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Lars Eriksson
Vehicular Systems, Linköping University:
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`VehProLib` – Vehicle Propulsion Library
Library development issues

Lars Eriksson
Vehicular Systems, Department of Electrical Engineering
Linköping University, SE-581 83 Linköping, Sweden
larer@isy.liu.se, http://www.fs.isy.liu.se/∼larer

Abstract

A Modelica library called *Vehicle Propulsion Library* `VehProLib` is under development. Its structure and important design issues are described and the current status is shown. The vehicle propulsion library aims at providing functionality for studying and analyzing the performance of different powertrain configurations. The included components cover the range from zero dimensional in-cylinder models to longitudinal models for complete vehicles.

1 Introduction

The performance of vehicles and their powertrains are continuously being improved and computer based models and simulation tools are used routinely in investigations. Models and libraries that can be reused also provide leverage to the investigations. Vehicle powertrains are truly multi domain and Modelica is therefore a well suited modeling language for building a library upon.

Intended users are both engineers in the automotive industry and less experienced students. The aim is to provide the engineers with a basic structure that provide a platform for collaboration and exchange of component models. Students should be provided with a set of basic components that can be used to learn the functionality of powertrains and to investigate different structures.

The initial development of the package is focused on the engine components since these form the foundation for the torque production in vehicles. Important phenomena in the engine components such as in-cylinder heat transfer and combustion propagation where well established models are used in the combustion engine models.

2 Library Structure

The library is under development and the structure will change with the acquired knowledge and from feedback from the users. Currently, the library has the following structure, only the package names are written and the indentation show the hierarchy.

```
VehProLib
     Types
     Functions
     Interfaces
     Partial
     GasProp
     Engine
          Functions
          Partial
          Examples
     Chassis
     Driveline
          Components
     HEV
     DrivingCycles
     Examples
     Tests
```

These packages contain models for the different components as well as full example models. Some of the components that are included in the library will be covered in the upcoming sections.

3 Development Guidelines

One aim of the package is that it shall be possible to use it jointly with the powertrain library, which provides more comprehensive component models for powertrains. Therefore the interfaces will be designed to agree with those of the powertrain library, currently the interfaces are implemented using the Modelica rotational library and there is no control bus implemented.

Furthermore it is important that it is easy to exchange different component models e.g. to exchange a sim-

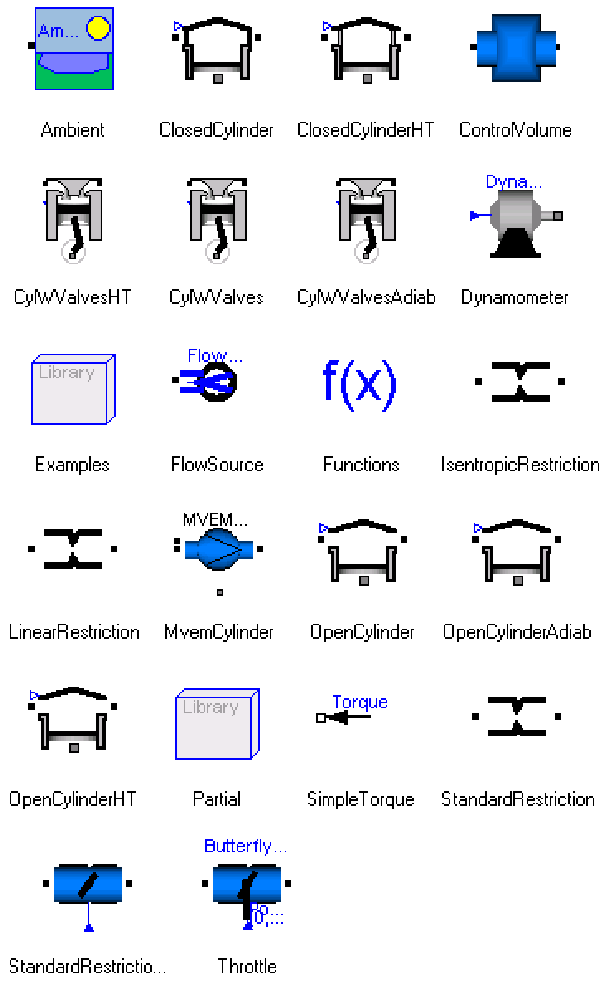

Figure 1: Components in the engine library that are building blocks in engines and that can be used to develop new engines.

ple model for an engine with one that is more complex when more detailed knowledge is needed. On the engine level it should also be possible to exchange the models for the working fluid in a simple manner and the fluid models are therefore separated from the engine components.
Finally the library should also facilitate the study of advanced driveline topologies like electric and hybrid vehicles.

