

Vehicle dynamics analysis using SimMechanics and TNO Delft-Tyre

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Abstract

This paper explores the usage of the SimMechanics multi-body toolbox for vehicle dynamics analyses. The tyres are a complicated, but crucial part of the vehicle model and the TNO Delft-Tyre model is discussed briefly. Some general ideas and issues when using SimMechanics to model vehicles are discussed. Finally three examples are given, a motorcycle, racing car and truck, which illustrate the feasibility of using SimMechanics in this field.

1. Introduction

Vehicle dynamics research covers the subjects of handling and ride. In this field computer simulations have been used already for quite a long time. In particular the analysis of vehicle behaviour using general purpose multi-body modelling tools became common practice in the late 1980's. Primary applications were the analysis of the suspension kinematics and full vehicle handling. It was quickly recognised that a proper model of the tyre was required to obtain meaningful simulation results. In 1987 Egbert Bakker and professor Pacejka of the Delft University of Technology published their first paper on a new pragmatic tyre model: The Magic Formula (ref. 1). This tyre model was relatively quickly adopted by the industry and, while some iterations have been made to improve it, can still be considered as the reference tyre model for vehicle handling studies today. TNO automotive plays a leading role in standardising and developing the Magic Formula tyre model and making it available for a large number of different simulation environments.

Next to the advances in simulation technology, the amount and complexity of vehicle control systems has grown very rapidly in recent years. In this field Simulink has become a very important simulation tool, being used by many as a platform to analyse and exchange control system technology. Obviously, to analyse the effect of the control system on the vehicle behaviour (and vice versa), a need develops to combine the Simulink model with the vehicle multi-body simulation model. This task is not exactly trivial because the multi-body simulation model may have been created using a different simulation package and techniques like co-simulation have to be used. This process can be numerically slow, forces the user to strictly separate multi-body dynamics from the control part and having to use two different software packages with different ways of defining and parameterising the model.

When the general purpose multi-body simulation toolbox SimMechanics became available in Simulink, we were quickly to recognise the potential of this tool for vehicle dynamics analyses. It also meant that the Delft-Tyre model had to be made available for the SimMechanics environment. This paper describes our experiences and results obtained in recent years. First a short introduction on tyre modelling will be given, next some practical issues using SimMechanics for vehicle dynamics applications will be discussed and finally a number of application examples will be shown.

2. Tyre modelling

In a multi-body modelling environment the tyre can be considered as a force element. In the direction normal to the road the tyre behaves as a spring/damper and for motions perpendicular to the road plane the tyre develops reaction forces as a result of the relative (sliding) motion with respect to the road surface. Unfortunately these force relations are quite complex and highly non-linear. To model the tyre forces two approaches can be followed:

- physical tyre modelling**
Based on the physical properties of the tyre (material, dimensions,...) a detailed mechanical model is created. In order to have some accuracy one rapidly has to resort to a coarse FEM model having already many degrees of freedom; simple brush type tyre models having analytical solutions will be insufficient.
- (semi-) empirical tyre modelling**
In this approach the measurements on the rolling tyre are the basis for the model. An obvious example is to store measurement data in a look-up table, which is then evaluated later during the simulation. Tyre models in this class would typically use e.g. spline interpolation or special mathematical formulae (like the Magic Formula).

Semi-empirical tyre modelling has the advantage that the resulting tyre model tends to be accurate and fast, but it relies on tyre measurements. Physical tyre models may have better predictive qualities when no measurement data is available, but will be slower and ultimately don't achieve the same accuracy as a semi-empirical tyre model or at high computational costs. For a full overview on tyre modelling, the Magic Formula in particular, we refer to reference 2. Here it is sufficient to say that TNO Automotive has supported the automotive industry for more than 10 years in applying the Magic Formula. The activities range from doing on the road tyre measurements, parameter identification and providing tyre models for different multi-body simulation packages, as shown in figure 1.

