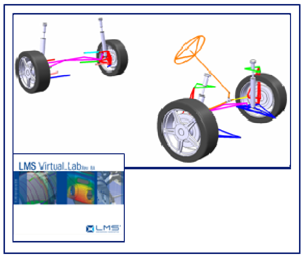
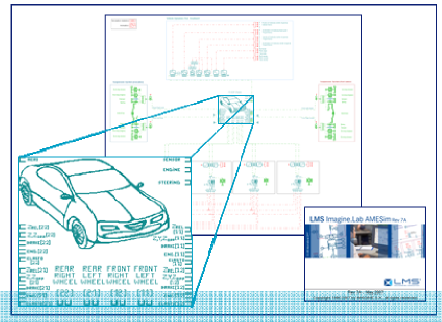
VEHICLE DYNAMICS EXPO 2008
6,7,8 MAY 2008 STUTTGART MESSE | STUTTGART | GERMANY





Suspension analysis through reverse engineering in the vehicle development concept phase

Virtual.Lab Motion ↔ Imagine.Lab AMESim

Ir. Valerio CIBRARIO Vertical Business Unit Manager, Automotive Solutions, C&S – LMS Italiana
Dr. Ir. Joris DE CUYPER Product Line Manager Virtual.Lab MOTION – LMS International
Ir. Marco GUBITOSA Research Engineer – LMS International

LMS ENGINEERING INNOVATION

Suspension analysis through "*reverse engineering*" in the vehicle development concept phase

The term *"reverse engineering"* as applied to software means different things to different people, prompting Chikofsky and Cross to write a paper researching the various uses and defining a taxonomy.

From their paper:

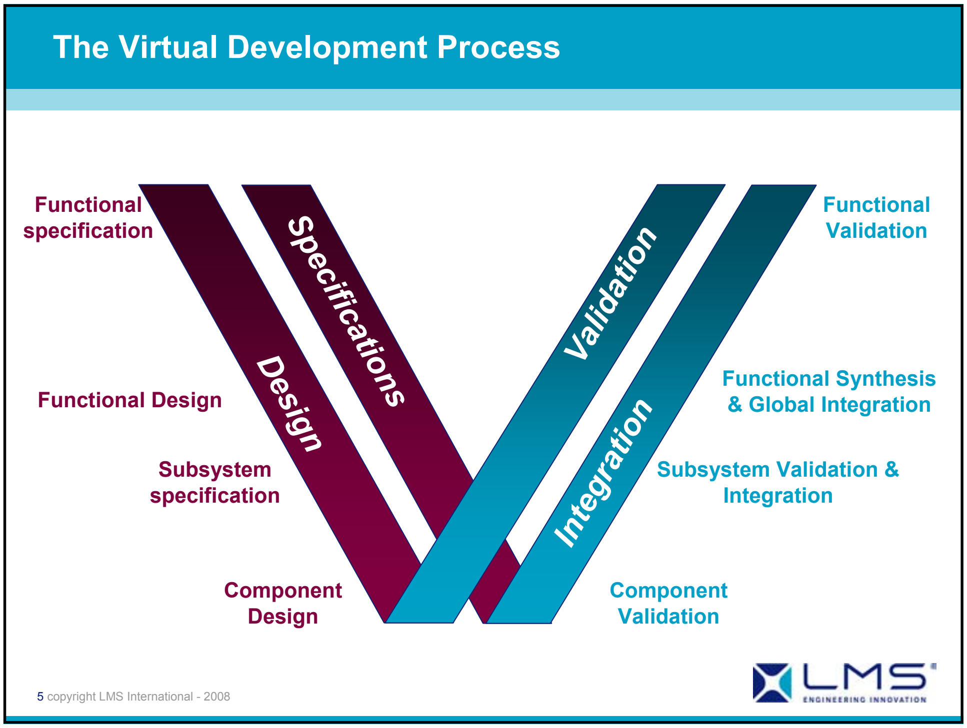
"Reverse engineering is the process of analyzing a subject system to create representations of the system at a higher level of abstraction".[1]

