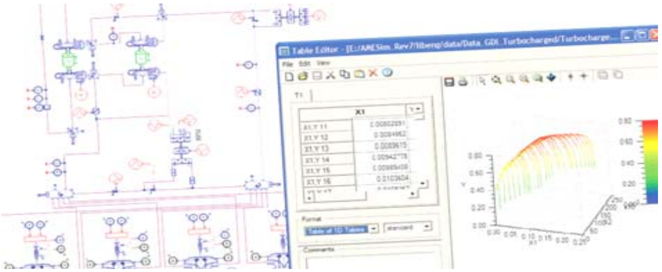
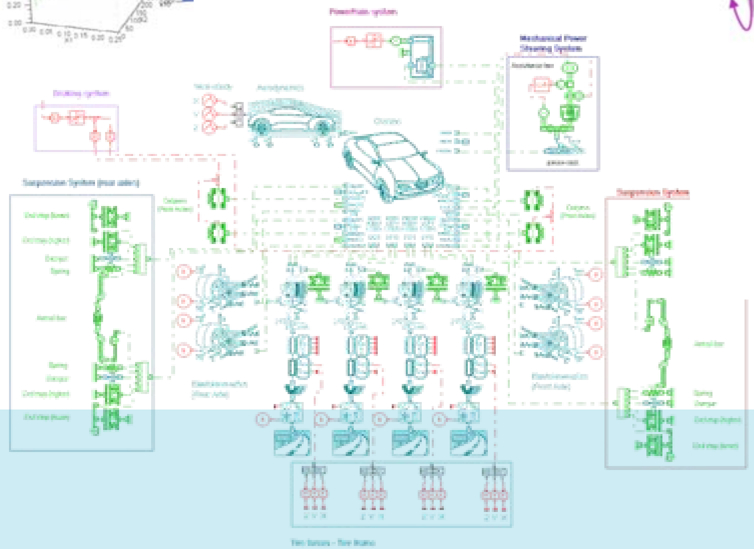
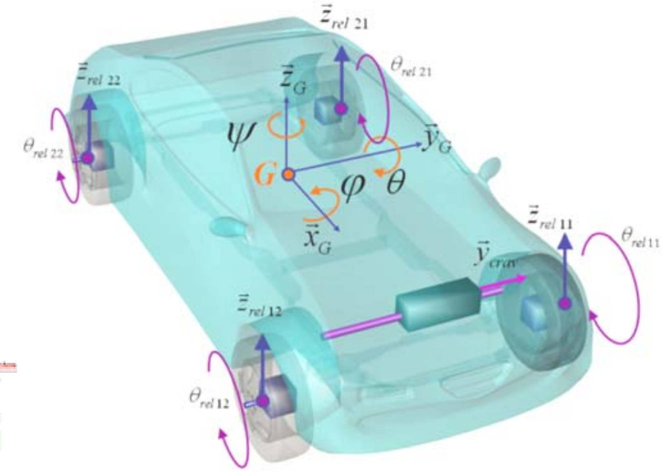






A system engineering approach for the design optimization of an active suspension

Marco GUBITOSA — Research Engineer Simulation Division

Jan ANTHONIS — Task Manager Engineering Services

Nicolas ALBARELLO — Project Engineer Engineering Services

VEHICLE DYNAMICS EXPO 2009

16, 17, 18 JUNE 2009 STUTTGART

LMS® ENGINEERING INNOVATION

1 The intelligent vehicle paradigm

2 The optimal design approach

3 Vehicle Model

4 Actuator Model

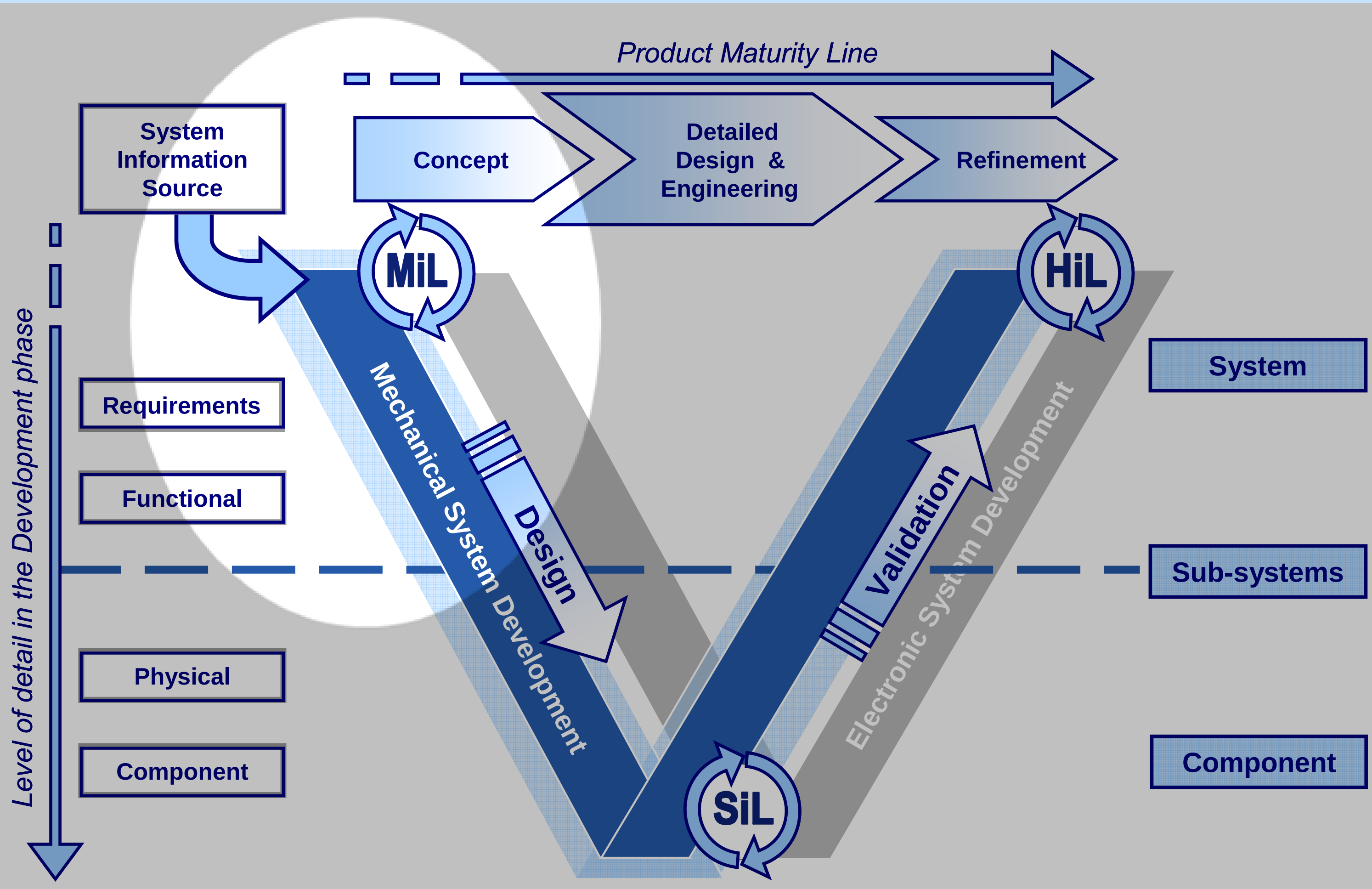
5 Conclusions & Outlooks

1

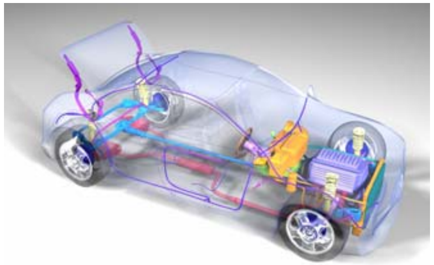
The intelligent vehicle paradigm

- Engineering challenges for intelligent vehicle systems
- LMS Imagine.Lab AMESim®
- noesis OPTIMUS®