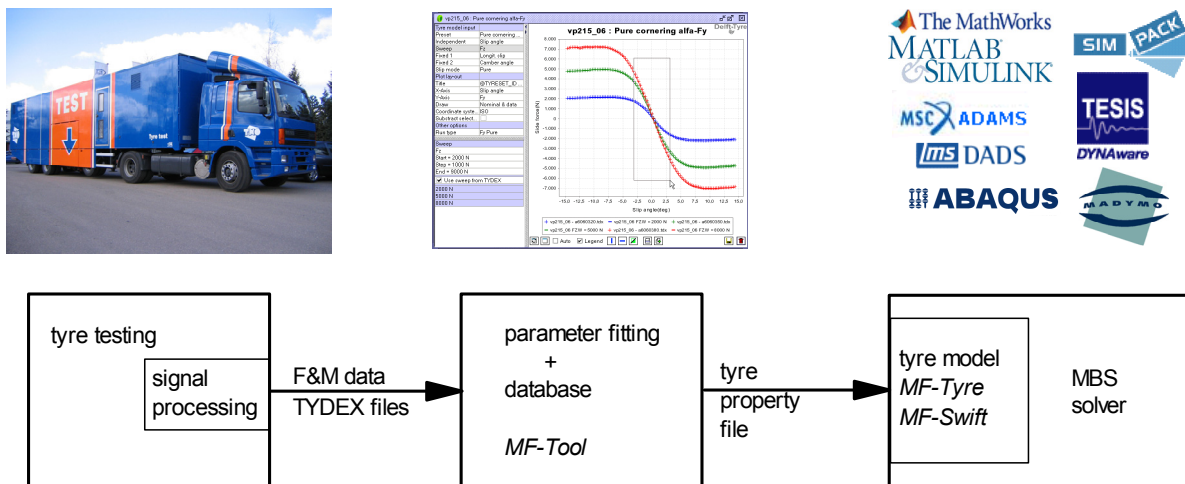


Figure 1 Capturing tyre behaviour: from tyre testing to multi-body simulation.

The Magic Formula is used to describe the non-linear steady-state representation of the tyre characteristics. Next to that the dynamic behaviour of the tyre has to be included. Taking into account the tyre relaxation behaviour is a first extension to cover the tyre dynamics up to 8 Hz. At higher frequencies the wheel and tyre can not be modelled as a single rigid body anymore. To include tyre dynamics up to 60-80 Hz it appears to be sufficient to describe the motions of the tyre belt and rim using two separate bodies, as shown in figure 2. Furthermore an enveloping model is necessary to cope with short wavelength road obstacles. Again for more details on this subject we point to reference 2.

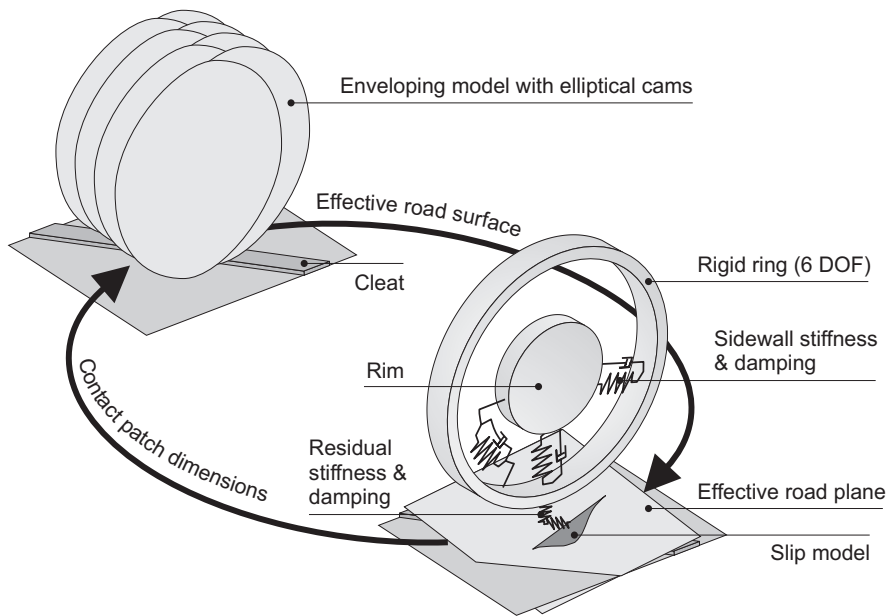


Figure 2 Schematic overview of the MF-Swift model, with rigid ring and enveloping model.

In principle a user of the TNO Delft-Tyre product has two choices:

- **MF-Tyre:** Magic Formula for handling simulations (up to 8 Hz) on a smooth road surface
- **MF-Swift:** Magic Formula extended with rigid ring dynamics (up to 60-80 Hz) on an arbitrary road surface, which is typically used for ride simulations.

Within the MATLAB®, Simulink® and SimMechanics environment these tyre models are supported in various ways. First a command line function exists to evaluate the Magic Formula (e.g. for the purpose of plotting of tyre characteristics). Next two Simulink blocks to include the Magic Formula in a vehicle model are available. And finally we have an easy to use block to include the wheel/tyre assembly in a SimMechanics model.

3. Creating vehicle models using SimMechanics

It is a good practice to make a sketch of the topology of the mechanical system you want create, before actually starting to use the multi-body package, see figure 3.

