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Johan Andreasson
Division of Vehicle Dynamics, Royal Institute of Technology, Sweden:
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VehicleDynamics library

Johan Andreasson
KTH Vehicle Dynamics, Sweden
johan@fkt.kth.se

Abstract

A Modelica library for vehicle dynamics problems has been developed and a pre-release version is available. The library is based on modular design and contain models of components as well as suspensions, chassis and vehicles. In this paper the modelling structure is discussed and it is illustrated how this simplifies the usage.

1 Introduction

Due to the multidomain qualities of Modelica, it has for long been thought of as a suitable tool for complete vehicle modelling. Detailed models of vehicle power train are available [1] and chassis models have also been presented [2, 3]. This paper presents the `VehicleDynamics` library that provides models for vehicle dynamics studies. A pre-release version is available [4] for download.

The library is divided into sub packages containing models of vehicle chassis and wheels, environments and drivers. The library structure is best understood by considering Figure 1. The chassis, which has been the main focus within this work, contains body, suspensions and wheels. To control the chassis' motion a driver model is used. This could either be open loop from a predefined input or a more advanced driver model to mimic human behaviour.

The chassis have connectors to the wheels to allow the addition of a power train. There is is also a `MultiBody` connector to the body to allow additional models to be attached. This is here illustrated by an aerodynamic model and an additional load, but it is also possible to attach e.g. trailers. Environments representing ground and atmosphere conditions are selected independent of the rest of the vehicle model.

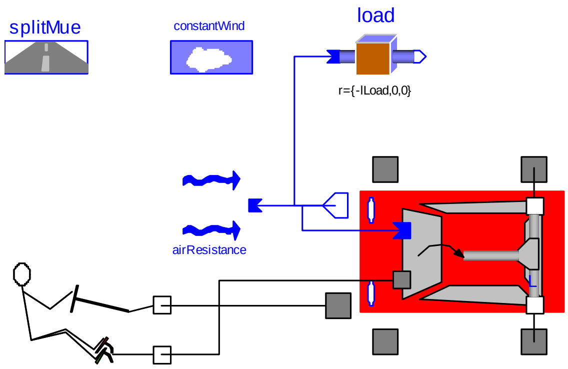

Figure 1: The layout of a vehicle model with a power train and an additional load.

2 Chassis

In vehicle dynamics studies, the chassis is of great importance. Not only the geometry of the suspensions but also bushing and strut characteristics are of great importance and thus, the models often tend to be detailed, containing models representing different fields of expertise. At the same time it is crucial that the models are easily reconfigurable and that it is possible to grasp the contents of a model without needing to understand the details. To allow this, the chassis is defined in a modular and hierarchical way based on four levels. The highest level is the vehicle level and can be seen in Figure 1. The three remaining levels are chassis, suspension and component levels and they are illustrated in Figure 2.

Chassis level Within the chassis level a complete chassis is built up using suspensions, wheels and a body. Here, a four wheel chassis with front wheel steer is shown, but other models can easily be defined, e.g. with four wheel steer or six wheelers. However, there is no need to define a new chassis model for each configuration