Engineering challenges for intelligent vehicle systems



LMS Imagine.Lab AMESim®



Transmission

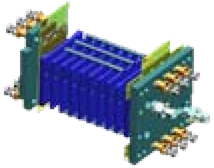
Performance and losses, Comfort, NVH

Vehicle Systems Dynamics

Braking, Steering, Suspension, Vehicle dynamics

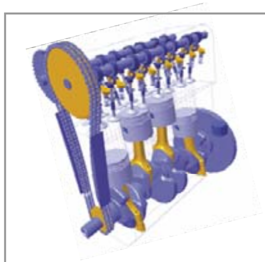
Energy Storage

Fuel Cell, Battery



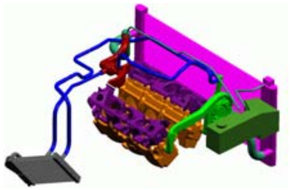
ICE Related Hydraulics

Fuel Injection, VVT, VVA, Engine compression brake



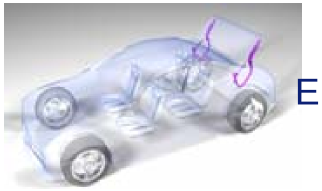
Internal Combustion Engine

Engine control, Air Path Management, Combustion, Hybrid Vehicle



Thermal Management

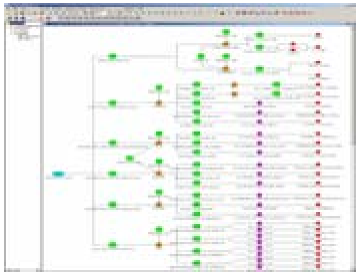
Lubrication, Cooling System, Air conditioning



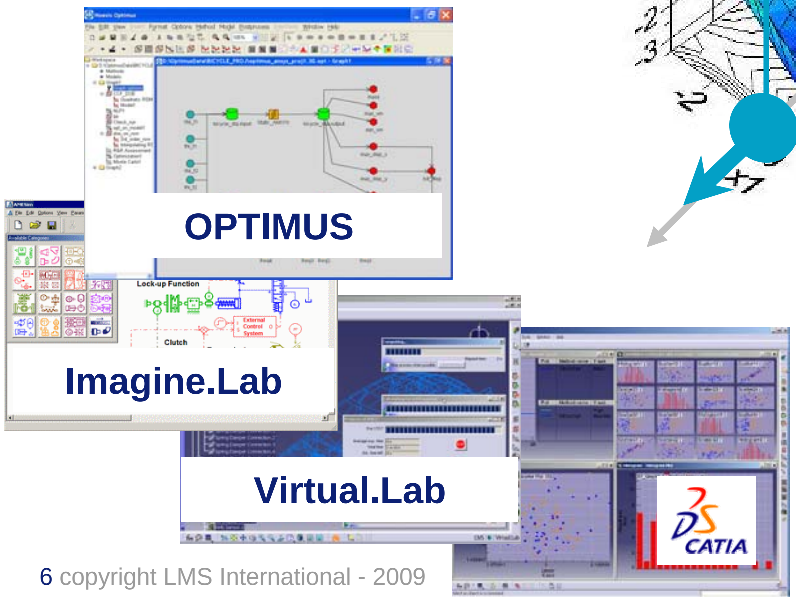
Electrical Systems

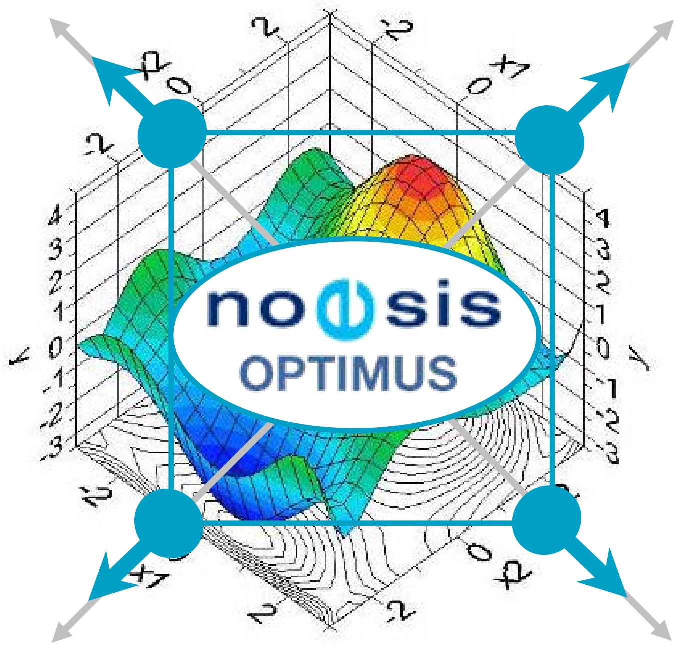
Electromechanical components, Electrical networks

Simulation process capturing



Simulation execution

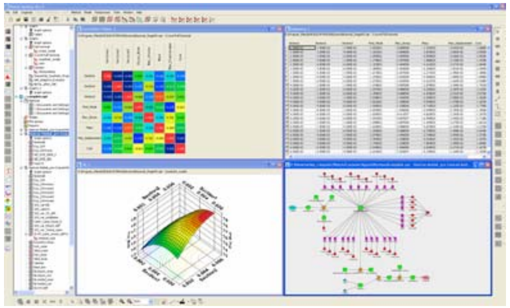




Design Optimization

- **D**esign-**O**f-**E**xperiments
- **M**ulti **O**bjectives **O**ptimization
- **Local** & **Global** Algorithms
- Robustness and **Reliability** analysis

Post-Processing



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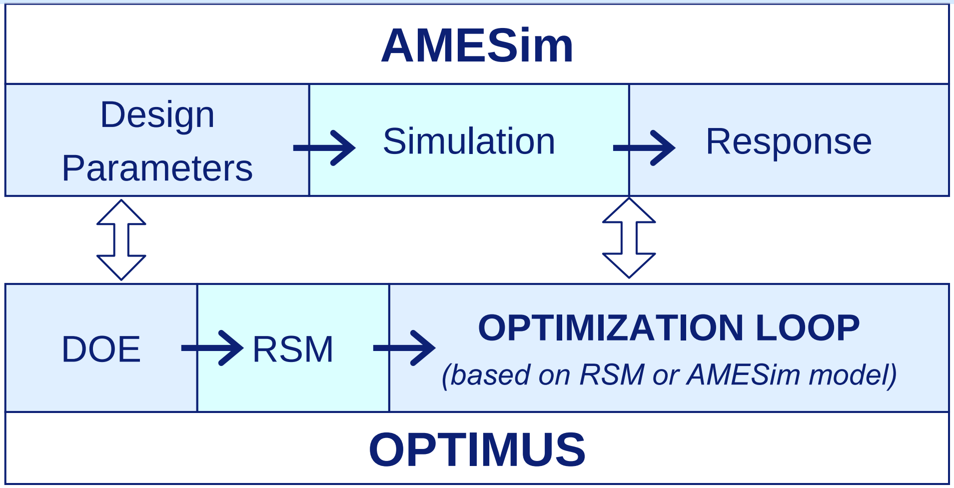
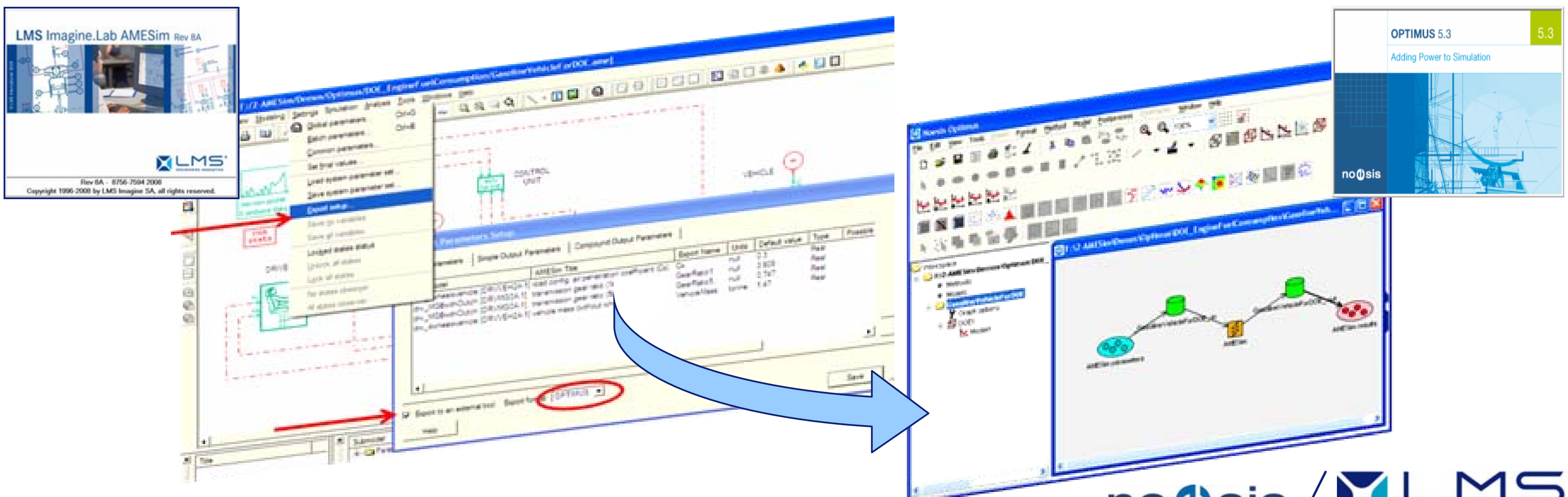
Imagine.Lab + OPTIMUS Functionality overview



