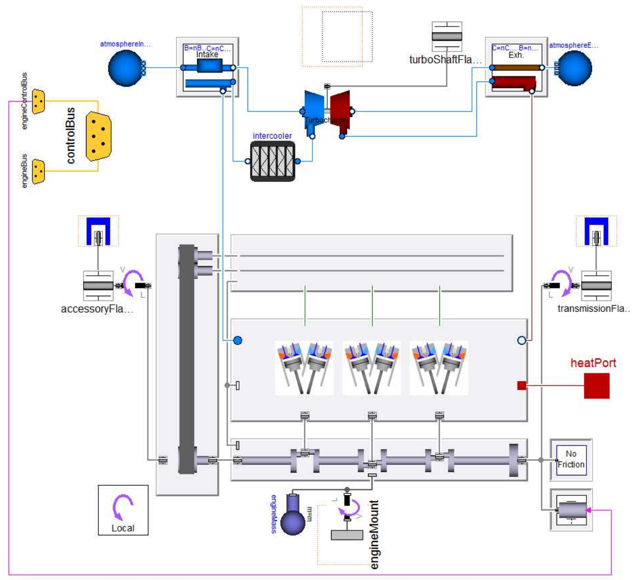

Figure 2: V6 turbocharged engine model

The Engines Library supports both mean-value and crank-angle resolved engine models and the model architecture, shown in Figure 2, is common to both. The only changes required to switch from a

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mean-value model to a crank-angle resolved model is to include the valve train and change the combustion model. The piston mechanics, crankshaft and intake and exhaust models do not have to be changed.

Using a crank angle resolved engine model we could investigate the torque pulsations due to each firing event and look in detail at the pressure and temperature during the engine operation. This includes being able to explore effects such as split injection, multiple injection and cylinder deactivation.

ERS Model

The engine and ERS model is shown in Figure 3. The crankshaft is coupled to an electric motor-generator through a gearset in the mGUK block. The motor-generator can be used to assist the traction torque of the engine or recharge the battery during braking. Compared to the current (2012) specification KERS, the 2014 specification will support a higher power output from the motor-generator and allow more energy to be stored in the battery each lap.

The turbocharger shaft is also gear-coupled to an electric motor-generator and can be used to spin up the turbocharger to improve throttle response. This is modelled in the mGUH sub-system. It can also be used to control the turbocharger shaft speed and recharge the battery if excess turbocharger shaft power is available. This part of the system is called MGUH.

The model enables the control strategy to be developed and refined by exploring the overall system characteristics and interactions. For example, the model can be used to identify when it would be possible to use the MGUH to charge the battery or power the MGUK directly without storing the energy.

The electrical systems are modelled using a table based approach as defined in the Alternative Vehicles Library. These models capture the main characteristics of the motors and power electronics whilst enabling the simulation to run in real-time. For more detailed analysis the higher fidelity motors and power electronics models from the Smart Electric Drives Library [8] could be used to replace the real-time models.

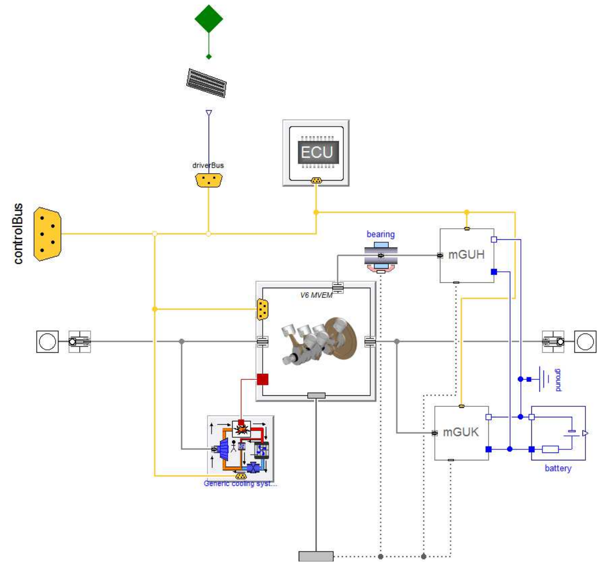

Figure 3: Engine model including ERS, ECU and cooling system

Cooling System Model

The cooling system for the engine and power electronics can be incorporated in to the model. Figure 4 shows the inclusion of the Engine Cooling system which could be modelled as a lumped capacitance heat transfer network or as a 1D thermofluid system as shown in Figure 4. The level of detail in each of the components can be varied to support simple sizing studies as well as the detailed investigation of heat exchanger geometries and stacking effects.

