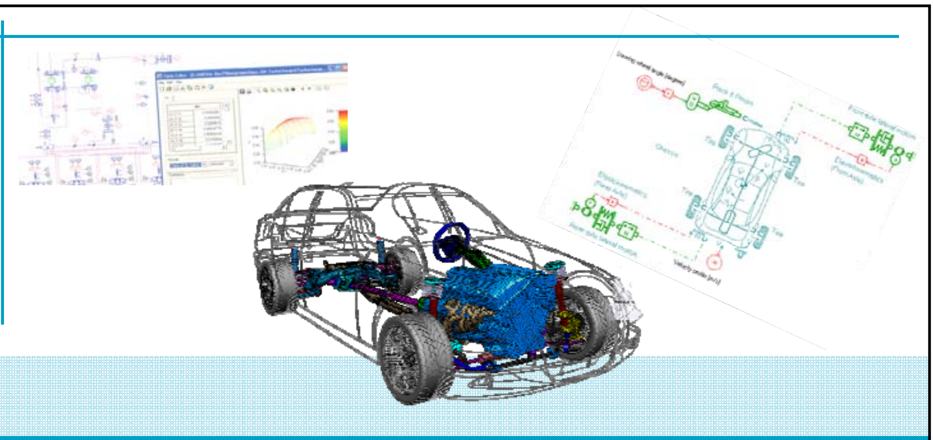

Impact of Multi-Body Component Flexibility on the Simulation of a Vehicle Active Braking Maneuver

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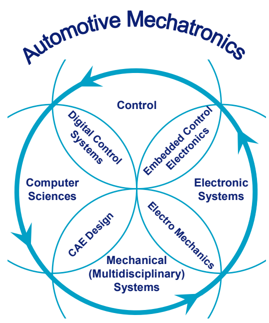
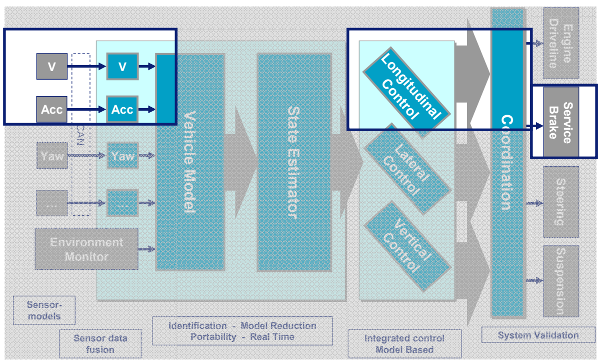
Automotive Mechatronic – The context

Mechatronics is a multidisciplinary engineering system design, that is to say it rejects splitting engineering into separate disciplines





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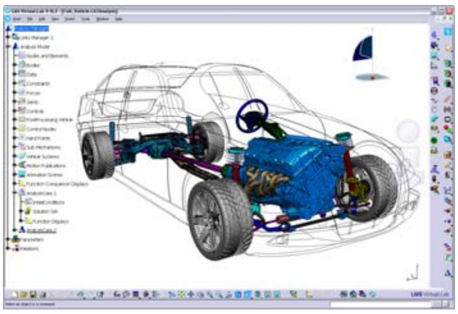
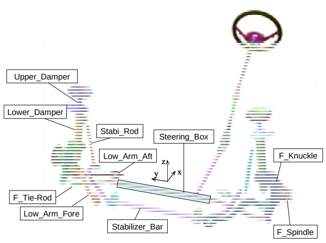
Modeling the vehicle by rigid subsystems





# of bodies	81
# of configuration params.	567
# of degrees of constraints.	403
# of degrees of freedom	164

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q},\dot{\mathbf{q}}) + \left[\frac{\partial \boldsymbol{\varphi}}{\partial \mathbf{q}}\right]^{\mathrm{T}} \boldsymbol{\lambda} = \mathbf{Q}(\mathbf{q},\dot{\mathbf{q}},\mathbf{z},\mathbf{s},t)$$