- Parameterize and automate any analysis sequence
- Experiment and fit models through the generated data
- Optimize the models or the analysis sequence
- Ensure the reliability and robustness of the design
- Process supported by an intuitive, user-friendly Graphical User Interface

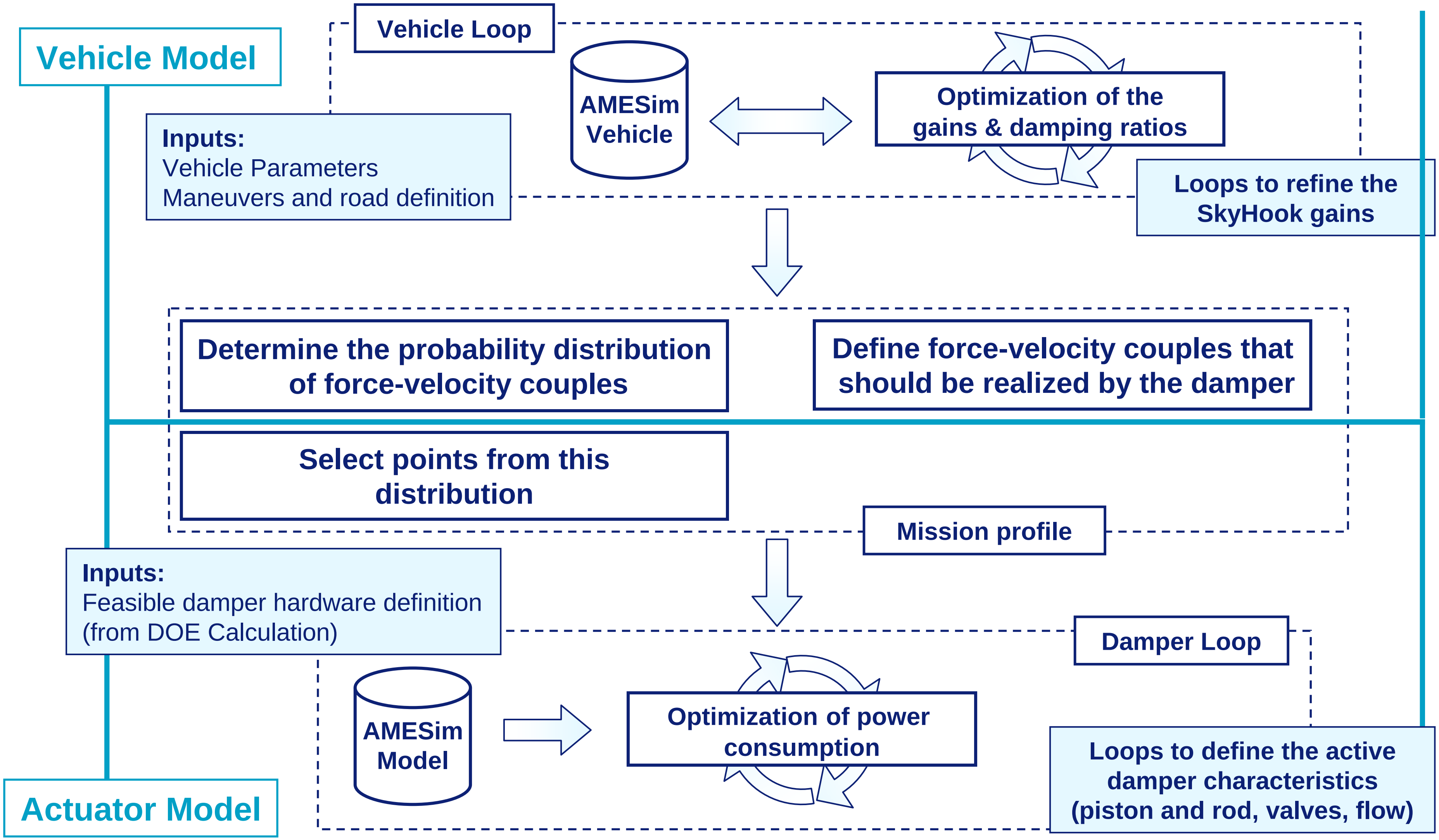


2

The optimal design approach

- Structured design scheme

Structured design scheme

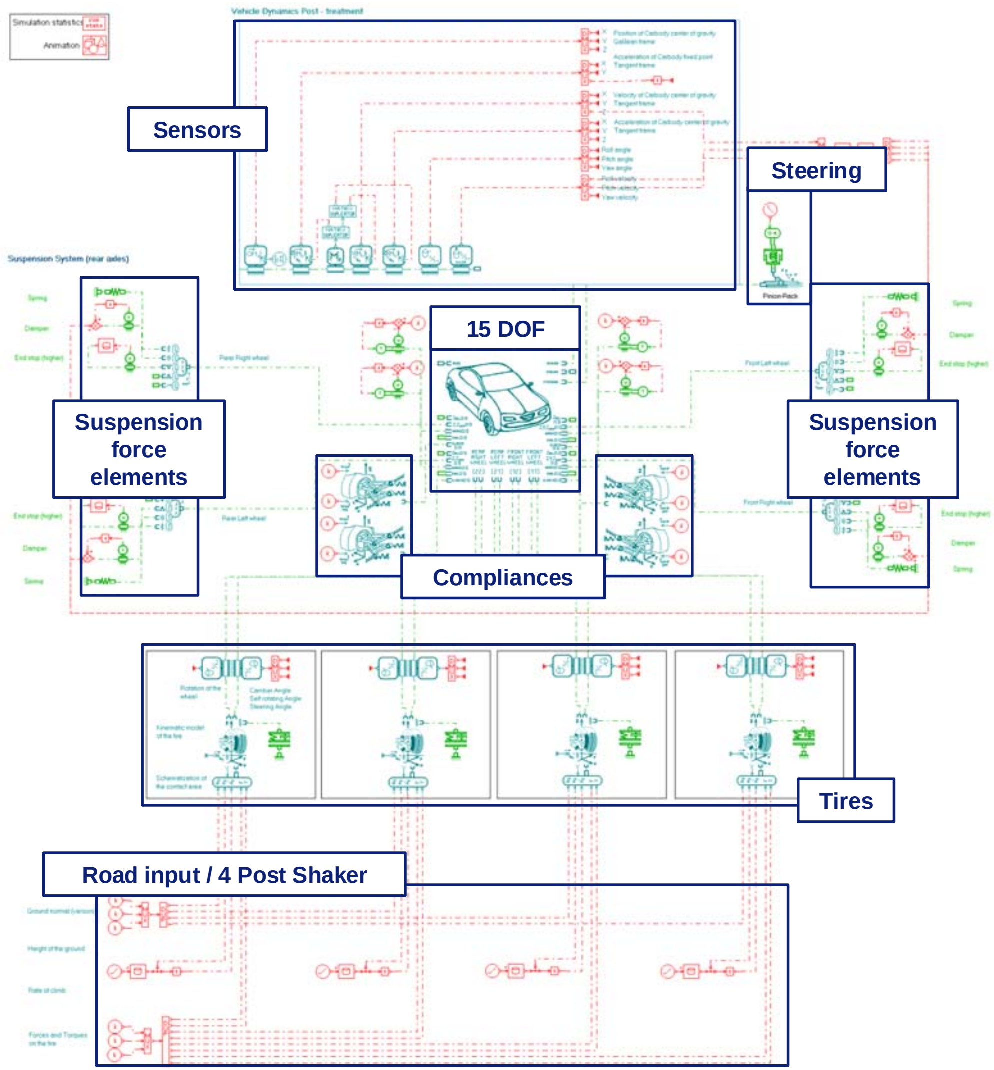


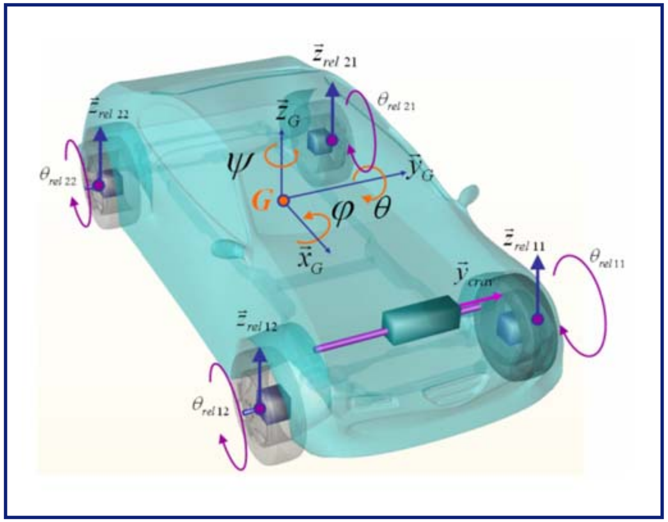
3

Vehicle Model

- Virtual model overview
- Measurement correlation – Model validity range
- The controlled vehicle – Active model set up
- Controller gains optimization

Virtual model overview





Car Body : 6 *DOF*	$X_G, Y_G, Z_G, \varphi, \vartheta, \psi$	15 *DOF*
Steering Rack Body : 1 *DOF*	y_n	
4 *Spindle Body* : 4×1 *DOF*	$4 \times z$	
4 *Wheel Body* : 4×1 *DOF*	$4 \times \omega$	

Virtual model overview

Wheel's attitude

- $$Trans_{Front} = \mathbf{d}_{rel\ KIN}\left(z, y_n, z_{opp}\right) = \begin{bmatrix} x\left(z, y_n, z_{opp}\right) \\ y\left(z, y_n, z_{opp}\right) \\ z \end{bmatrix}$$