4 Engine Components

Several components are included in the `Engine` package, see Figure 1. The library contains basic components for flow restrictions and control volumes.

- compressible and isentropic restrictions (fixed and variable area)
- incompressible restrictions (fixed area)
- control volumes
- exchangeable gas properties
- mean value engine models
- single zone, zero dimensional in cylinder models with and without heat transfer.

Many of the components in the model library are partial components that provide a basis for users to develop new components at a suitable level of refinement for their usage. The basic structure for the components are to use flow components in series with control volumes. An assumption in all these engine models is that the influence of the potential energy (due to gravity) on the gas flow is so small that it can be neglected.

4.1 Flow Connector

The simplest approach for flow connectors are used in the current implementation. There are two intensity variables pressure and temperature, and two flow variables enthalpy flow rate and mass flow rate.

```
connector FlowCut_i "Standard connector"
  package SI = Modelica.SIunits;
  SI.Pressure p(nominal=100000, start=100000)
    "Pressure sensed by the connector";
  SI.Temperature T(nominal=500, start=300)
    "Temperature sensed by the connector";
  flow SI.EnthalpyFlowRate H
    "Enthalpy flow through the connector";
  flow SI.MassFlowRate W
    "Mass flow through the connector";
end FlowCut_i;
```

Inertia effects that rely on the momentum balance are neglected when using this connector.

4.2 Control Volume Design Issue

Control volumes are described using mass- and energy-balance equations (positive directions are inward)

$$\frac{dm}{dt} = \sum_i W_i$$

$$\frac{dU}{dt} = \frac{d}{dt}Heat + \frac{d}{dt}Work + \sum_i H_i$$

Using these formulation directly in the code results in that mass and energy will be selected as state variables. This in turn results in trouble when specifying initial conditions since an engineer working within this area can specify initial values on temperature and pressure.

The energy equation is therefore rewritten by assuming an ideal gas, which gives

$$m c_v \frac{dT}{dt} = \frac{d}{dt} Heat + \frac{d}{dt} Work + \sum_i (H_i - m_i u_i)$$

The result when implementing this equation is that the temperature is selected as state variable. A differential equation for the pressure could also be determined by differentiating the ideal gas law, but this is a special case for the pressure, therefore the mass balance is selected as the second balance equation. The initial pressure, which is a parameter in the control volume, is then used together with the temperature and the ideal gas law to give an initial value for the mass. It is important to note that the equation above and the initial conditions for the mass will be revised when non ideal gases will be included in the library. It is worth to note that the base class for the gas model, shown in Appendix A, does not contain any assumptions about ideal gases. So it is general.

4.3 In-Cylinder Models

The in-cylinder models considered here are zero dimensional and have a single zone, see e.g. [2]. In-cylinder models are control volumes and the discussion about initial conditions also apply here. Several different versions of the in-cylinder models are implemented there are those that are adiabatic and other that have heat transfer and these are implemented for comparing the effects, these are shown in Figure 1.

There are two heat transfer functions implemented, one comes from Woschni [6] and the other comes from Hohenberg [3]. To describe the combustion two different choices are available one is the standard Sigmoid function and the other is the well known Vibe-function [5].

Currently the equations for mechanics and fluid are collected in only one component but these will be separated in the future, so that the cylinder is modeled in a truly multi-domain manner.

4.3.1 MVEM

There are also engine components implemented that fall in the category of Mean Value Engine Models (MVEM). These have lower complexity and are faster to simulate compared to the in-cylinder pressure models. Since they are less complex and faster they are used for studying control design and for complete vehicle simulation. Both the in-cylinder models and the MVEMs have inherited the same interfaces so they are easily exchangeable with the models. A common scenario is to set up a simulation problem using a MVEM to see that all components work together as expected. Then when more detailed knowledge is required and the more advanced engine model is inserted instead of the MVEM.