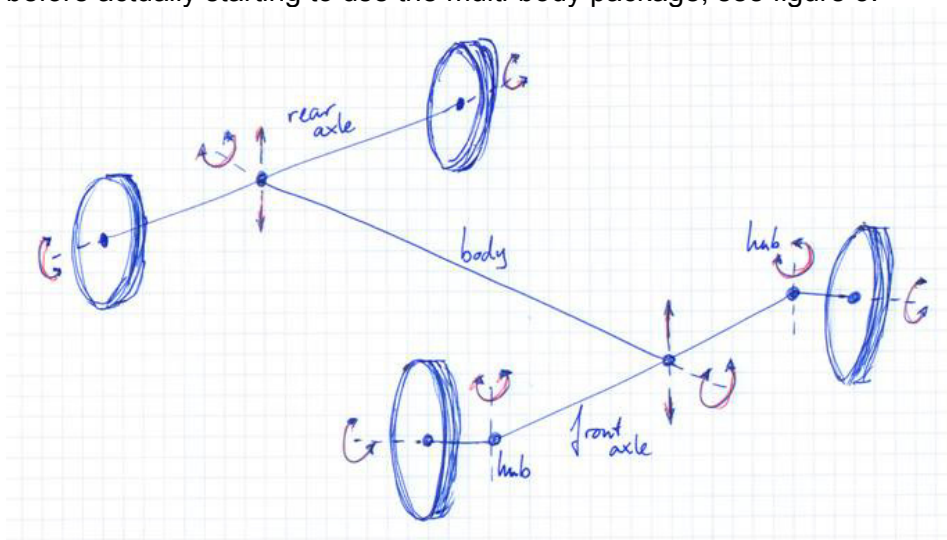


Figure 3 Sketch of a roll axis vehicle model

This sketch can then be translated quite easily into SimMechanics, it is not much different from drawing the system topology again in Simulink, see figure 4. In this way it is possible to create models, which are easy to interpret and to a large extent self-explanatory. This is not only important in the model development phase, but perhaps even more afterwards: some years later when the original sketch is lost, only a model file is available and one wonders how the multi-body model was exactly put together.

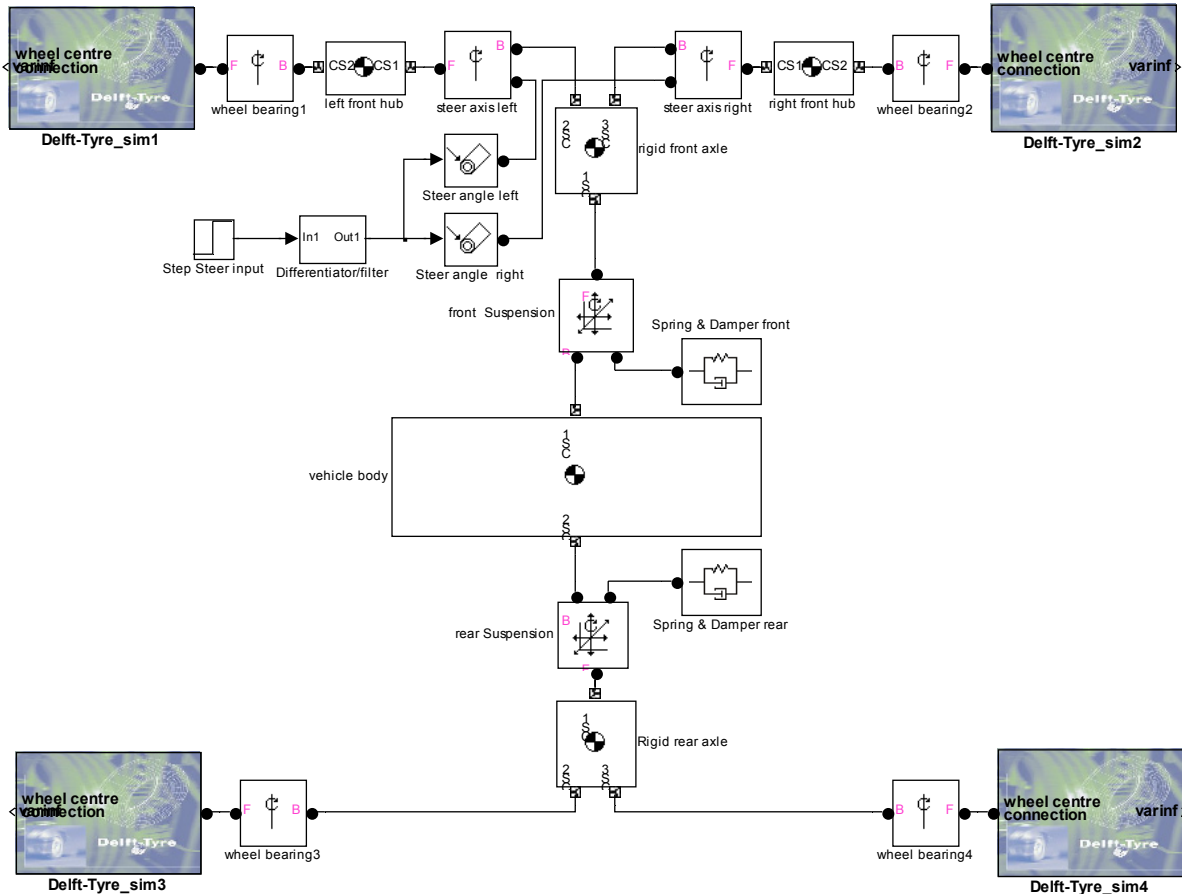


Figure 4 SimMechanics implementation of the roll axis vehicle model.

Just like any normal Simulink model it is possible to create subsystems, which can contain parts of the multi-body system. These subsystems can then be masked, parameterised and put into a library. This can be quite useful when modelling for example a commercial vehicle. At the Eindhoven University of Technology we have started to develop a component library containing elements like axles, driveline, cabin, braking system, etc. When building a new truck model, the existing components can be used again and it is surprisingly simple to add or delete for example an axle or create different vehicle configurations. Figure 5 gives an impression of the top level tractor model, which uses various components from the library and is part of a complete tractor-semitrailer model. Also picking a component from the library and creating a test rig for it, does not pose special challenges.