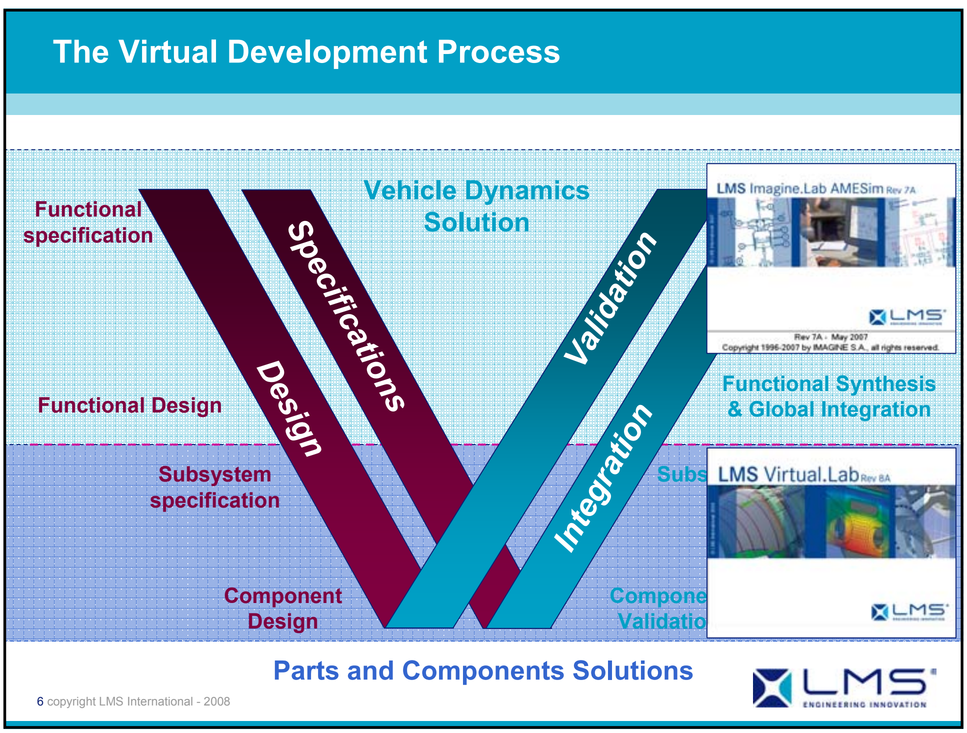
It can also be seen as:

***"going backwards through the development cycle"**.[2]*

[1] Chikofsky, E.J.; J.H. Cross II (January 1990). "Reverse Engineering and Design Recovery: A Taxonomy in IEEE Software". *IEEE Computer Society*: 13–17.
[2] Warden, R. (1992). *Software Reuse and Reverse Engineering in Practice*. London, England: Chapman & Hall, 283–305.

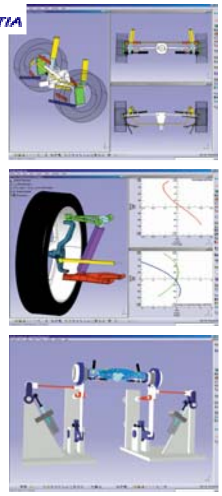
LMS ENGINEERING INNOVATION


The Virtual Development Process
Functional specification
Functional Design
Subsystem specification
Component Design
Design
Specifications
Validation
Integration
Functional Validation
Functional Synthesis & Global Integration
Subsystem Validation & Integration
Component Validation
5 copyright LMS International - 2008
LMS ENGINEERING INNOVATION


The Virtual Development Process
Vehicle Dynamics Solution
Functional specification
Functional Design
Subsystem specification
Component Design
Design
Specifications
Validation
Integration
LMS Imagine.Lab AMESim Rev 7A
Rev 7A - May 2007
Copyright 1996-2007 by IMAGINE S.A., all rights reserved.
Functional Synthesis & Global Integration
LMS Virtual.Lab Rev 8A
Parts and Components Solutions
6 copyright LMS International - 2008
LMS ENGINEERING INNOVATION