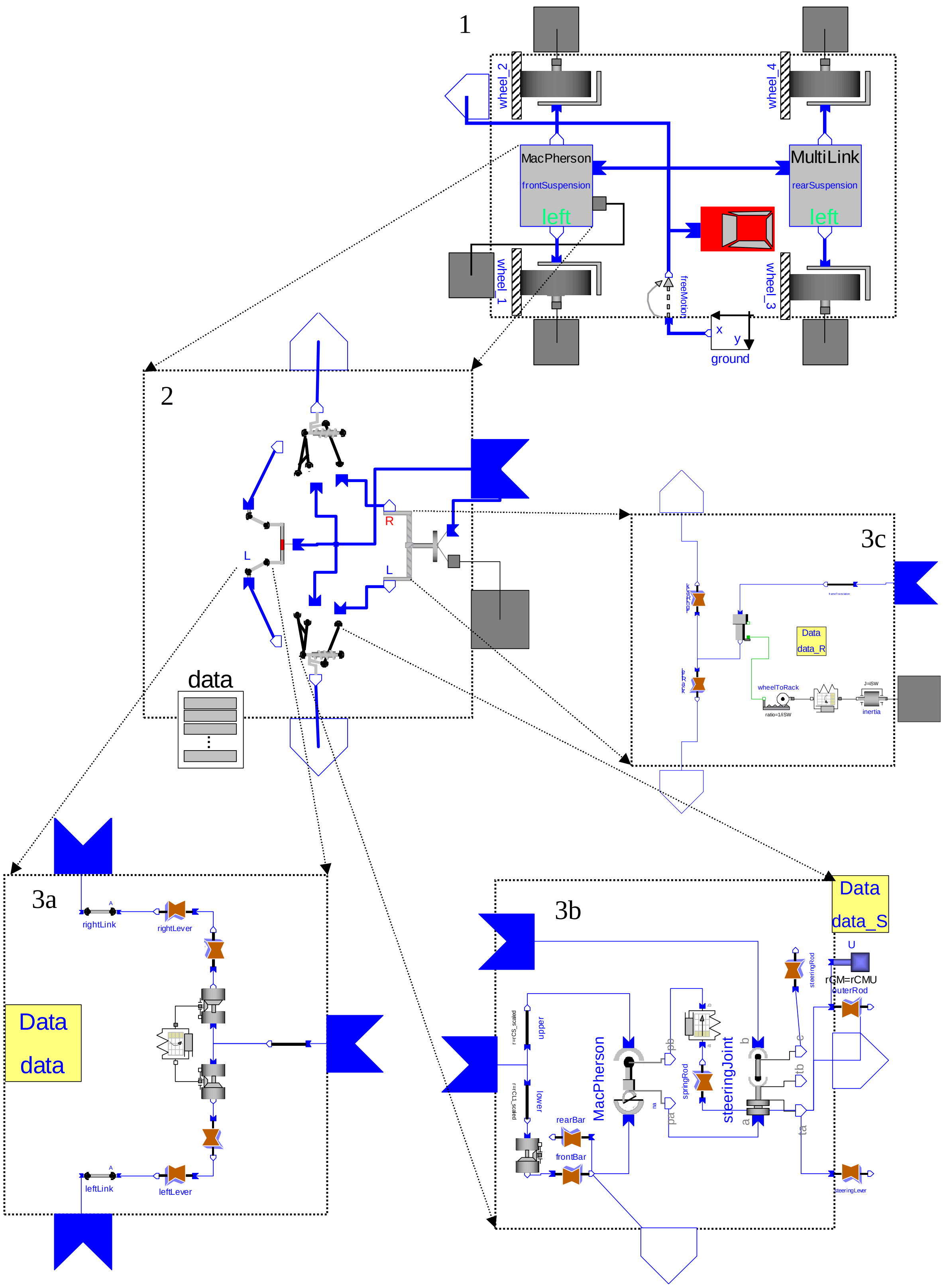

Figure 2: The hierarchical levels of a chassis model. 1: the chassis level, 2: the suspension level, 3: the component level represented by an anti roll bar linkage: 3a, a MacPherson linkage: 3b, and a steering rack: 3c.

of different suspensions or wheels. This is instead handled as described in Section 6, using the `redeclare` constructs in Modelica.

Suspension level Common for all individual suspensions are the linkages that carry the wheels and normally there is some kind of roll-suppressing mechanism between these. If the suspension is steerable there is also a steering rack. Each of theses components can be used to build up new suspensions. Thus, the suspension linkage, here a MacPherson, could easily be replaced by another linkage, e.g. a double wishbone or a multi-link. In the same manner, the steering and the anti roll linkages can also be replaced. Furthermore, all parameters are gathered in a data record, making it easy to change a whole suspension setup.

The idea with the suspension level is to make it easy to reconfigure a car by just swapping suspension and therefore, all suspension models should share the same basic interface, i.e. one MBS-cut for the connection to the body. There should also be an MBS cut for each wheel (normally two) that is to be connected to the suspension. Additionally, there may be some extra connectors depending on the suspension. For example, a steerable suspension will also have a connector for a steering wheel.

Component level Within the component level, the foundation for efficient reuse of vehicle models is laid. Components like a-arms, bushings, Mac Pherson struts, trailing arms, multi-links, anti roll linkages, rack steerings etc. are available. In this version, these components are based on the `Modelica` and `ModelicaAdditions` libraries. Other basic models that are needed in the component models, such as nonlinear spring-dampers, are described in Section 4.

2.1 Parameterisation

The parameterisation of the chassis is based on a Body Geometric Reference frame (BGR). This frame is orientied according to the DIN standard, the *x*, *y* and *z* axes point forward, left and upward respectively, see Figure 3.