Visualisation of the multi-body system is a different matter. The standard visualisation possibilities of SimMechanics are rather basic and some elements can not be visualised at all (e.g. spherical-spherical connection). Especially for complex vehicle models the results are not very usable and it is difficult to identify modelling errors based on the graphics. The alternative offered by The MathWorks is the Virtual Reality toolbox. This allows to create presentation worthy animations, but it definitely requires some effort to get good results.

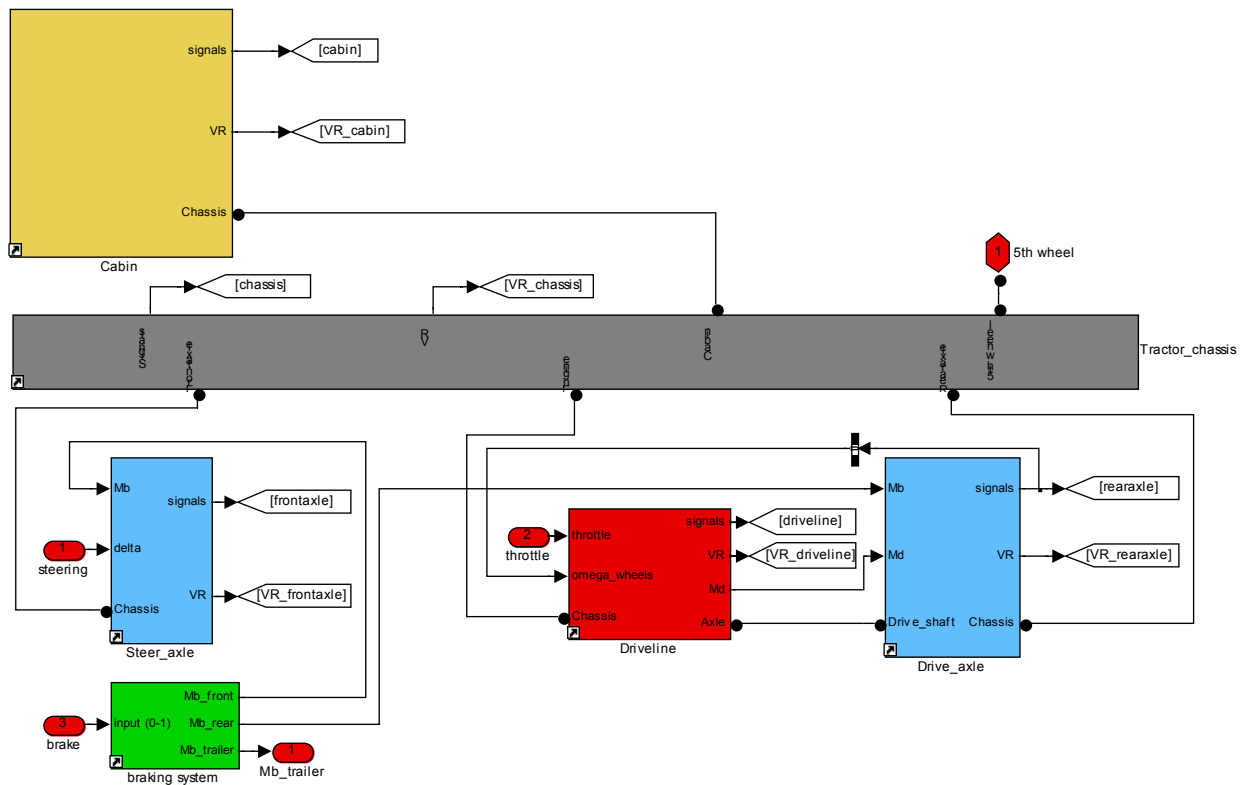


Figure 5 SimMechanics tractor model using (truck-) component subsystems from a library.

Some issues we faced:

- in VRML the ground plane is defined with x-z coordinates, whereas in vehicle dynamics this is usually the x-y plane. This leads to some additional transformations and confusion when defining primitives (boxes, cylinders, etc.) in the *.wrl source file which is used by the Virtual Reality toolbox.
- the position and orientation of each body to be visualised has to be send to the VR Visualisation block. In the case of complex models having a large number of bodies, the user is completely responsible for organising this large stream of data. Since the models don't simulate real-time or you may want to see the animation results afterwards (without re-running the simulation), the animation results are stored in a *.mat file first. A separate Simulink model is used then to execute the animation. This approach is very similar to the Octavia Virtual Reality demo model.
- the definition of the model to be visualised is stored in a single source file (though references to other wrl files are possible). This conflicts with the idea of a component library for different parts of the vehicle. If we, for example, eliminate an axle from the SimMechanics vehicle model, the source file and port to the VR Visualisation block has to be modified to get a proper animation again.
- as the simulated vehicle is moving, we want the camera to follow the vehicle. This is possible by programming some additional camera viewpoints, but then the "fly" and "examine" options don't behave as expected anymore. Also slowing down the animation, running it backwards, etc. is not really trivial and is difficult to explain to a new user.