- $$Rot_{Front} = \mathbf{r}_{rel\ KIN}\left(z, y_n z_{opp}\right) = \begin{cases} \delta\left(z, y_n, z_{opp}\right) & Toe\ in \\ \varepsilon\left(z, y_n, z_{opp}\right) & Camber \\ \eta\left(z, y_n, z_{opp}\right) & Self\ Rotating \end{cases}$$

$$\mathbf{d}_{rel\ TOT} = \boxed{\mathbf{d}_{rel\ ELAS}} + \boxed{\mathbf{d}_{rel\ KIN}}$$

$$\mathbf{r}_{rel\ TOT} = \boxed{\mathbf{r}_{rel\ ELAS}} + \boxed{\mathbf{r}_{rel\ KIN}}$$

Compliances

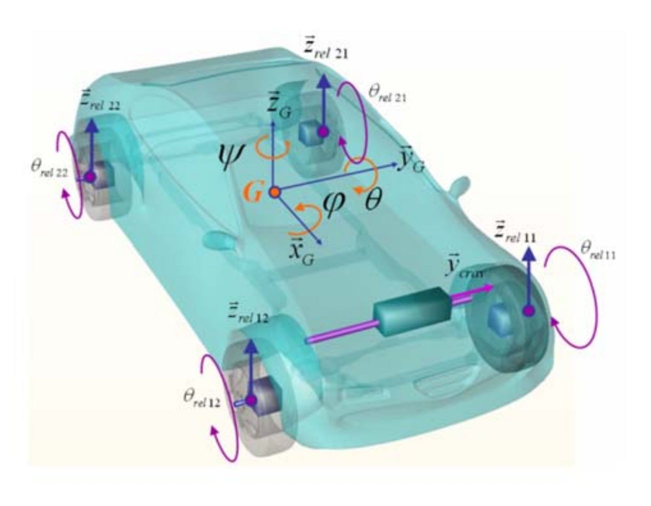
- $$\begin{bmatrix} \Delta x_{elas} \\ \Delta y_{elas} \\ \Delta \varepsilon_{elas} \\ \Delta \eta_{elas} \\ \Delta \delta_{elas} \end{bmatrix} = \left[M_{\substack{Flexibility \\ Current\,Wheel}}\right] \cdot \begin{bmatrix} F_x \\ F_y \\ M_\varepsilon \\ M_\eta \\ M_\delta \end{bmatrix} + \left[M_{\substack{Coupling \\ Current\ Wheel}}\right] \cdot \begin{bmatrix} F_{x\,opp} \\ F_{y\,opp} \\ M_{\varepsilon\,opp} \\ M_{\eta\,opp} \\ M_{\delta\,opp} \end{bmatrix}$$

$$\left[M_{\substack{Coupling \\ Current\ Wheel}}\right] = \left[q_{\substack{Coupling \\ CONSTANT \\ Current\,Wheel}}\right]$$

$$\left[M_{\substack{Flexibility \\ Current\,Wheel}}\right] = \left[q_{\substack{Flexibility \\ CONSTANT \\ Current\,Wheel}}\right] + \left[m_{\substack{Flexibility \\ REL\ to\ dZ \\ Current\,Wheel}}\right] \cdot z$$