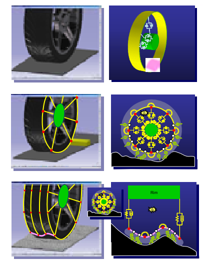
LMS Virtual.Lab Motion®

Suspension Motion Simulation



Full Vehicle Motion Simulation

Dedicated tire model the ‘Comfort-Durability’ tire model



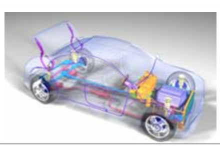
CDTire 20
Rigid ring model
Long wavelength surfaces

CDTire 30
Single flexible ring model
Short wavelength surfaces,
lateral height profile constant

CDTire 40
Multiple flexible rings
Suited for
irregular road surfaces
like “Belgian Block” or
cleats with variable height
or arbitrary position

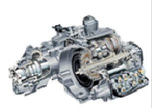
- **Scalable modeling for handling, comfort and durability**
- **Customization automation**
- **Integrated controls simulation**

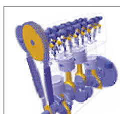
LMS Imagine.Lab AMESim®



ICE Related Hydraulics
Fuel Injection, VVT, VVA, Engine compression brake

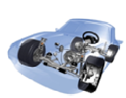
Transmission
Performance and losses, Comfort, NVH

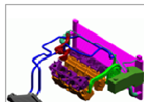




Internal Combustion Engine
Engine control, Air Path Management, Combustion, Hybrid Vehicle

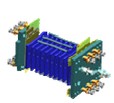
Vehicle Systems Dynamics
Braking, Steering, Suspension, Vehicle dynamics

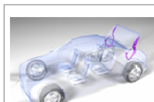




Thermal Management
Lubrication, Cooling System, Air conditioning

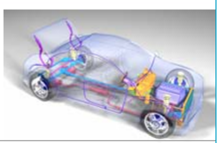
Energy Storage
Fuel Cell, Battery





Electrical Systems
Electromechanical components, Electrical networks

LMS Imagine.Lab AMESim®



Transmission

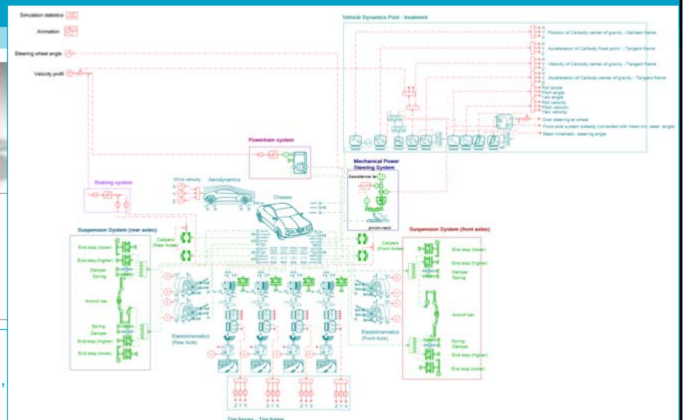
Performance and losses, Comfort, NVH

Vehicle Systems Dynamics

Braking, Steering, Suspension, Vehicle dynamics

Energy Storage

Fuel Cell, Battery

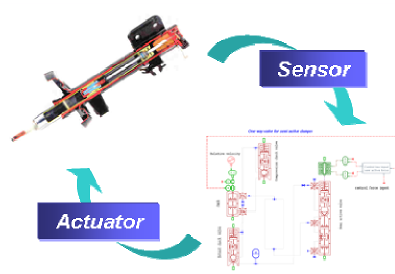


- **Global vehicle behaviour** with usage of conceptual suspensions
- Dedicated library for Vehicle Dynamics able to run **Real-Time**
- Linear analyses and optimization
- Parametric functions to modify the shape of the kinematics tables
- Suitable for vehicle **data management**
- Fully open for connections with **Simulink**

Unique "1D - 3D" simulation for scalable mechanical and mechatronic system simulation