The geometry of the chassis and the suspensions are then defined by a set of points where joints and

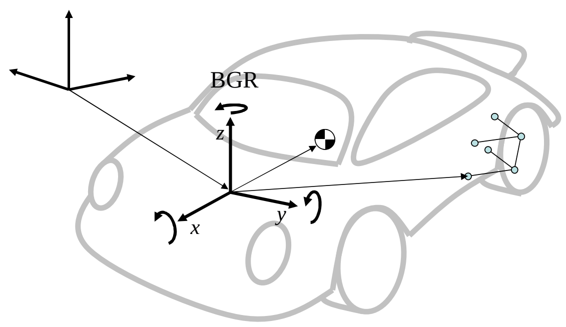

Figure 3: The vehicles motion is specified by how the BGR moves relative to the ground frame. From the BGR, locations of e.g. centre of mass and construction poins are defined.

bushings are located. Additionally, the mass and inertia properties of the parts within the linkage can be defined. For a comprehensive parameterisation of these properties, a systematic definition of the parameter names is necessary.

The geometry is mainly defied by the connection joint locations, connection points. Additionally, the direction(s) of a joint's degree(s) of freedom must be given if not defined by the connection joint points. The geometry parameters are defined as:

```
[geometry parameter]
  =[property][connection]_[wheel no]
[connection]
  =[part 1][part 2]..[part n]
```

While the mass and inertia properties are component specific and are thus named according to:

```
[component parameter]
  =[property][part]_[wheel no]
```

Where `[property]` and `[part]` are defined according to Table 1.

When there are more than one part of the same type, a number is added to the character. For example, if there are more than one link, as in a double-wishbone, they are numbered L1, L2, etc., starting at the front upper link. The wheels are numbered from front left towards right and rear. Some examples of parameter names are give below:

`rCL1_2` Location of connection joint between chassis and link 1 at front right wheel.

`r`	location
`n`	direction of rotation or translation
`m`	mass
`rcm`	location of centre of mass
`c`	stiffness
`d`	damping
`f`	force
`t`	torque
`i`	inertia element, (gear) ratio
`q0`	Relative offset
`qInit`	Initial value
`C`	chassis
`R`	steering (rack)
`U`	upright, part that holds the wheel
`P`	pivot element
`S`	strut, 1D force element
`L`	link or rod
`B`	body or bushing
`A`	antiroll
`X`	undefined/general part
`W`	wheel

Table 1: Naming of parts and properties.

`i22L1_3` Inertia element i22 of link 1 at rear left wheel.

`nCU_4` Direction of revolution of the joint that connects the upright 1 to the chassis at the right rear wheel. This could for example be the rotation axis of a swing axle.

`rUL1L2_1` Location of connection joint between the upright and link 1 and 2 at the front left wheel. This could for example be the upper spindle joint at a double wishbone suspension.

In many cases it is convenient to mirror components in a car, for example left and right suspensions. To handle this, a three-dimensional scale factor is used. This can rescale and mirror objects, for example `scaleFactor={1,-1,1}` mirrors the model around the xz-plane.

3 Wheels

Good tyre models are essential for driving simulation of all ground vehicles using pneumatic tyres. However, tyre behaviour is extremely complex, often requiring different models to cover various aspects. Therefore, these are packaged together with the rim and the hub to form ready-to-use wheel models. The models used in this package are based on a tyre model suggested in [5] and implemented in Modelica in [2]. This model uses steady state force characteristics together with a simple tyre belt deflection model. Additionally, the Magic Formula [6, 7] is also available for the tyre force calculation.

Common for both models are the assumption that the contact patch between the tyre and the road can be approximated by a point. To avoid coupling the wheel and the road models, this contact point is calculated using the `inner/outer` Modelica language constructs to get information from the Environment model about the current altitude and road condition. As a consequence, the road properties can be defined at the top-level of the model and can also be easily changed.

Due to the contact point assumption, this model has troubles travelling on roads with sharp edges, which often is the case when a real road profile is meshed. To manage this and other issues, a new Wheels library is currently under development [8].

4 Utilities

For vehicle dynamics studies it is essential that the characteristics of flexible elements such as struts and bushings are modelled. To deal with this, a set of basic force elements are available. These are either taking into account the deformation along one degree of freedom, 1D-forces, or six degrees of freedom, 3D-forces.