Force elements tables

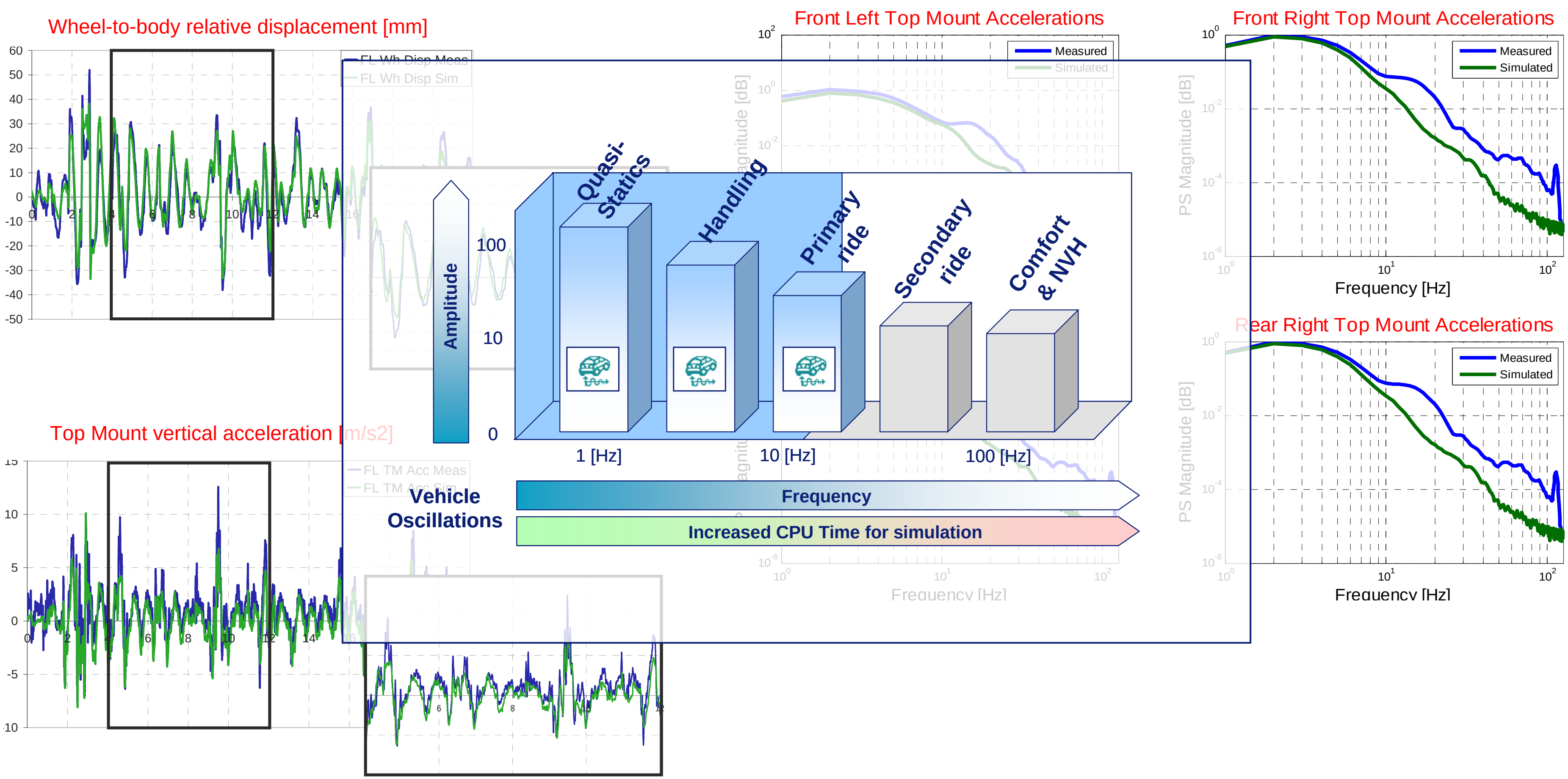
- $$\Delta_{Spring} = f\left(z, y_n, z_{opp}\right) \longmapsto \begin{cases} F_z = \dfrac{\partial f\left(z, y_n, z_{opp}\right)}{\partial z} \cdot F_{Spring} \\ F_{y_n} = \dfrac{\partial f\left(z, y_n, z_{opp}\right)}{\partial y_n} \cdot F_{Spring} \\ F_{z_{opp}} = \dfrac{\partial f\left(z, y_n, z_{opp}\right)}{\partial z_{opp}} \cdot F_{Spring} \end{cases}$$



Car Body : 6 *DOF*	$X_G, Y_G, Z_G, \varphi, \vartheta, \psi$	15 *DOF*
Steering Rack Body : 1 *DOF*	y_n	
4 *Spindle Body* : 4×1 *DOF*	$4 \times z$	
4 *Wheel Body* : 4×1 *DOF*	$4 \times \omega$	

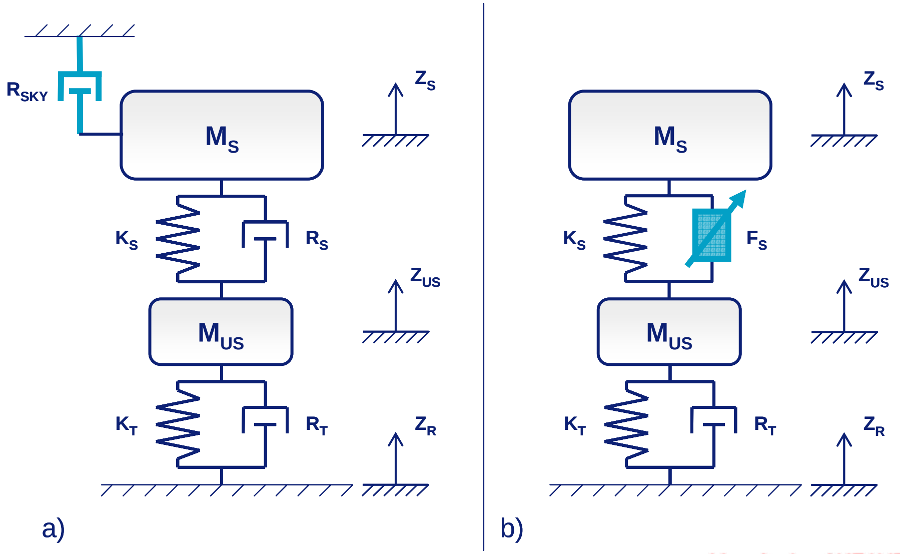
Measurement correlation – Model validity range

Measurements and virtual test with the vehicle running on *Road_1* at 80km/h



The controlled vehicle - Active model set up

The sky-hook approach

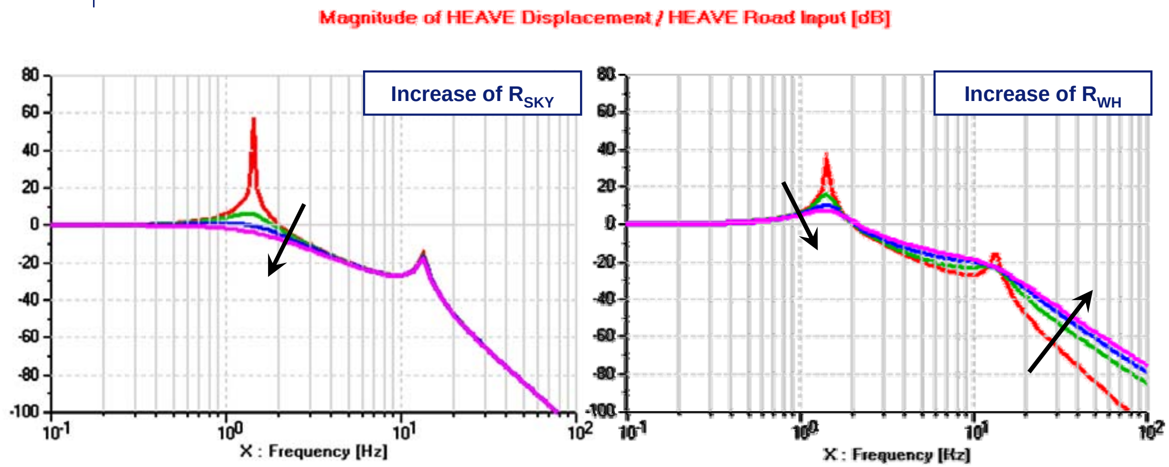


$$F_{SKY} = -\frac{dZ_S}{dt} \cdot R_{SKY}$$

$$F_S = F_{SKY} + F_{WH} = -\frac{dZ_S}{dt} \cdot R_{SKY} - \left(\dot{Z}_S - \dot{Z}_{US}\right) \cdot R_{WH}$$

Generalized on the full vehicle body modes

$$\begin{Bmatrix} F_Z \\ M_X \\ M_Y \end{Bmatrix} = \begin{bmatrix} -R_{SKY\_z} & 0 & 0 \\ 0 & -R_{SKY\_rx} & 0 \\ 0 & 0 & -R_{SKY\_ry} \end{bmatrix} \cdot \begin{Bmatrix} \dot{Z} \\ \dot{\varphi} \\ \dot{\theta} \end{Bmatrix}$$



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Controller gains optimization - 1

1 ● ● ● 2 ● 3 ● ● ● ◉ ● 4 ● ● ● ● ● 5 ●

1 **Full vehicle NON LINEAR model**

Complete Ride Maneuver:

Soft Spring Set
Normal Spring Set

RIDE Road_**1**
RIDE Road_**2**
RIDE Road_**3**

Tuning of the Wheel-Hop dampings in function of the performances requirements

2 **Full vehicle LINEARIZED model**

Static settling & linearization:

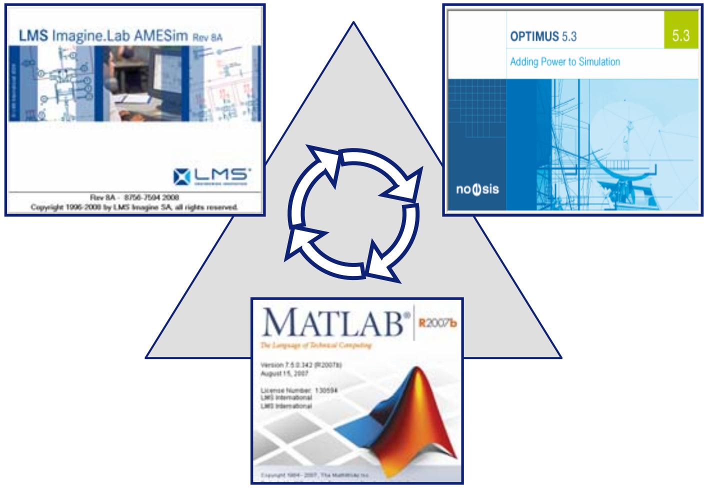
Soft Spring Set
Normal Spring Set

Tuning of the Sky-hook gains with respect to the modal damping ratios

1 $$Minimize \begin{cases} abs\left(Max\ and\ Min\ \theta\right) \\ abs\left(Max\ and\ Min\ \varphi\right) \\ abs\left(Max\ and\ Min\ \dot{Z}_{CG}\right) \\ abs\left(Max\ and\ Min\ \ddot{Z}_{CG}\right) \end{cases}$$

2 *Modal Z, θ, φ damping* $$\xi = \frac{1}{\sqrt{2}}$$

Interfacing **Optimus** – **AMESim** – **Matlab**



The optimizations ran with the *Differential Evolution Algorithm* (Global Optimization Scheme) in a nested loop

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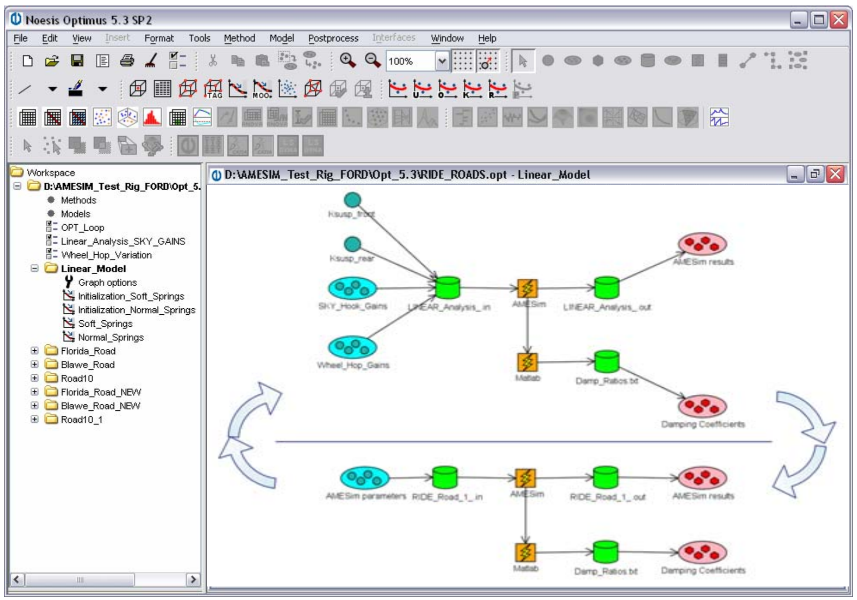
Controller gains optimization - 2

The set up of the active vehicle has been done with two different sets of springs ("***Normal***" and "***Soft***"), which leads to a small influence on the optimization results of this selection, because of the compensation offered by the active elements.



Soft Springs Set up			
	Ride Roads		
	1	**2**	**3**
R WH_Front	1155	1541	1348
R WH_Rear	1899	542	1221
R SKY_z	16025	18046	27290
R SKY_rx	1402	1402	1251
R SKY_ry	788	681	849
MAX_HeaveSpeed	0.372	0.136	0.041
MIN_HeaveSpeed	0.389	0.157	0.039
MAX_Roll	1.322	0.932	0.273
MIN_Roll	1.088	1.068	0.288
MAX_Pitch	0.556	0.537	0.080
MIN_Pitch	0.842	0.614	0.126
DampCoeff 1.1	0.499	0.751	0.964
DampCoeff 1.2	0.499	0.751	0.964
DampCoeff 2.1	0.733	0.446	0.631
DampCoeff 2.2	0.733	0.446	0.631
DampCoeff 3.1	0.692	0.746	0.673
DampCoeff 3.2	0.692	0.746	0.673

From the three ride maneuvers the *Mission Profiles* have been extracted.

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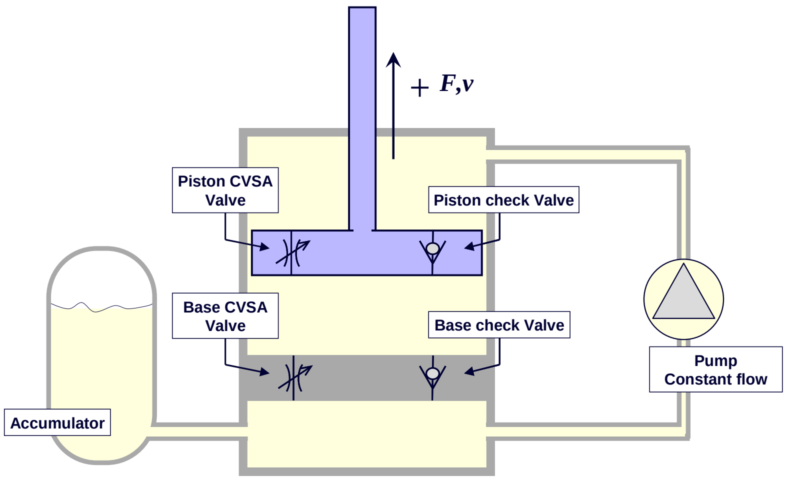
4

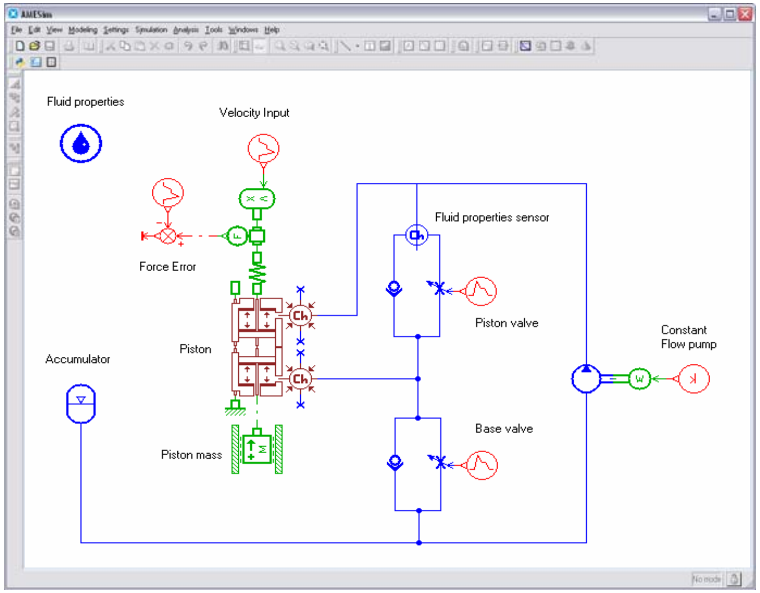
Actuator

Model

- Actuator representation and functional model
- DOE for performance achievement
- Mission Profiles & Iso-Power curves
- Optimization for energy consumption minimization
- The optima achievement