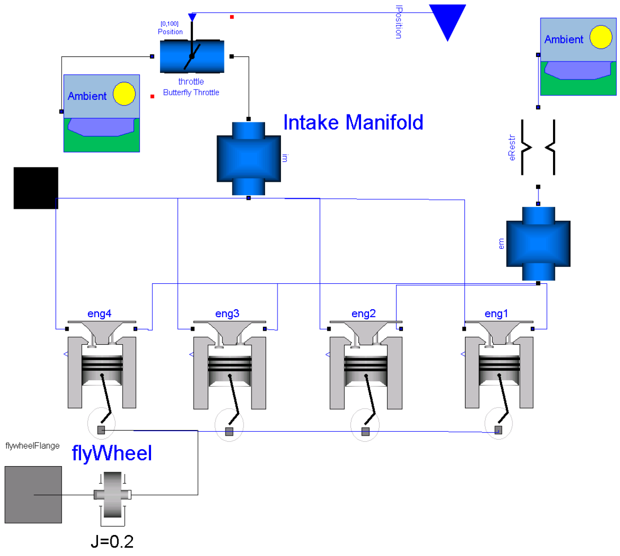

Figure 2: The components in the four cylinder engine used in the example. This model shows the components that are included in the `MultiCylEngine1` in Figure 3.

4.4 A Four Cylinder Engine

A four cylinder engine on a dynamometer, that is included as an example in the package, is used as an demonstration to show the simulation results from one of the models. Figures 2 shows the components in the four cylinder engine, where the throttle input goes to the butterfly throttle. Figure 3 shows how the four cylinder engine is arranged with the dynamometer tank and the step change in the accelerator pedal at t=0.2 s.

The resulting cylinder pressure traces are shown in Figures 4 and 5. Figure 4 shows the cylinder pressures for the four cylinders and the result from the step change in throttle angle is clearly visible. Note that there is a delay from the step to when the maximum cylinder pressure is affected by the change, this i due to the delay caused by the intake stroke and compression stroke.

Figure 5 shows the simulation result presented in a pV-diagram. Two groups of loops can be seen, the lowest comes from the period before the step change and the