Though the flexibility of MATLAB certainly allows you to create workarounds, it is felt that in comparison to other general purpose multi-body packages the time gained in the modelling process by the ease of use of SimMechanics, is lost to some extent again when creating a VR animation of the system.

When implementing the Delft-Tyre model in SimMechanics a number of benchmarks were executed to compare the simulation results against the time histories obtained with some other general purpose multi-body simulation packages. These tests are done to ensure identical behaviour of the tyre model in the different simulation environments and can be seen as a form of quality checking. These tests showed that, in comparison to other multi-body packages, the simulation times and accuracy are quite good. But it is also difficult to make general statements on the performance based on the limited testing we did, in particular for large size models.

4. Applications

The applications shown hereafter have been developed at the Eindhoven University of Technology and use the TNO Delft-Tyre model. In general there is a close cooperation between Eindhoven and TNO in the field of tyre model development and vehicle dynamics.

4.1 Motorcycle model

The SimMechanics motorcycle model was created to improve the representation of the tyre behaviour at large camber angles (ref. 3). The model is based on the PhD work of Koenen (1983, ref. 4) and the structure is shown in figure 6. The model consists of eight bodies: two wheels, frame + driver lower body, driver upper body, rear suspension, handle bars, front fork upper part, front fork lower part. Perhaps the least intuitive joint in this model is the twist axis at the front of the motorcycle. This twist axis is important to get a correct representation of the dynamic behaviour of the motorcycle, which includes phenomena like weave and wobble. At the time Koenen derived the equations of motion by hand, a rather laborious and particularly error prone process. Using SimMechanics it was possible to recreate the same model in a few weeks time.

In this study the first aim was to look at the steady-state cornering behaviour for large roll angles (up to 50 degrees). The aim was to have the motorcycle (slowly) follow a reference profile for the roll angle. A controller was developed to achieve this and stabilise the motorcycle. Some simulation results are given in figure 7, which shows the transition from straight line driving to severe cornering and back. Current work focuses on improving the tyre model and our understanding of the interaction between tyre and motorcycle dynamics.