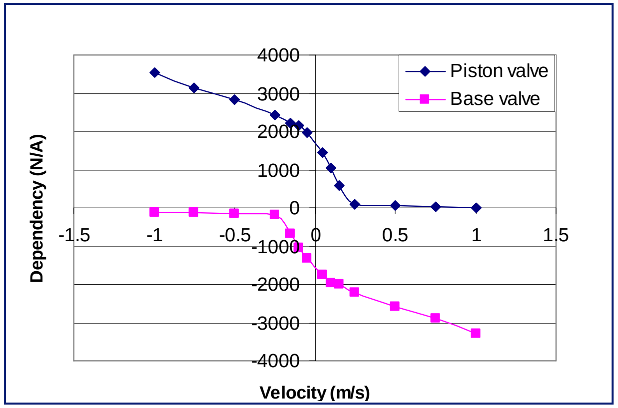
Actuator representation and functional model





$$F = \begin{cases} \dfrac{\rho \cdot S_1 \cdot (Q - S_2 \cdot \dot{x})^2}{2 \cdot C_q^{\ 2} \cdot S_{pv}^{\ 2}} - p_3 \cdot (S_2 - S_1) & if \quad \dot{x} > 0 \\ -\left[\dfrac{\rho \cdot (Q + (S_2 - S_1) \cdot \dot{x})^2}{2 \cdot C_q^{\ 2} \cdot S_{bv}^{\ 2}} + p_3 \right] \cdot (S_2 - S_1) & if \quad \dot{x} < 0 \end{cases}$$

- ρ: fluid density
- Q: pump flow
- p_3: accumulator pressure
- S_1: surface on the rod side
- S_2: surface on the piston side
- S_{pv}: orifice of the piston valve
- S_{bv}: orifice of the base valve
- C_q: flow coefficient
- $\dot{x}$: relative velocity of the piston w.r.t. the cylinder



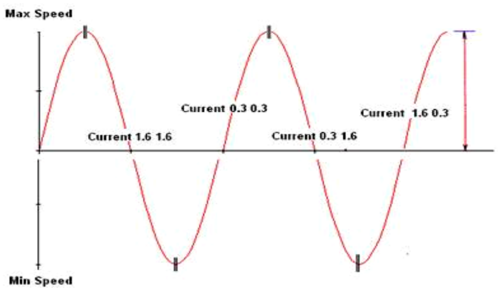
DOE for performance achievement

Define the feasible combinations to achieve the performance requirements defined by the mission profiles in terms of deliverable power achievement

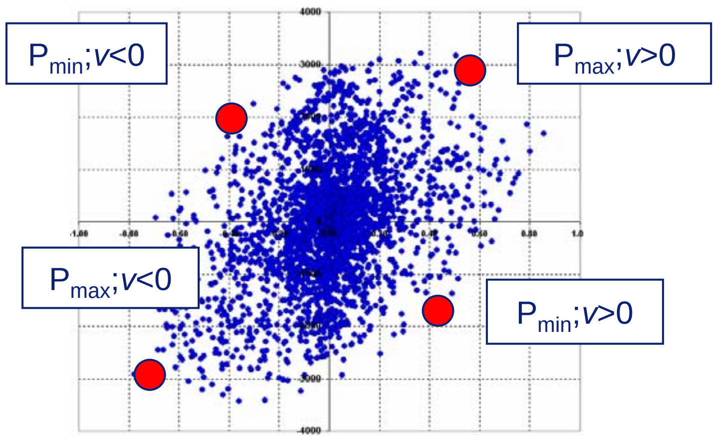
This DOE simulates all combinations of damper, valves and flow (discretized in 3 flows: 1, 5 and 10 L/min.) for a total of 1296

A **combination** is composed of:

- Rod (4)
- Piston (3)
- Piston valve (6)
- Base valve (6)
- Flow (3)



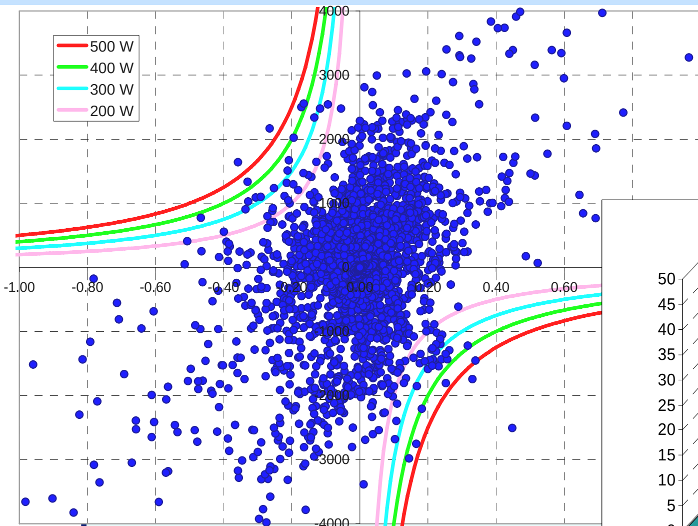
Selection of 4 critical points (P, v)



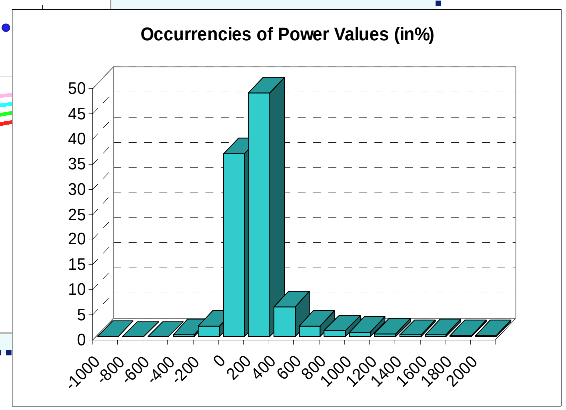
Index	Rod diameter [mm]	Cylinder diameter [mm]
1	12,4	25,4
2	15,8	
3	12,4	27
4	15,8	30
5	18	
6	20	
7	18	32
8	20	
9	22	
10	20	35
11	25	
12	25	45

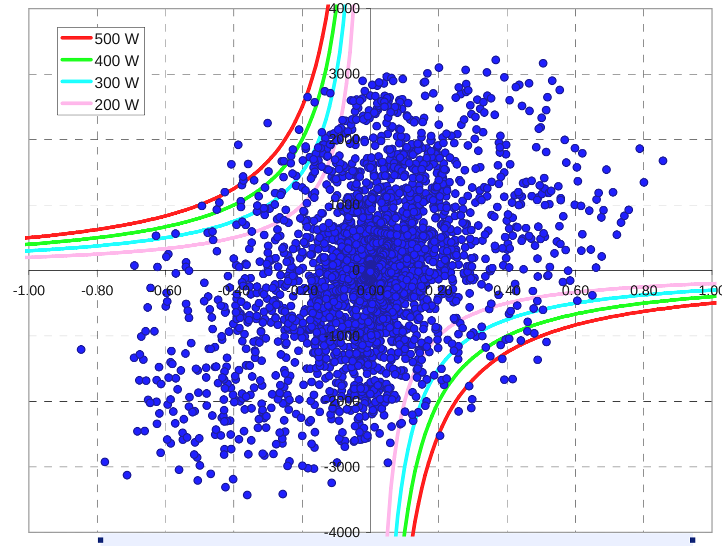
Those *feasible combinations* will be considered in the optimization loop