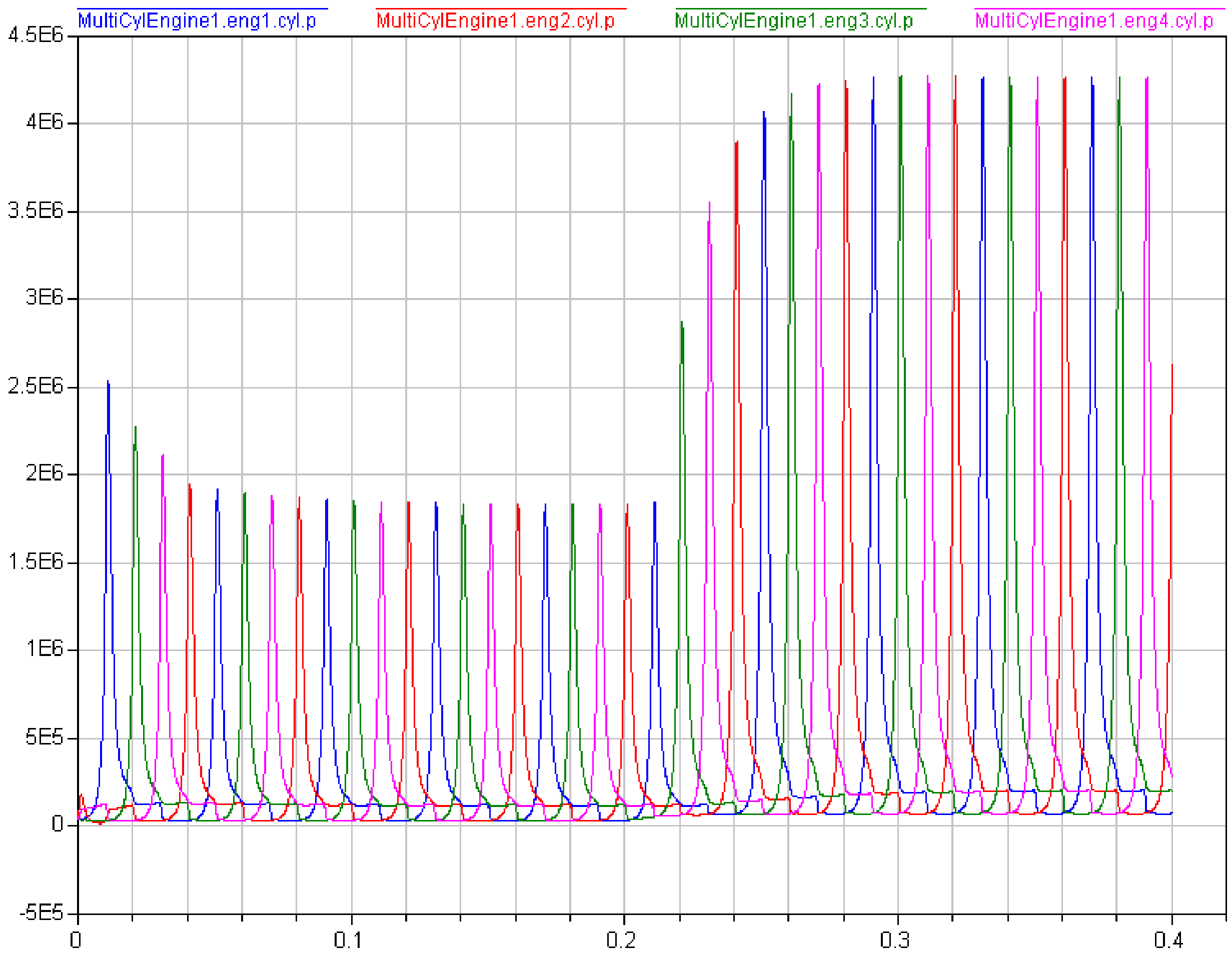

Figure 4: Figure showing the cylinder pressures from a four cylinder engine included in the examples of the library. At $t = 0.2$s a step change is made in the throttle angle, and the response is clearly seen in the model.

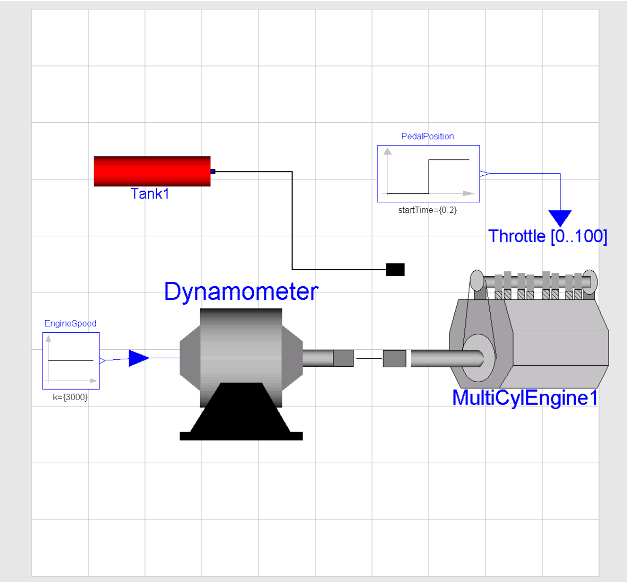

Figure 3: The multi-cylinder engine on the dyno. The dyno maintains the engine at a constant speed. A step input is applied to the throttle input at t=2 s.

higher comes from the period after the step change. This model family was proposed by Gatowski et.al. [1] and has been widely studied and is well known that it is can give a good description of measured in-cylinder pressures during an engine cycle.

5 A Complete Vehicle

To show some of the components that are available in the Driveline and Vehicle packages an example is used. Figure 6 shows an example of a model for a vehicle in longitudinal motion, with engine, driveline, and vehicle components. This example shows some of the components that are included in the library. For example there are models for vehicle body with air drag and rolling resistance, tires. The basis for the driveline modeling was presented in [4]. The driveline consists of clutch, five step gearbox, final drive, flexible drive shafts, brakes and wheels. Also included in the library is a driver which uses a driving cycle, implemented as a speed and gear table. Finally the engine is selected from the mean value engine, since it is less complex and gives much shorter simulation time compared to the multi cylinder engine model that was shown previously.