The 1D-forces apply force depending on the deformation according to the `Modelica.Mechanics` definitions or depending on the distance between two frames. The force versus deformation and its time derivative are defined as look-up tables.

The 3D-forces calculates the relative rotation between two frames, either as a linearisation around a zero deformation or nonlinear allowing deformations up to π radians. The force can be calculated as a nonlinear spring-damper element, without considering the coupling effects. Linear spring-damper elements with bump stops, taking into account the coupling between the degrees of freedom, are also available. These use two 6×6 matrices for stiffness and damping to calculate the resulting force and torque vectors from the deformation:

```
[fa+f_bump; ta] =
-C*[r_rela-r_rela0;phi_rela-phi_rela0]
-D*[v_rela;w_rela];
```

The `f_bump` is an additional, stiff, spring-damper force that is active when `r_rela` is outside the edge of the linear region. It is directed perpendicular to the edge that can be defined either as a cylinder, sphere or box. More complex geometries and models, using e.g. fractional derivatives, are currently not implemented.

In addition to the force elements, there are also a set of joints particular relevant for vehicle dynamics studies. Composite joint models (e.g. an aggregation of a revolute, a spherical and a universal joint) are available to reduce the nonlinear algebraic loops that normally occur in suspensions with ideal joints [9].

Also there are joints that applies unphysical constraints to the vehicle. For example, it is in many cases interesting to be able to perform a maneouvre at constant speed. In other simulation packages like e.g. ADAMS [10] this is solved by adding a power train and applying a cruise control. The drawback is then that the user need to add unnecessary complexity as well as unwanted dynamics to the analysis. Here, it is instead possible to constrain the velocity along the longitudinal axis of the car.

Other cases where it may be interesting to constrain the vehicle in an unphysical way is when studying the effects of flexibility in the suspensions. Typically, there are very high eigen-frequencies due to high stiffness and low mass that are irrelevant for the analysis and thus using joint models that do not consider the acceleration may speed up the simulation without loosing relevant accuracy.

5 Drivers

The driver models used in vehicle dynamics studies are either open loop drivers that apply a predefined motion on the steering wheel or more advanced models that try to mimic the human behaviour, taking into account some states of the body and sometimes also the force-feed-back through pedals and steering wheel.

More advanced studies considering combined cornering and braking/acceleration requires a tight interaction of steering wheel and pedal output. The interface is prepared to be able to handle the aspects described above, it consists of two rotational flanges for steering and drive. For closed loop driver models, an MBS connector is used to make the model able to sense the vehicle's motion.

6 Usage

The modular design of the vehicle models gives three significant advantages. First, it is easy to reuse already developed models. Secondly, because of the standardised interfaces, much of the test rigs already implemented can be used for new models as well, making it easy to test and verify these. A third aspect that will be illustrated further is the ability to exchange sub models without redesigning the original model which leads to very flexible use.

To illustrate this, it is here described how one model can cover different combinations of suspensions of a front steered four wheeled chassis.

1 Double-clicking the chassis in the `StandardCar` example opens the dialog box showed in Figure 4.1. Here it is possible to select the desired models for all the wheels as well as for the front and rear suspension, respectively. As indicated in the figure, a drop down box appears, listing all possible choices.

2 Once the desired suspensions and tyre models are chosen, the corresponding parameters can be edited by pressing the triangle at the end of each row. Since all suspension parameters are set in a `data` record, Figure 4.2, it is easy to select the desired setup from the dropdown box, again only showing the relevant options. The geometry is also indicated in a figure to make it more easy to verify that the right suspension is selected and to understand the parameterisation.

3 Even if a specific setup is chosen for the suspension or not, it is still possible to edit each value separately as illustrated in Figure 4.3. Except for the geometry parameters, it is also easy to change mass and inertia properties as well as the characteristics of the force elements.

4 To facilitate the modification of force elements, which can be rather complex, it is possible to both edit these as Modelica code, Figure 4.4 and to visulise the characteristics, Figure 4.5.