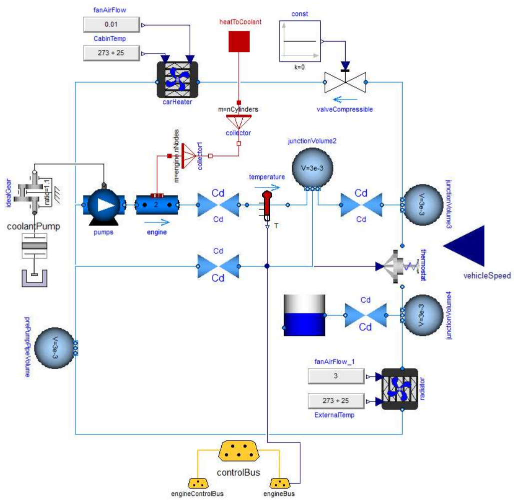

Figure 4: Engine Cooling System modelled as a 1D thermofluid system

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Transmission and Driveline Model

In this example the focus of the modelling effort has been on the engine, ERS and chassis systems with the aim of achieving real-time simulation. The transmission and driveline models are, therefore, low fidelity models with idealised shift dynamics. Using other Modelica libraries like the Powertrain Dynamics Library [9] it would be possible to include more detailed models.

Using the Powertrain Dynamics Library it would be possible to include detailed models of the transmission and driveline to capture the full torsional response of this system including the shift dynamics. An example gearbox model is shown below in Figure 5 that includes the individual bearings with friction, mesh points with efficiency, stiffness and backlash and torsional compliance in all the shafts.

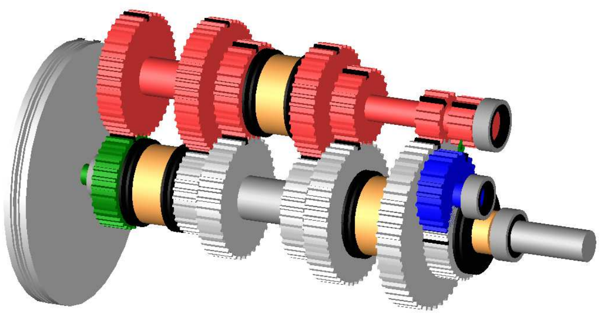

Figure 5: Animation of a gearbox model in Dymola

Chassis Model

The VDLMotorsports Library has been used to create a full multibody chassis model, the architecture of which is shown in Figure 6. A similar application of this library is described in [7]. The library contains a number of double wishbone suspensions with pushrod and pullrod examples with different rocker arrangements for anti-roll and heave control. The compliance in the chassis can also be optionally modelled.