The results from a simulation running the longitudinal vehicle model with the driver following the New European Driving Cycle is shown in Figure 7. The top plot shows the vehicle speed as a function of time. Both

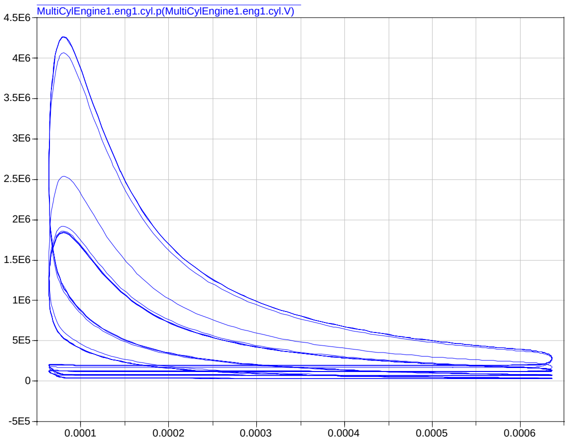

Figure 5: Figure showing the pv diagram for cylinder one shown in Figure 4 The step change in throttle at $t = 0.2$s gives a change between the lower pressure traces to the higher in the pv-diagram.

the desired and actual vehicle speeds are shown and it is seen that the driver is well tuned and manages to follow the desired speed well. The middle plot shows the engine speed and the bottom plot shows the gear number and clutch position.

6 Future Work

The library is continuously being developed and some of the areas with highest priority are:

- Decoupling of the mechanics and thermodynamics in the engine.
- A more general gas model and an extended connector that includes multi-component flow. Follow the work by the Modelica standardization group on thermofluid library and decide if the full library should be implemented.
- Implement and incorporate more engine components, foremost turbocharger models.
- Implement and incorporate more driveline and vehicle components, for example hybrid components.
- Continuously build up test models for the components that are added to the library.

The model library development is an ongoing task and everybody that are interested in contributing to the library are encouraged to contact the author by e-mail.