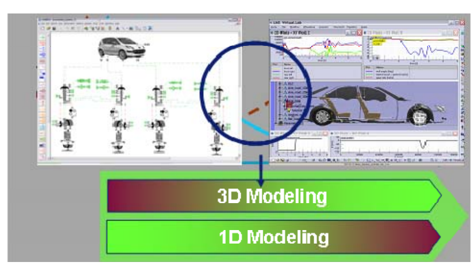
Mechatronic System Analysis

- LMS Virtual.Lab Motion
  - LMS Imagine.Lab AMESim
- Coupled simulation of mechanical, electrical, pneumatic…systems including controls



Fusion of 1D – 3D Simulation

- Scalable simulation
  Support all stages of design
- Vehicle dynamics – Ride& Handling, Comfort, NVH
- Powertrain/driveline comfort and NVH
- …



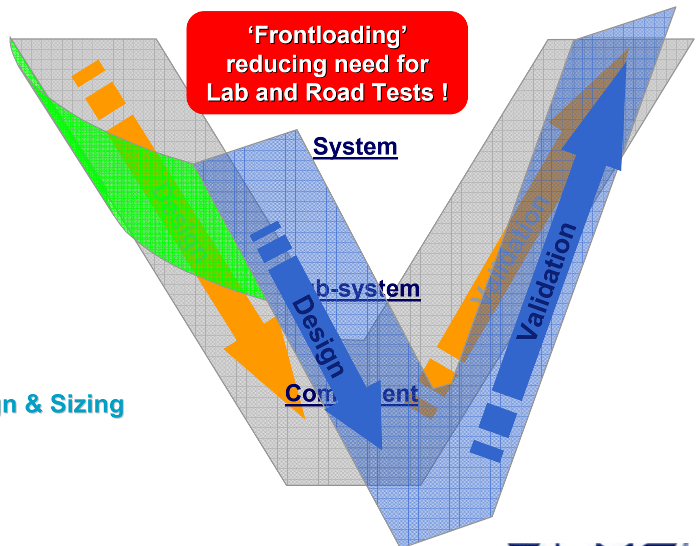
Reverse Engineering approach in new developing cycles