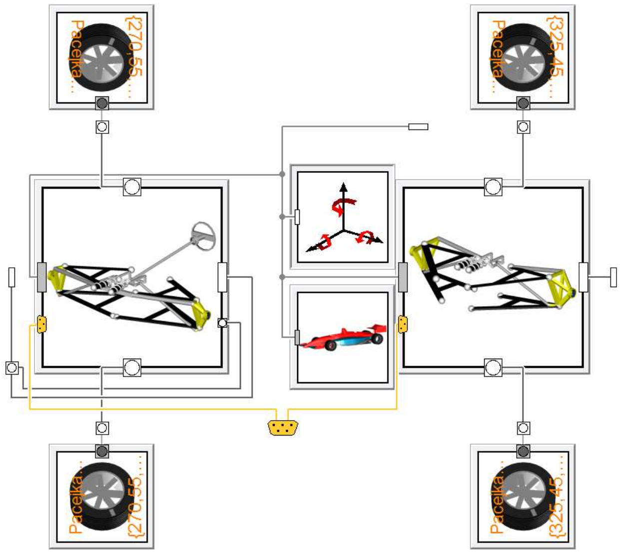

Figure 6: Chassis model

The suspension model incorporates the adjustments to enable the suspension setup to be defined in a realistic manner. Once the basic geometry of the suspension is defined the characteristics can be adjusted by changing the shim thickness in the pushrod and suspension links. The library contains setup experiments for determining the adjustment shims and preloads required to achieve the desired suspension setup.

The tyre model uses the Pacejka 2002 tyre slip model to calculate tyre forces. The model architecture for the tyre makes it very easy to replace this slip model with your own in-house model that could be written in Modelica or as C-code and linked to Dymola.

Aerodynamic effects are included in the car body model, which features separate aerodynamic models for the body, front and rear wings and tyres. Simple aerodynamic models are used based on coefficients but these can easily be extended to use available aerodynamic data.

Example Applications

Dymola enables the use of the models in a wide variety of ways to maximise the reuse of the model through its application to different types of analysis and deployment in to 3rd party applications.

Within Dymola the created model, or any of the subsystem models, can be used in an experiment to investigate their behaviour. Dymola's acausal modelling methodology means that the same model can be used without modification in many different simulations to explore different aspects of its behaviour. The optimisation feature can be used to run multiple parameter, multiple case optimisation studies. In addition the scripting language enables the automation of a sequence of tests including the post-processing of the simulation results.

A typical use case of the models would be to explore the fuel economy and control strategies to minimise the fuel used while also minimising the lap time. The operation of the ERS system will have a significant impact on this and needs to consider effects on the car stability during braking and how an when during a lap the system can be used to accelerate the car.

Thermal management of the engine and power electronics is another significant area that needs to be analysed in detail and will also affect the control strategy and operation of the ERS.

Further options within Dymola then enable the models to be used in Simulink and other 3rd party tools and to be compiled for use in HIL and Driver-in-the-loop environments.

Integrate with Simulink

Dymola supports a number of different ways to integrate models with control system models in Simulink. The 3 main options available are:

1. Export the Dymola model as an s-function that uses the Simulink solver [10], [11]
2. Export the Dymola model as an FMU [12] that runs in co-simulation with Simulink [13]
3. Import the Simulink model after compiling it with the Simulink Coder [14]

The appropriate choice really depends on your application and the complexity of the physical model.

The FMI Blockset for Simulink [14] allows models that are exported from Dymola as FMU's to be imported into Simulink. An FMU is a Functional Mock-up Unit and means a model compiled and exported from Dymola that is compliant with the FMI Standard [15]. The exported model runs with its own solver in co-simulation with Simulink. This approach enables the control engineer to use a complex physical model while continuing to work in the Simulink environment on the refinement of the control software.

Figure 7 shows the use of an FMU within Simulink and Figure 8 shows the FMI Blockset for Simulink user interface that enables you to load the FMU and set its' parameters.