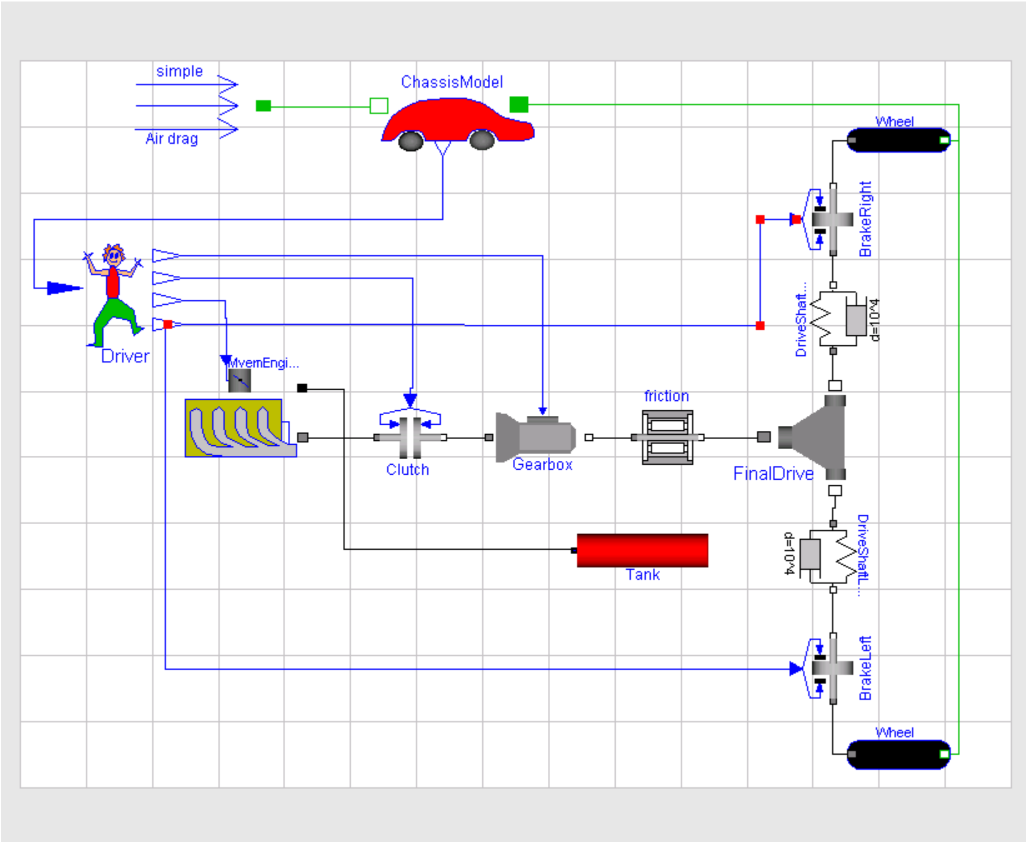

Figure 6: A complete vehicle modeled using components from VehProLib and standard Modelica components. The example shows some of the components included in the library. Here the mean value engine model is used instead of the multi cylinder model since the vehicle follows a longer driving cycle.

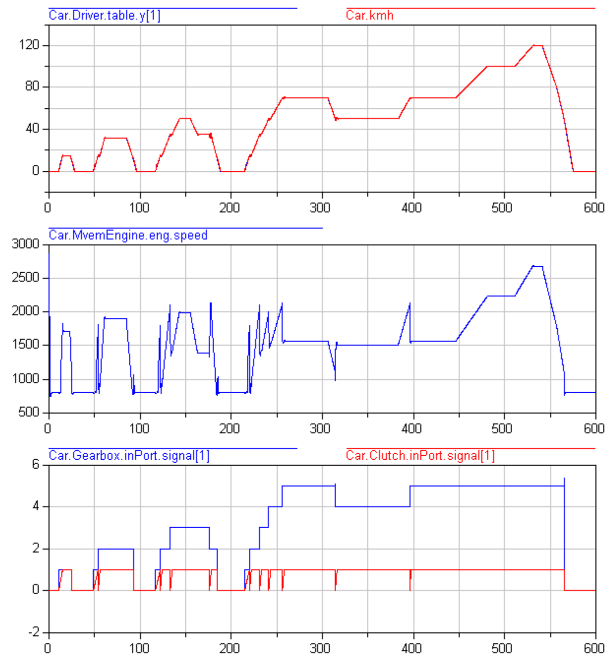

Figure 7: Simulation results from the model shown in Figure 6. The plots show: top–vehicle speed, middle–Engine speed, and bottom–gear and clutch position. The top plot shows both desired and actual vehicle speed.

7 Summary

A library `VehProLib` for vehicle propulsion modeling is being developed. Design issues related to the engine components have been addressed. The components in the `Vehicle` and `Driveline` packages have been illustrated using a model for a complete vehicle in longitudinal motion.

Acknowledgments

The library is currently being extended with the help of the MSc students Otto Montell and Johanna Wallin. Some icons for the models have been provided by Michael Tiller at Ford and he is greatly acknowledged.

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A Gas property base

The gas property base, shown below, defines what functionality the gas model must have. This partial model is then extended by the gas models in the library.

```
partial class GasPropBase
     "Base class for gas properties"
  package SI = Modelica.SIunits;
  SI.Pressure p "Pressure";
  SI.SpecificVolume v "Specific volume";
  SI.Temperature T "Temperature";
  SI.Density rho "Gas density";
  SI.SpecificEnthalpy h "Mass specific enthalpy";
  SI.SpecificEnergy u "Mass specific internal energy";
  Real R(final unit="J/(kg.K)") "Gas constant";
  SI.MolarMass M "Molar mass";
  SI.SpecificHeatCapacityAtConstantPressure c_p
    "Specific heat capacity at constant pressure";
  SI.SpecificHeatCapacityAtConstantVolume c_v
    "Specific heat capacity at constant volume";
  SI.RatioOfSpecificHeatCapacities gamma
    "Ratio of specific heats";
equation
  gamma = c_p/c_v;
  h = u + p*v;
  rho*v = 1;
end GasPropBase;
```