Requirements

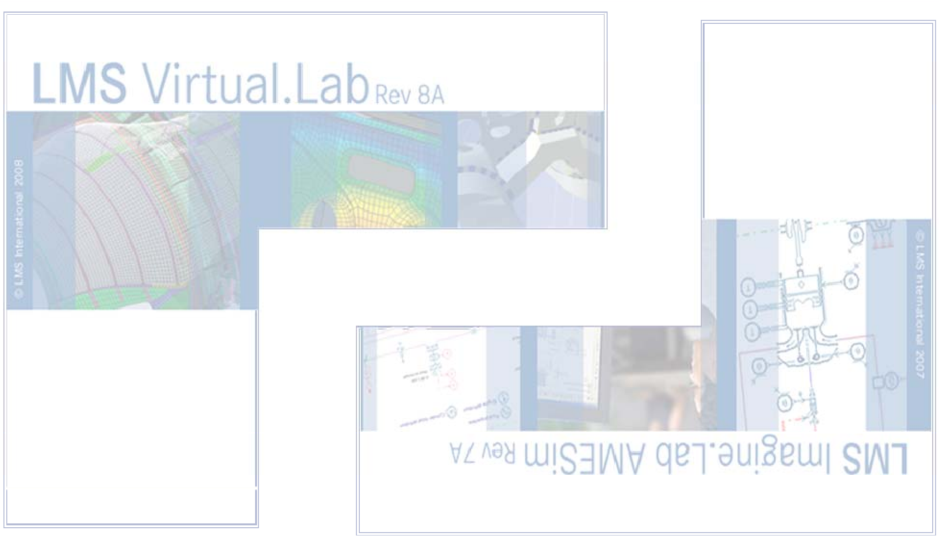
Functional

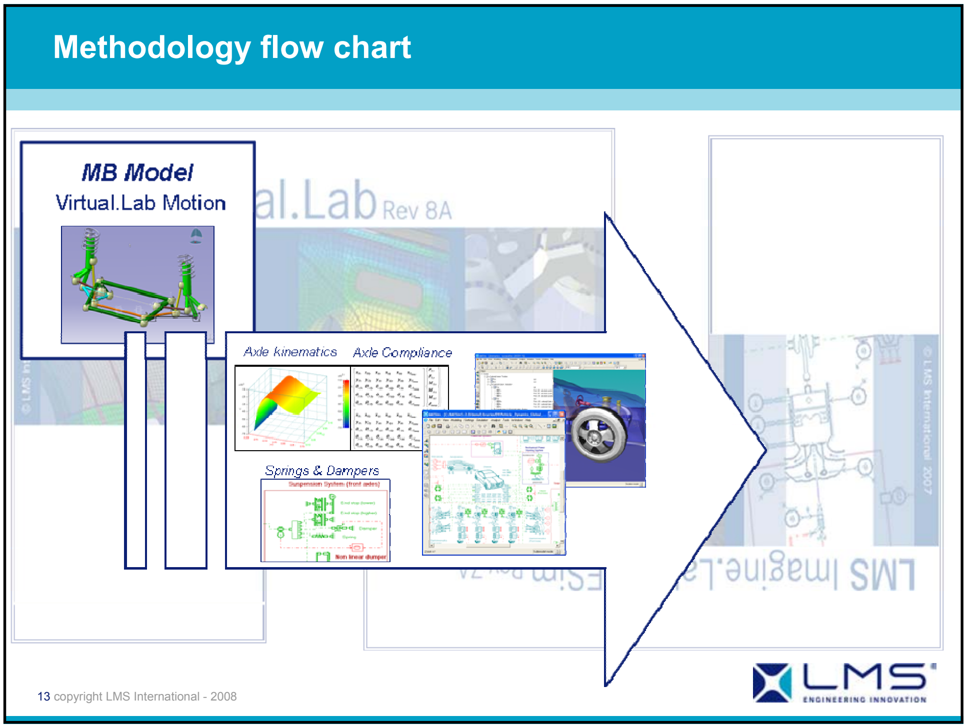
Physical

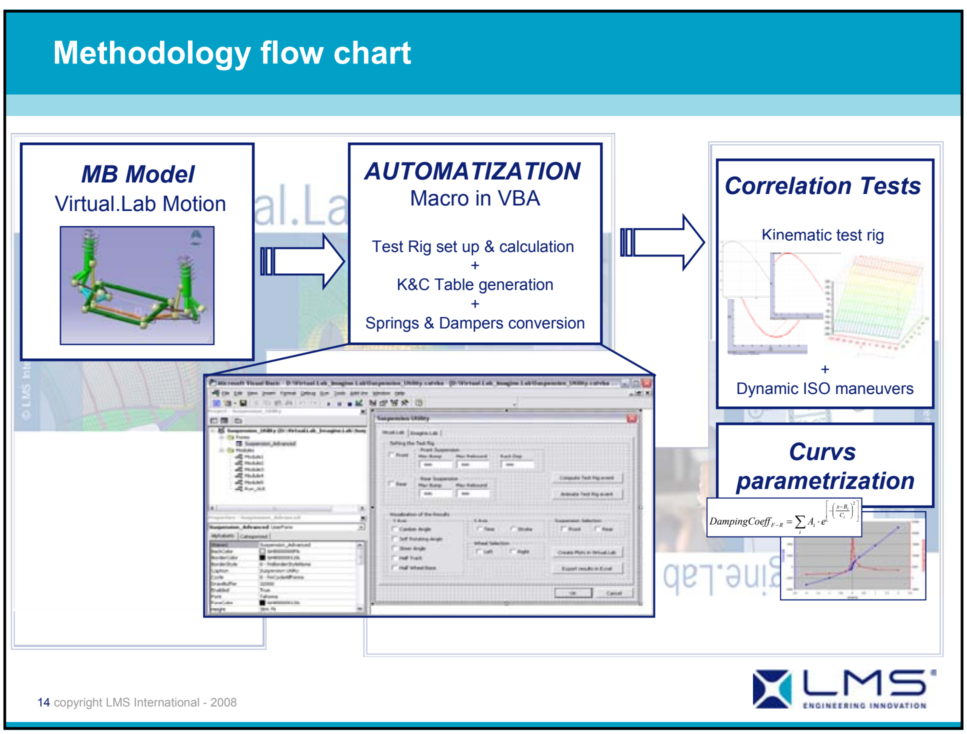
Component Design & Sizing

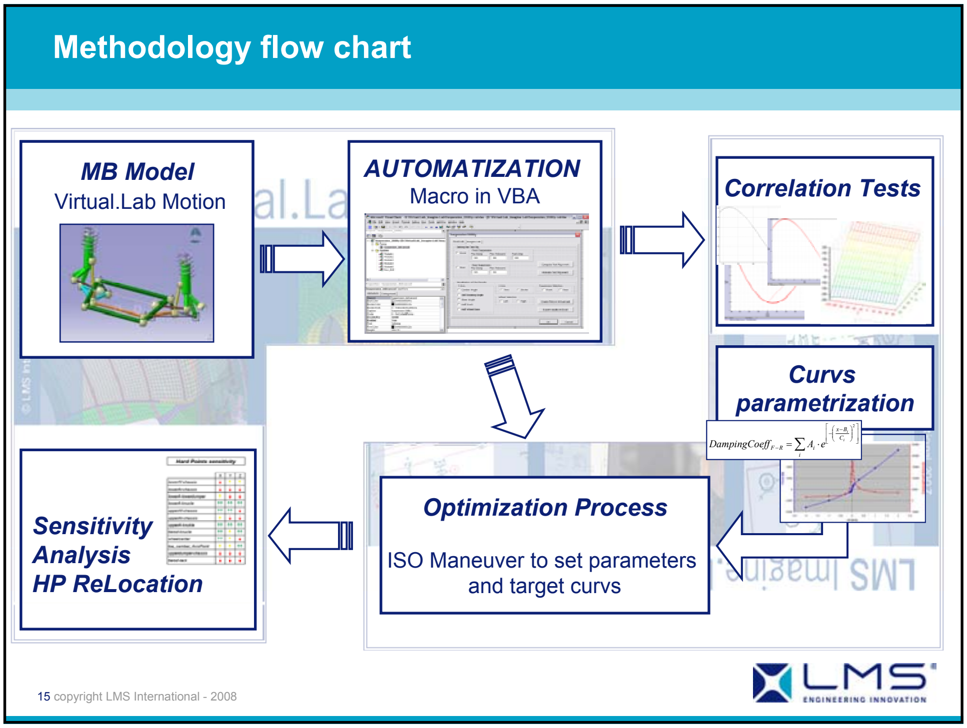


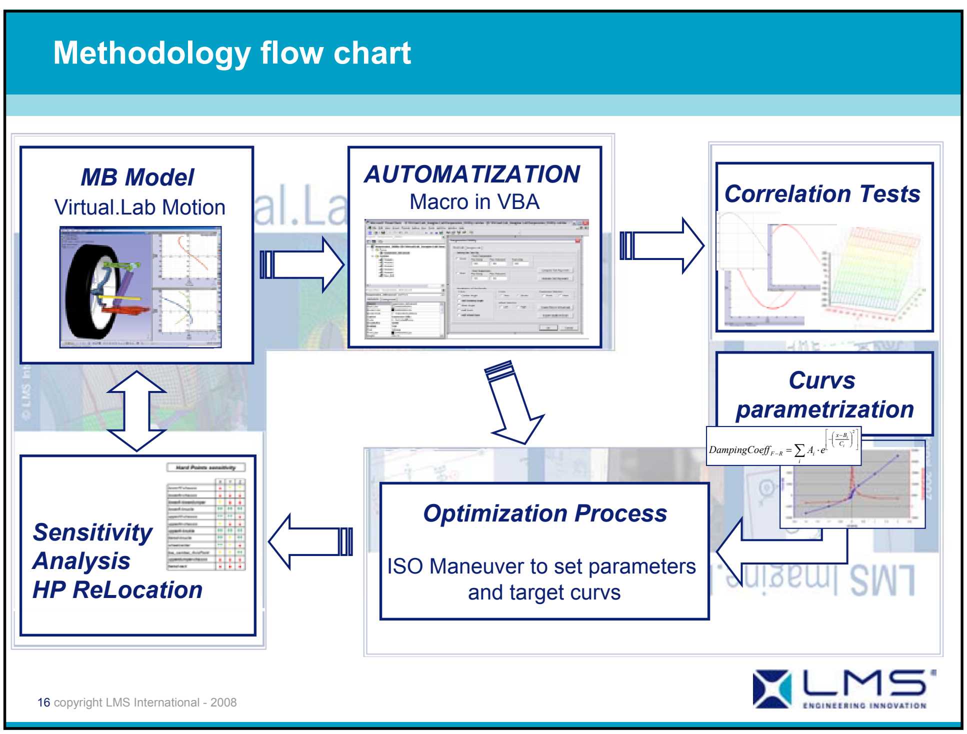
Methodology flow chart




Methodology flow chart
MB Model
Virtual.Lab Motion
Axle kinematics
Axle Compliance
Springs & Dampers
13 copyright LMS International - 2008
LMS
ENGINEERING INNOVATION

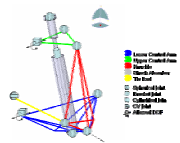

Methodology flow chart
MB Model
Virtual.Lab Motion
AUTOMATIZATION
Macro in VBA
Test Rig set up & calculation
+
K&C Table generation
+
Springs & Dampers conversion
Correlation Tests
Kinematic test rig
+
Dynamic ISO maneuvers
Curvs parametrization
14 copyright LMS International - 2008
LMS
ENGINEERING INNOVATION