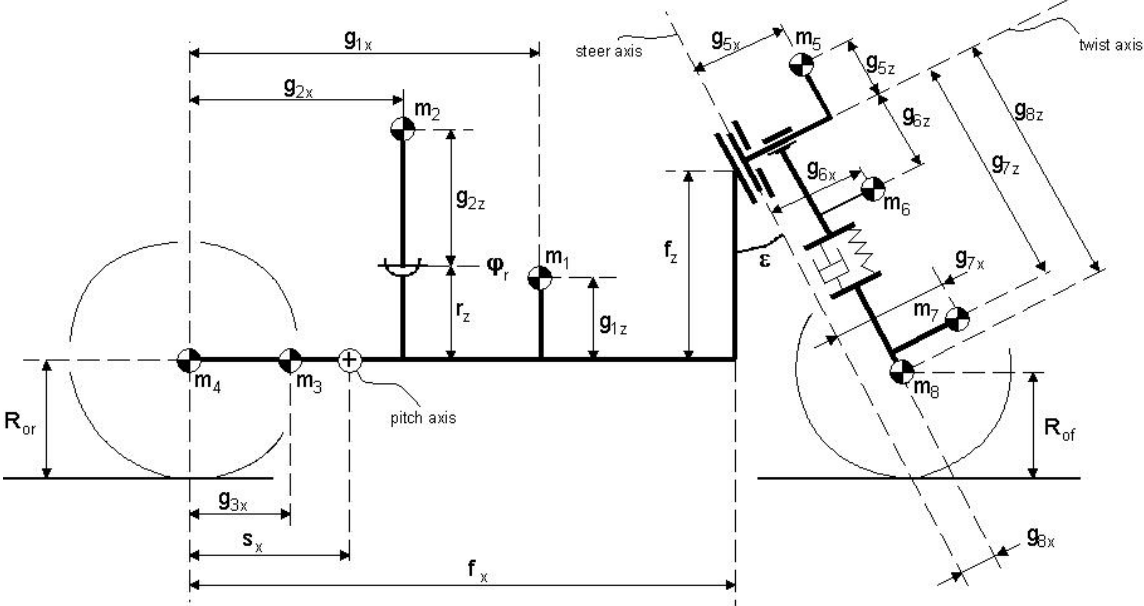


Figure 6 Mechanical lay-out of the motorcycle model

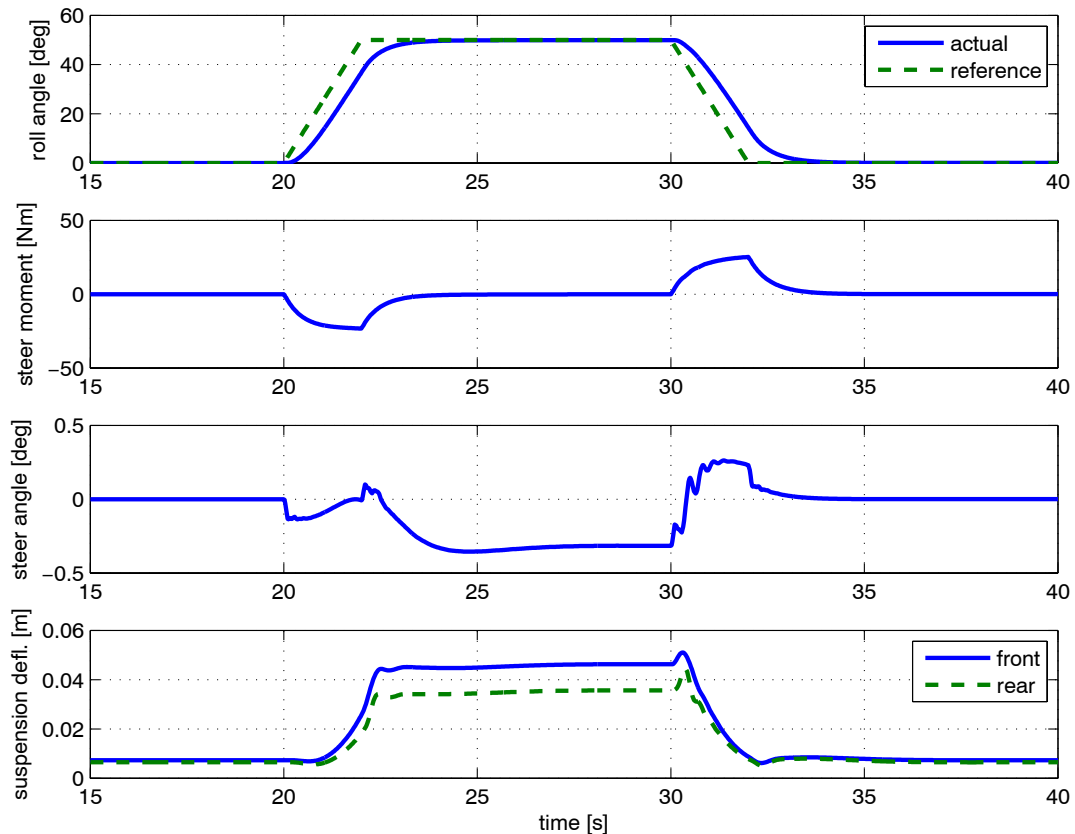


Figure 7 Simulation results motorcycle model (cornering at 100 km/h)

4.2 Formula Student racing car

The Eindhoven University of Technology participates in the international Formula Student competition (see www.formulastudent.com). For the design of the 2006 racing car a SimMechanics model was developed to analyse the suspension geometry and overall vehicle performance. The final model has the following features:

- front and rear double wishbone suspension
- mono shock spring/damper configuration operated by pushrods
- steering system with rack and pinion
- powertrain model
- braking system
- rigid chassis

The model consists of 32 bodies and the whole suspension geometry has been parametrised to easily investigate the effect of design changes. The powertrain and braking system are plain Simulink models, which can be easily integrated into the complete multi-body vehicle model. Figure 8 gives an impression of the Simulink model and the controllers to prescribe a specific manoeuvre. Figure 9 shows the SimMechanics model using the default viewer. Several tests have been executed, for example straight line acceleration, emergency braking, J-turn, fish hook manoeuvre, slalom, driving over a bumpy road and suspension kinematics. Since only very limited tyre data is available, the built-in estimation procedures of the Delft-Tyre model are used. The simulation results have been used to improve the stability of the vehicle by optimising the suspension geometry and to size certain components.