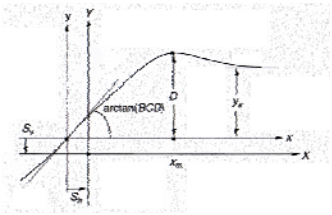
$$\boldsymbol{\varphi}(\mathbf{q}) = \mathbf{0}$$

$$\dot{\mathbf{z}} = \mathbf{g}(\mathbf{q},\dot{\mathbf{q}},\mathbf{z},\mathbf{s},t)$$

$\mathbf{M}$ → Mass matrix
$\mathbf{q}$ → Generalized coordinates
$\mathbf{Q}$ → Generalized forces
$\boldsymbol{\lambda}$ → Lagrange multipliers vector
$\boldsymbol{\varphi}$ → Constraint equations
$\mathbf{h}$ →Vector containing the non quadratic terms
$\mathbf{z}$ →Control system states
$\mathbf{s}$ →Control inputs

Tire force element – Steady state behavior

The model is based on the well known "Magic formula" of Pacejka:



- Y the reaction force to be calculated
- x input variable, depending from the calculation (s, α, γ)

$$y(x) = D\sin\{C\arctan[Bx - E(Bx - \arctan Bx)]\}$$

$$Y = y(x) + S_V$$

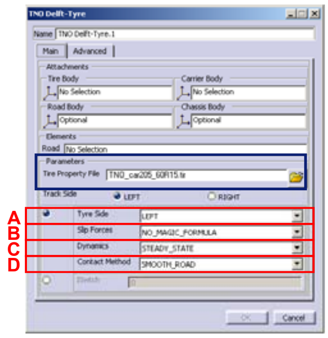
$$x = X + S_H$$

The level of detail of the calculation to be implemented has a high modularly

- **A: position of the tire**
- **B: calculation type** (Fx, Fy, Mx…)
- **C: frequency range** (Steady state to Rigid Ring)
- **D: calculation of the contact point** (Smooth road to 3D Road)

The big number of parameters are collected in an external file and identify a particular tread:

`TNO_car205_60R15.tir`

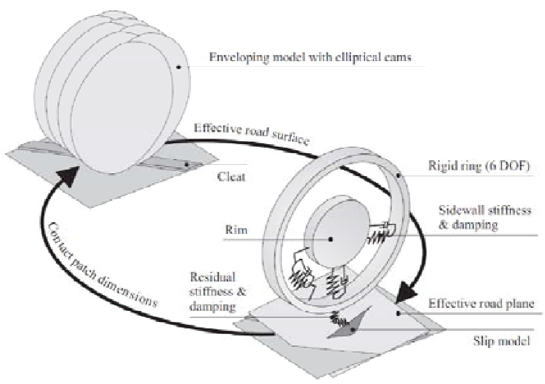


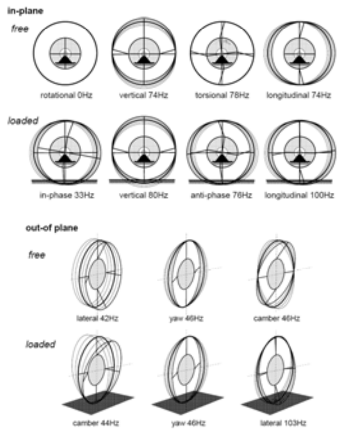
Tire force element – Dynamic behavior plus SWIFT

Short **W**avelength **I**ntermediate **F**requency **T**yre model

Rigid ring dynamics < 100 Hz, nonlinear
Road contact for 2D roads (using travelled distance)

Below 60 to100 Hz tread band may still be considered as a rigid body





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Modeling the vehicle by flexible components - 1

The method of **C**omponent **M**ode **S**ynthesis is used in formulating the flexible bodies in the multibody system.