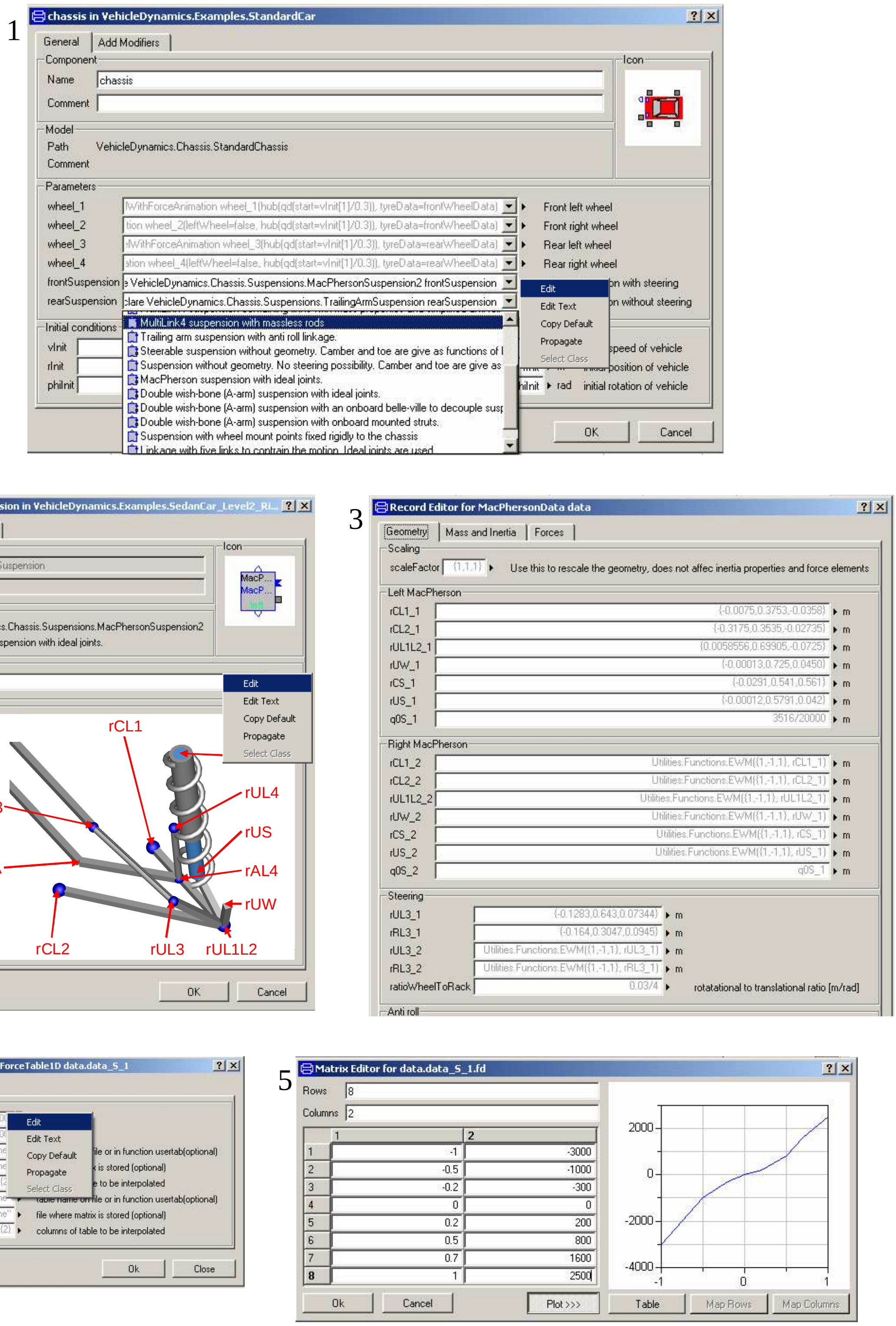

Figure 4: Dialog boxes for modification and parameter settings.

Within the `VehicleDynamics` library, there is a set of samples available to illustrate the use of the library. Except for the `StandardCar`, there is a model of a Formula 3 race car, Figure 5 and a car with a trailer. Furthermore, there are some examples showing how components and suspensions can be tested in-

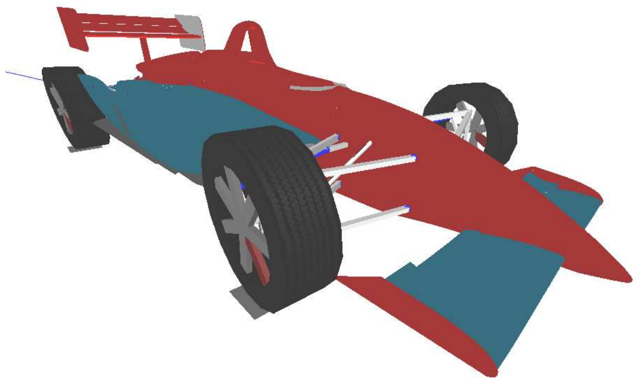

Figure 5: Animation view of the Formula 3 car example.