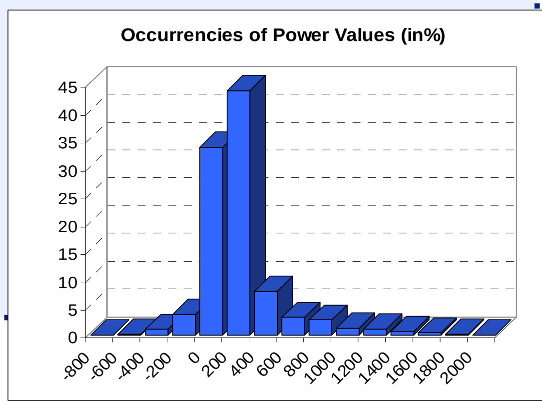
Mission Profiles & Iso-Power curves



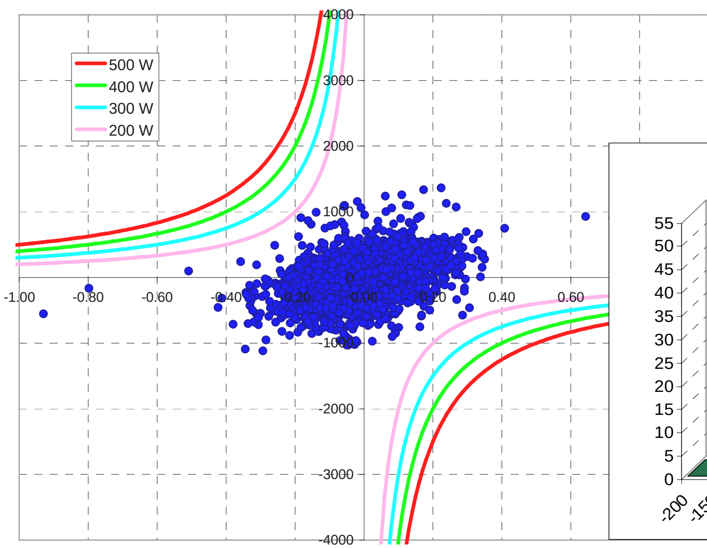
RIDE Road 1 - (5%)



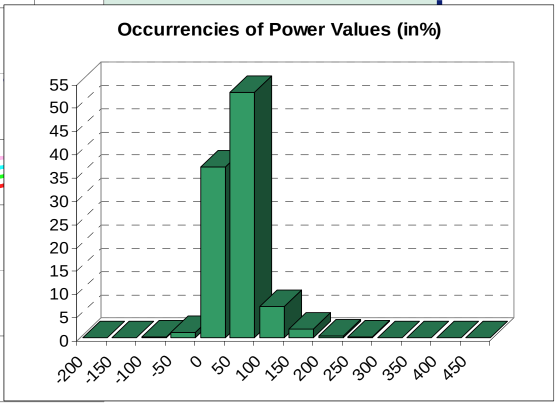




RIDE Road 2 - (5%)



RIDE Road 3 - (90%)



Optimization for energy consumption minimization

The objective function takes into account the mean error and the mean power consumption.

- **Cost function:**
  - Power Consumption & Mean Error with weighting factor

$$F(p) = w \cdot \int \left| error_{Force\ Observed} \right| + w \cdot \int \left| torque_{Pump} \cdot speed_{Pump} \right|$$

- **Optimization parameters:**
  - Rod and piston diameters
  - Valves characteristics
  - Pump flow
  - Input currents (at discretized time steps)
- **Criterion:**
  - Selection of random points in the required performance subset

5%	from RIDE Road 1
5%	from RIDE Road 2
90%	from RIDE Road 2

Optimization run for selected points using Genetic Algorithm

The optima achievement

Front Damper

Cylinder Ø [mm]	Rod Ø [mm]
30	20
32	20
	22
35	20

These combinations all use high pressure (HP) valves (min or max)

- ✓ *Damper: 35-20 (piston diameter 35mm and rod diameter 20mm)*
- ✓ *Valves: High Pressure with minimal characteristic*
- ✓ *Flow rate: 1L/min*

	Mean error (N)	Mean consumption (W)
Optimum (weight 5)	488	23
Optimum (weight 10)	314	53

Rear Damper

Cylinder Ø [mm]	Rod Ø [mm]	Piston valve	Base valve
32	22	*N min*	*HP min*
		N max	
35	25	*HP min*	*N min*
		HP max	
45	25	*HP min*	
		HP max	

- ✓ *Damper 45-25*
- ✓ *Piston valve: High Pressure maximum*
- ✓ *Base valve: Normal minimum*
- ✓ *Flow rate: 1L/min*

	Mean error (N)	Mean consumption (W)
Optimum (weight 10)	368 N	57 W

5

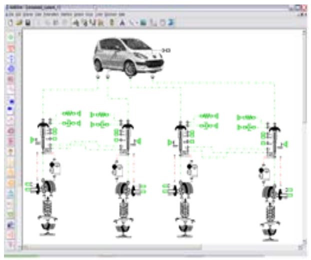
Conclusions & Outlooks

- The Intelligent Product development workflow

The Intelligent Product development workflow

1 ● ● ● 2 ● 3 ● ● ● ● ● 4 ● ● ● ● ● 5 ○

“Physical” models
connected to design data



Real Time Models

Real Time Requirement

Controller
Testing & Calibration
In ***Virtual***
Product Environment

Model in the Loop

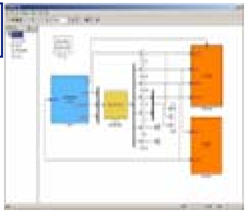
Software in the Loop

Hardware in the Loop

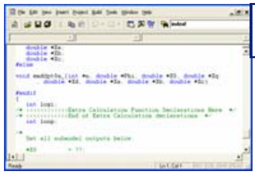
Control development

Control Logic Modeling

The MathWorks
MATLAB® & SIMULINK®



Embedded Software Code



Control Code Libraries

ECU Hardware

Emulated ECU “Rapid Prototyping”

Vehicle Integration

Controller
Testing & Calibration
in ***Physical***
Vehicle Environment

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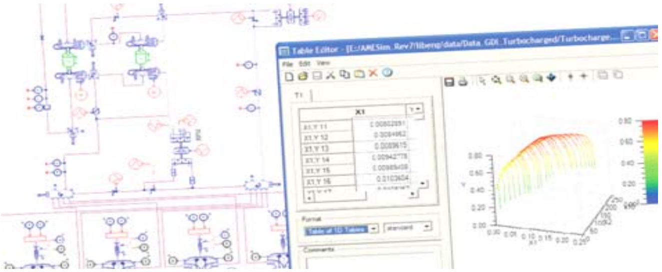

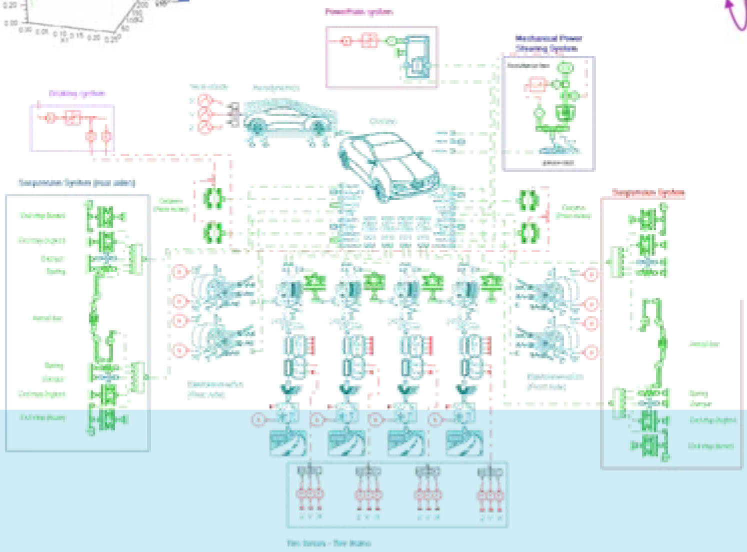

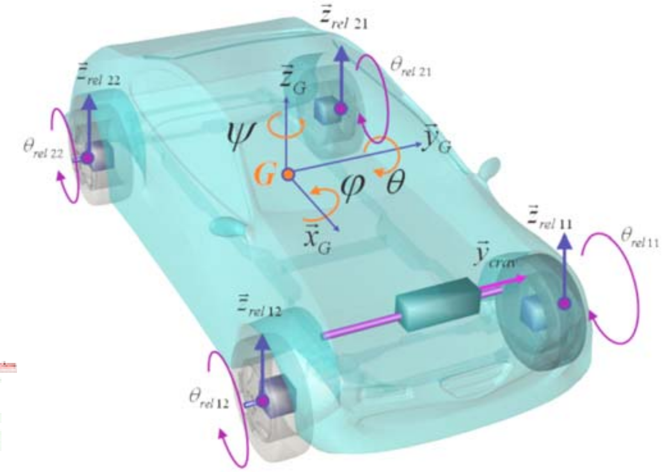

Thank you!

Time for Q & A…

ENGINEERING INNOVATION