Floating Frame: a frame that follows the gross motion of the body describes the large displacements of the system so that the deformation given by the flexibility of the component are expressed as a deviation from that motion

Using this formulation and splitting the system's coordinated into translational, rotational and modal, the equation of motion of any flexible body in the system can be expressed using the following:

$$\begin{bmatrix} \mathbf{m}^i_{rr} & \mathbf{m}^i_{rp} & \mathbf{m}^i_{ra} \\ & \mathbf{m}^i_{pp} & \mathbf{m}^i_{pa} \\ sym & & \mathbf{m}^i_{aa} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{r}}^i \\ \ddot{\mathbf{p}}^i \\ \ddot{\mathbf{a}}^i \end{bmatrix} = \begin{bmatrix} \mathbf{Q}^i_r \\ \mathbf{Q}^i_p \\ \mathbf{Q}^i_a \end{bmatrix} + \begin{bmatrix} \gamma^i_r \\ \gamma^i_p \\ \gamma^i_a \end{bmatrix} - \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{K}^i_a\mathbf{a} + \mathbf{D}^i_a\dot{\mathbf{a}} \end{bmatrix} - \begin{bmatrix} \Phi^T_{\mathbf{r}^i} \\ \Phi^T_{\mathbf{p}^i} \\ \Phi^T_{\mathbf{a}^i} \end{bmatrix} \lambda$$

Mass matrix that contains different inertia shape integrals.

Externally applied forces

Modal stiffness and damping forces

Lagrange multipliers of defined constraints

Vector of the body's generalized accelerations and second time derivatives of the modal coordinates

Quadratic velocity vector

Constraint Jacobian matrices

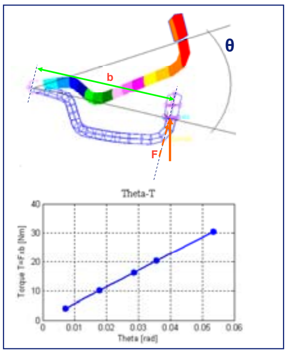
LMS ENGINEERING INNOVATION

Modeling the vehicle by flexible components - 2

To include a correct representation of both the static and dynamic response of the system the use different sets of dynamically responding vectors (namely normal modes) and a set of static vectors is necessary. Here Craig-Bampton approach to CMS is adopted, combining the ***constraint modes*** with a limited number of the lowest Eigen modes of the structure, the ***fixed-interface normal modes***,

Rear Suspension	
Part Name	**# modes**
Lower Arm (x2)	9
Control Arm (x2)	9
Leading Arm (x2)	9
Upper Arm (x2)	9
Trailing Arm (x2)	9
Knuckle (x2)	15
Stabilizer Bar	21
Sub-frame	118

Front Suspension	
Part Name	**# modes**
Lower Arm Fore (x2)	37
Lower Arm Aft (x2)	37
Knuckle (x2)	37
Tie Rod (x2)	37
Stabilizer Bar	21



Extraction of the lumped torsional stiffness of the rear stabilizer bar

Example of the **sub-frame** has a modal subspace of **118 vectors**
Deducing the 6 rigid modes from
19 Interface points: 10 with Suspension → **114 Constraint modes**
2 Stabilizer Bar
4 Vehicle Body
3 Differential
→ **10 fixed interface modes**

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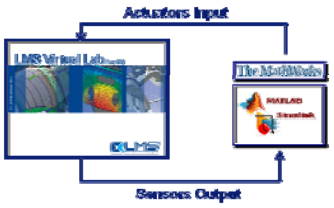
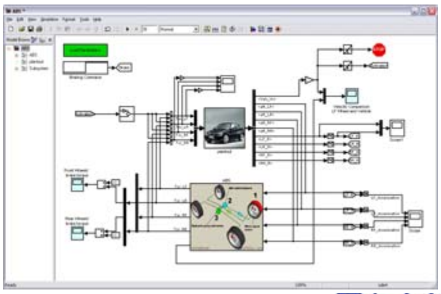
Architecture of the controlled system

To permit this coupling, three different possibilities for connecting Virtual Lab Motion with MATLAB/Simulink are available:

- ***Coupled Simulations*** (sometimes called master/slave simulation), which calls Virtual Lab Motion as a subroutine of Simulink at each integration time step
- ***Co-Simulations***, in which Virtual Lab Motion and MATLAB/Simulink integrators run simultaneously
- ***Linearization***, for classical controls design, where the equations of motion from Virtual Lab can be linearized and exported in Matlab/Simulink

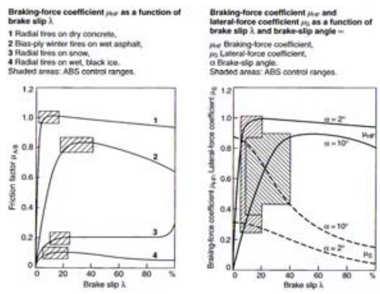


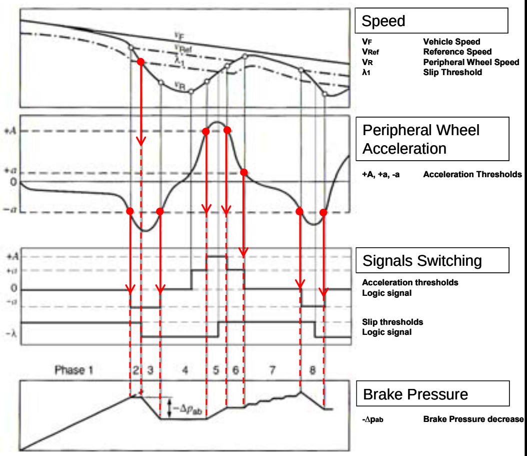
Simulink block scheme representing the implementation of the outer layer of the interface between the "plantout" S-Function of the vehicle model and the ABS control logic



Architecture of the controlled system

Braking force coefficient and lateral force coefficient as functions of the longitudinal slip, with evidence of the ABS control ranges [Bosch GmbH, *"Driving Safety systems,2"* SAE international 1999]





Controlled Variables:
- **Acceleration/deceleration of the wheel**
- **Longitudinal Slip**
  - Estimating Vehicle Velocity
  - Identification road friction

Different Control Logic for:
- **High Friction** •**μ-split**
- **Low Friction** •**μ-jump**

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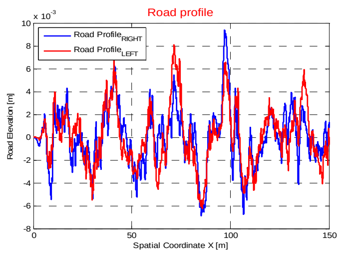
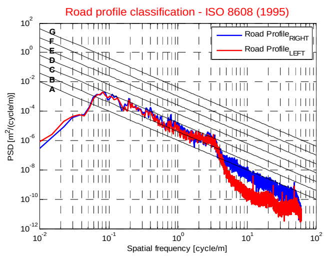
Simulation set up and results - 1

The vehicle is let run in straight driving configuration with an initial speed of 27.7 m/s on a flat road surface. The steering wheel is kept locked. After 50 meters (i.e. slightly less than 2s of simulation time) the vehicle incurs in a rough road surface

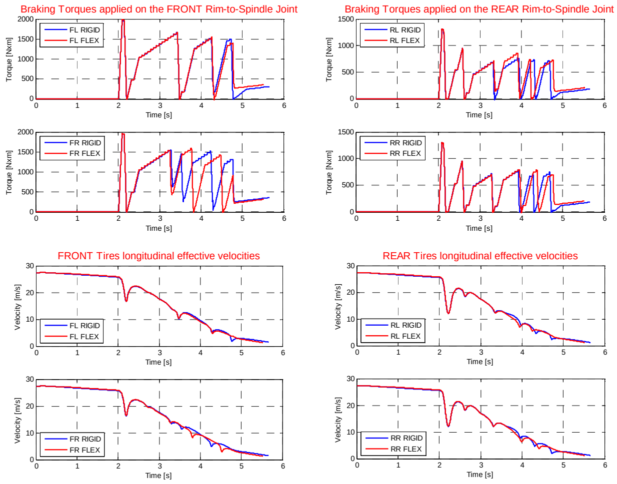




Portion of the road profile (on the left) and its ISO 8608 classification by PSD (on the right)