TU/e Formula Student 2006

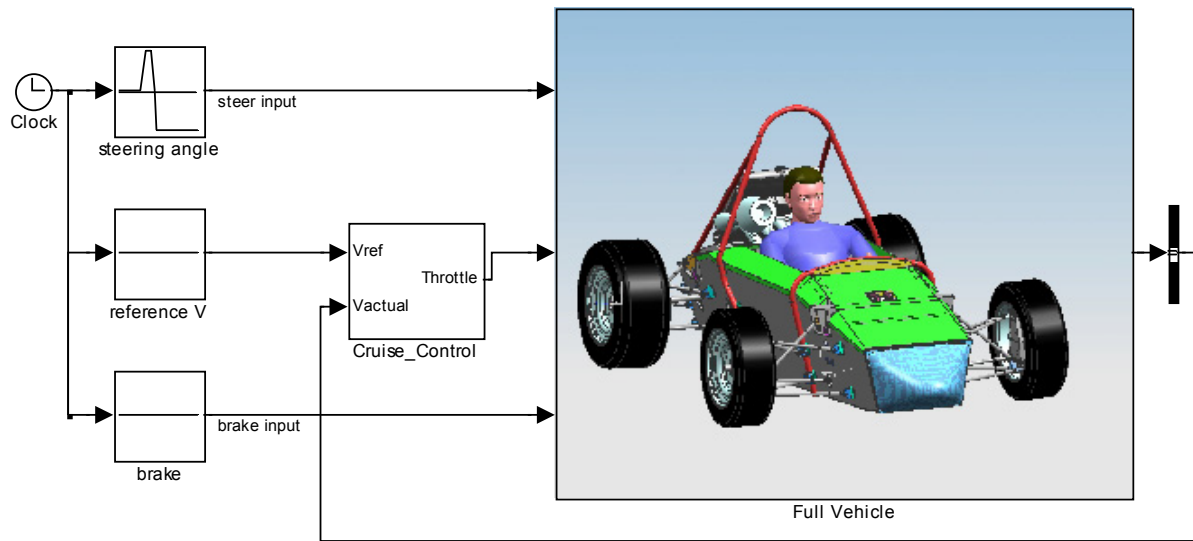


Figure 8 Formula Student Simulink model

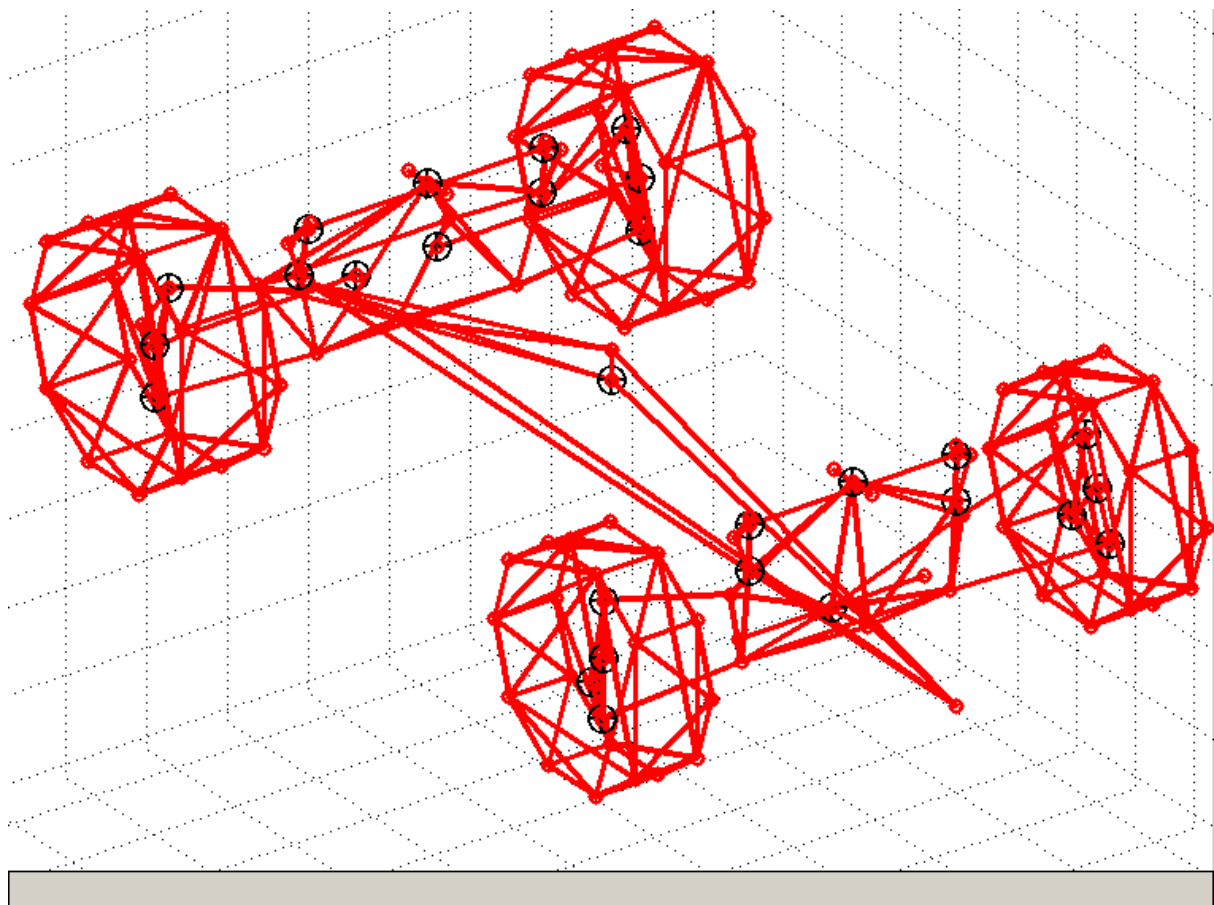


Figure 9 Model visualisation using the default SimMechanics viewer

4.3 Truck front suspension

The SimMechanics truck model is the central part of the examination for the course “Advanced Vehicle Dynamics” this year. The students are challenged with a number of design issues when developing a front axle for a truck (secondary steering effects, shimmy and fatigue) and it is their task to optimise the front suspension and make the necessary calculations. Figure 10 gives an impression of the front axle and figure 11 of the full vehicle as created using SimMechanics and the Virtual Reality toolbox. The full vehicle model consists of 29 bodies. The front suspension geometry is completely parameterised and when modifications are made (e.g. changing the length of rods, coordinates) the VR animation is updated automatically. Simulations executed with this model include kinematics, compliance, severe braking and cornering.