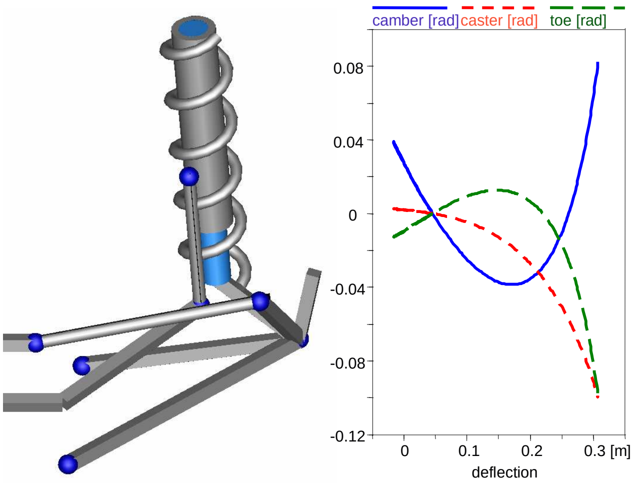

Figure 6: Animation of a MacPherson suspension along with a mapping of the change of camber, caster and toe angles as function of bump motion.

dividually, see for example Figure 6.

Additionally, there are four variants of the `StandardCar` corresponding to four different levels of detail of a mid-sized car with a front MacPherson suspension and a rear multi-link suspension. The main idea is to illustrate how Modelica can be used to model vehicles with a wide range of level of detail. The simplest model uses look-up tables to define the deflection of the suspension and an Ackermann function for the steering geometry. The second level uses linkages with ideal joints while level three and four use bushings. A more detailed description of these models can be found in [9]. In Figure 7, two pictures of the level 2 car when performing a double lane change maneouvre, ISO3888-1:1999, is shown.

7 Conclusions

In this work, a library for modelling of vehicle dynamics related problems is realised. It uses the interfaces from the `Modelica` and `ModelicaAddtions` packages to be compatible with other libraries.

`VehicleDynamics` provides an architecture for vehicle modelling as well as components, suspensions and chassis model to simplify for the user to extend the library according to his/her needs. The modular structure of the model design allows to take advantage of the potential of the Modelica language.

`VehicleDynamics` is freely available and the source code is completely open. The library can also be used together with the `PowerTrain` package to model complete vehicles.

8 Future work

The library is under constant development. Upcoming improvements concern an extension of the flexibility to include swapping between bushings and joints and better ability to add active components such as controllable dampers. To be able to study the gyroscopic effects of the power train and torque oscillations due to Cardan joints, multi-body models of drive shafts and brakes will also be included. The intention is also to convert the `VehicleDynamics` to the new MBS-library [11] and to improve the documentation.

9 Acknowledgements

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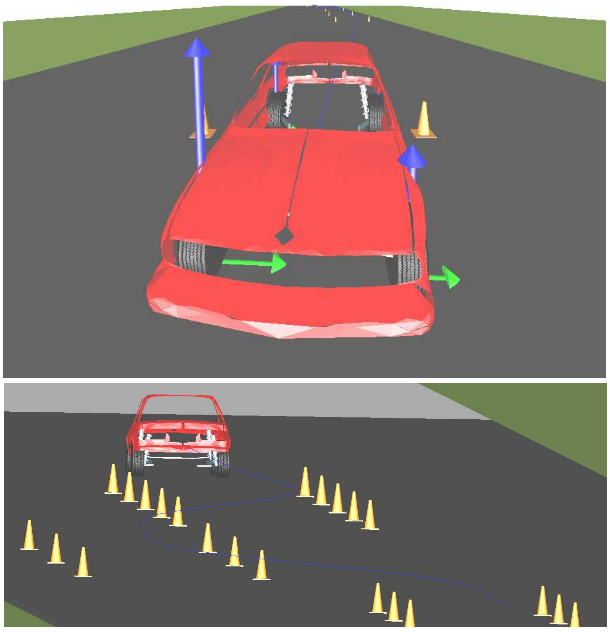

Figure 7: Vehicle performing a double lane change at 20 m/s.

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