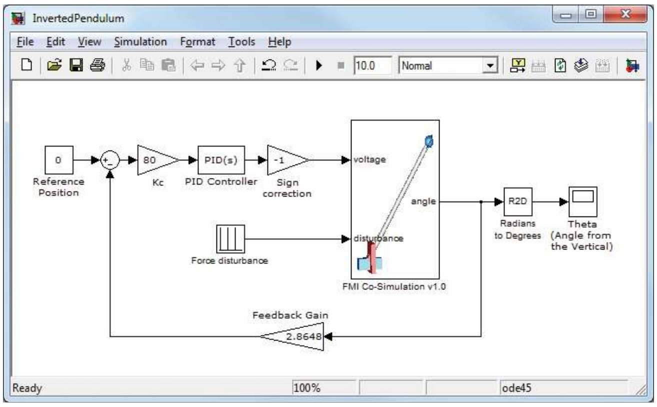

Figure 7: Simulink model including a Dymola generated FMU

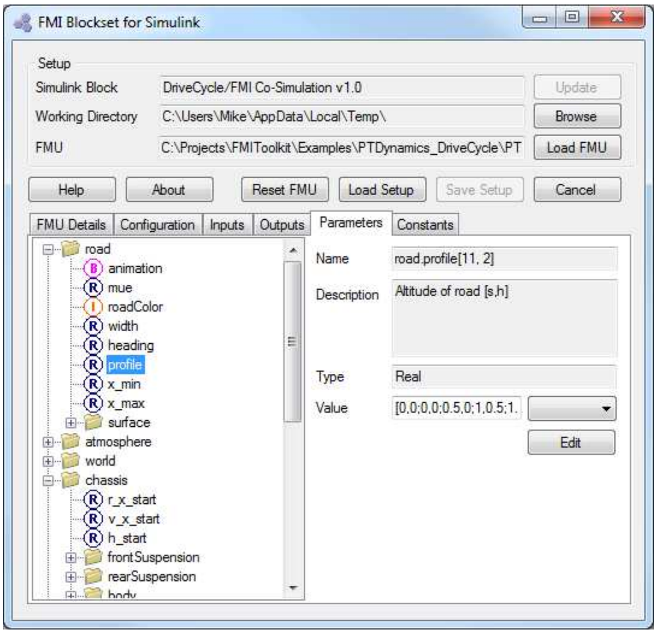

Figure 8: User interface for the FMI Blockset for Simulink

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HIL Simulation

Dymola supports the use of HIL systems such as dSpace, xPC and vTAG for real-time simulation. To achieve this, a technology called inline integration is used. This means that the model equations and the integration algorithm are combined and then symbolically manipulated to generate the most efficient simulation code possible. This code is optimised to run at a fixed step size and includes special methods to handle events and nonlinear systems of equations to minimise the number of iterations that might occur at each time step.

In this case, inline integration with an implicit Euler method optimised for a 1ms time step is used. Additional advanced settings for real-time simulation are also used to tune the performance of the model and these are described in section 6.3.3 of the second volume of the Dymola documentation [16].

To test the model performance in Dymola before exporting the model and integrating it with the real-time system we create an experiment that runs the main model through different transient events. This enables the model and real-time settings to be fine-tuned on the desktop.

Figure 9 shows the turnaround time when running this experiment on our test PC. The analysis shows that for the majority of the simulation the turnaround time for each solver step is around 0.7ms and well below the available 1ms. At isolated points in the simulation, namely when heavy ERS assist or regen starts, overruns are observed. It is expected that with further refinement of the model it would be possible to reduce and even completely eliminate these spikes. Most real-time systems are able to tolerate occasional overruns such as these.

Integration with vTAG

Models exported from Dymola are compatible with the range of vTAG tools [17]. This is achieved by exporting the model from Dymola using the Binary Model Export [18] or Source Code Export [19] options together with the real-time simulation techniques. McLaren Electronics then provide a tool called DMI (Dynamic Model Integrator) that takes the exported

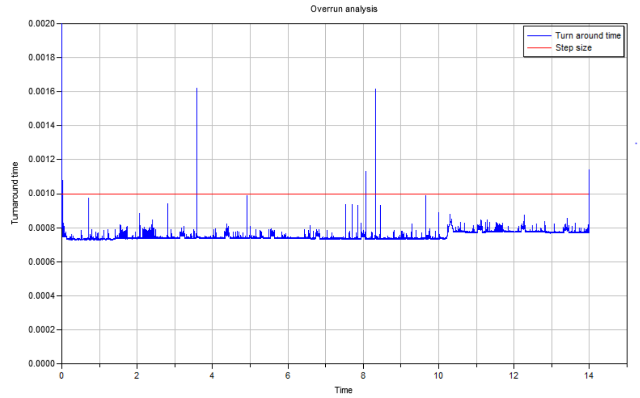

Figure 9: Turnaround time running with 1ms time step on test PC

model and builds it into an App for use in the vTAG products.