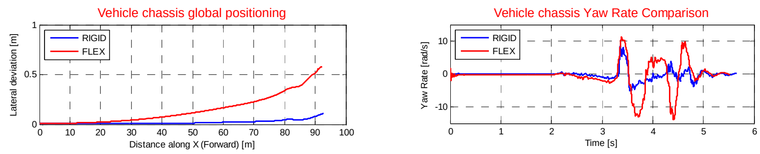
Simulation set up and results - 2

Braking torques are applied directly on the hubs.
From the plots of the braking torques it is evident that a different reaction of the control logic has occurred.
This variability is then reflected in the tire peripheral velocities

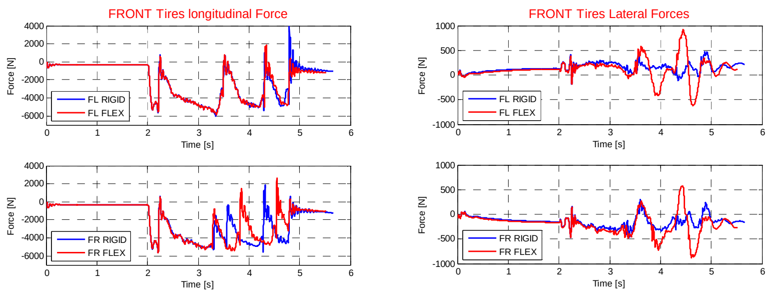


Simulation set up and results - 3

Yaw rate oscillations indicate a higher variability in the lateral forces



Forces exchanged between the tire and the ground are subject to a high variability due to the modified pulsation of the braking torque. Moreover the lateral force shows substantial modification, with an evident contribution to the yaw rate amplification



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Summary and conclusion

The study presented here shows the effects that including flexible components in the front and rear suspension mechanisms has on the braking behavior when an emergency braking maneuver occurs with the adoption of a traditional ABS logic.

In both the cases, the vehicle behavior is simulated during braking in a straight line while running over a rough road surface.

Results from both vehicle representations show that differences between rigid and flexible components can affect the braking action, **resulting in an accentuated steering drift**.

The investigation of this matter will, in the authors' future activities, further focus on the specific added contribution of the compliance each flexible element brings to the overall directional behavior.

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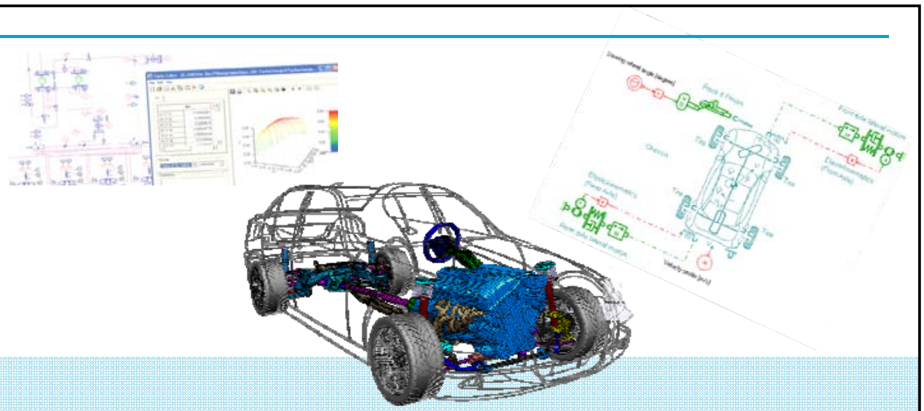
VECOM Vehicle Concept Modelling



Thank You!