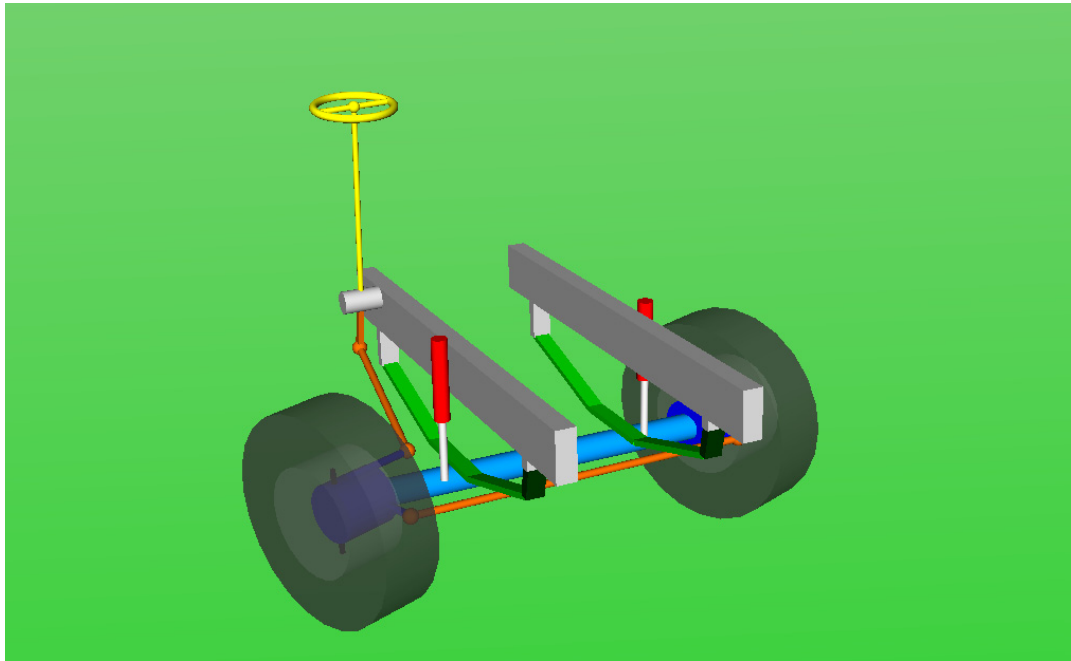


Figure 10 Truck model front suspension

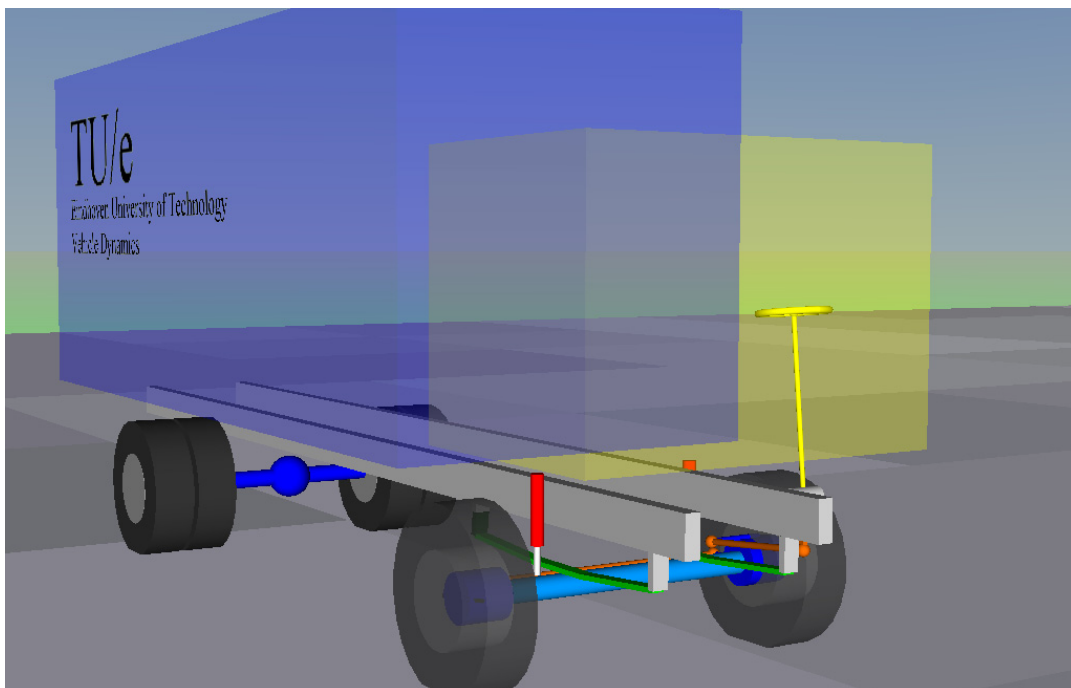


Figure 11 Full truck model

Conclusions

As shown in this paper, SimMechanics has been applied successfully to analyse the dynamic behaviour of different vehicles. An essential part of these models is the TNO Delft-Tyre model. In comparison to other general purpose multi-body packages SimMechanics offers advantages in terms of ease of use, Simulink integration, parametrisation of models and creating subsystems. The visualisation of a multi-body model can be improved. By using the Virtual Reality toolbox this is solved to some extent, but it still requires quite a bit of effort to make it work.

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