This capability enables a number of additional uses for the models including:

1. Software-in-the-loop (SIL) testing of the Formula 1 ECU together with a complex physical model using vTAG-310
2. Hardware-in-the-loop testing running the model in a hard-real time environment using vTAG-RT
3. Integrating the model in to the telemetry data stream using vTAG Server

Driving Simulator

Dymola generated MultiBody vehicle models are successfully used on several driving simulators to provide the physics model of the car [7]. These systems are currently in use in a variety of race series including Formula 1.

A number of different motion platforms and graphics solutions have been used together with Dymola models running on a variety of platforms including Window's PC's, vTAG, dSpace and other real-time operating systems.

Integration with in-house tools

Using the source code and binary model export options it is also possible to integrate the models in to other systems. Dymola models have been successfully used within trackside and lapsim tools enabling the same model to be used across the team.

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This approach enables the models used within the trackside and lapsim tools to be quickly updated to the latest car specification as soon as the model development is completed.

For use in lapsim applications the model equations are coupled to a QSS solver or optimisation routine and used to solve the quasi-static problem at each point around the lap. For integration in trackside tools, the model equations and integration method are exported as one object and integrated in to the existing tool as a Windows dll or FMU.

Conclusions

Dymola enables a complete model of the Formula 1 2014 specification car to be modelled and simulated in a variety of different ways. The Modelica based modelling approach means that the models can be quickly created from a number of existing, and proven, application libraries minimising the model development time. This means more effort is spent on the development, integration and optimisation of the new systems.

Dymola enables the same model to be used for many different applications including different types of analysis on the desktop as well as integration with other parts of the development process such as SIL, HIL and Driver in the loop testing. By using a physical modelling tool to provide the models for all of the systems quickly and efficiently there is a reduction in the modelling effort across the team and an improvement in the consistency of the tools used.

References

[1] 2014 F1 Technical Regulations, 20 July 2011, FIA, http://www.fia.com/sport/Regulations/f1regs.html

[2] Engines Library, http://www.claytex.com/products/dymola/model-libraries/engines-library/

[3] VDLMotorsports Library http://www.claytex.com/products/dymola/model-libraries/vdlmotorsports-library/

[4] Alternative Vehicles Library, http://www.claytex.com/products/dymola/model-libraries/alternative-vehicles-library/

[5] Vehicle Dynamics Library, http://www.claytex.com/products/dymola/model-libraries/vehicle-dynamics-library/

[6] Dempsey M. Picarelli A. Investigating the MultiBody Dynamics of the Complete Powertrain System. Como, Italy: Proceedings 7th Modelica Conference, 2009.

[7] Dempsey M., Fish G., Picarelli A,. Using Modelica models for Driver-in-the-loop simulators. Furstenfeldbruck, Germany: Proceedings 9th Modelica Conference, 2012

[8] Smart Electric Drives Library, http://www.claytex.com/products/dymola/model-libraries/smart-electric-drives-library/

[9] Powertrain Dynamics Library, http://www.claytex.com/products/dymola/model-libraries/ptdynamics-library/

[10] Dymola Simulink Interface, http://www.claytex.com/products/dymola/features/simulink-interface/

[11] Dymola Users Manual Volume 2, Dymola 2013 version, Page 230-240

[12] Dymola Users Manual Volume 2, Dymola 2013 version, Page 265-268

[13] FMI Blockset for Simulink, http://www.claytex.com/products/fmi-blockset-for-simulink/

[14] Dymola Users Manual Volume 2, Dymola 2013 version, Page 269-273

[15] FMI Standard, https://www.fmi-standard.org

[16] Dymola Users Manual Volume 2, Dymola 2013 version, Page 240-255

[17] McLaren Electronics vTAG products, http://www.mclarenelectronics.com/Products/Product/vTAG

[18] Dymola Binary Model Export Option, http://www.claytex.com/products/dymola/features/binary-model-export/

[19] Dymola Source Code Export Option, www.claytex.com/products/dymola/features/source-code-export/