Methodology flow chart
MB Model
Virtual.Lab Motion
AUTOMATIZATION
Macro in VBA
Correlation Tests
Curvs
parametrization
Optimization Process
ISO Maneuver to set parameters
and target curvs
Sensitivity
Analysis
HP ReLocation
15 copyright LMS International - 2008
LMS
ENGINEERING INNOVATION


Methodology flow chart
MB Model
Virtual.Lab Motion
AUTOMATIZATION
Macro in VBA
Correlation Tests
Curvs
parametrization
Optimization Process
ISO Maneuver to set parameters
and target curvs
Sensitivity
Analysis
HP ReLocation
16 copyright LMS International - 2008
LMS
ENGINEERING INNOVATION

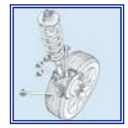
Steps performed – MB Vehicle Modeling

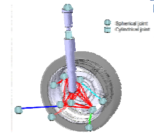
- **Front suspension: Double Wishbone**

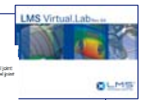


An important simplification to take care of is the missing modeling of compliances (bushings)

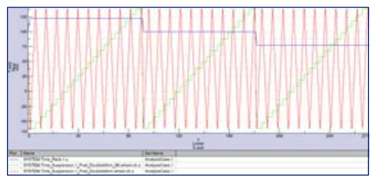
- **Rear suspension: Multi Link**







- **Set up a testing environment (Test Rig Event) to extract kinematic tables**



LMS ENGINEERING INNOVATION

Steps performed – 1 D Vehicle Modeling

- **The mathematical model used is a 15 DOF :**

Car body: 6 DOF
Steering rack body: 1 DOF
4 Spindle body: 4×1DOF
4 Wheel body: 4×1DOF

} *Complete model with joints 15 DOF*

- **The mathematical formulation of kinematic constraint in Trans & Rot parts :**

Front axle

$$\vec{A_1A_2}_{front\ axles} = \vec{d}_{rel}(z, y_n, z_{opp}) = \begin{bmatrix} x(z, y_n, z_{opp}) \\ y(z, y_n, z_{opp}) \\ z \end{bmatrix}_{R_1}$$

Rear axle

$$\vec{A_1A_2}_{rear\ axles} = \vec{d}_{rel}(z, z_{opp}) = \begin{bmatrix} x(z, z_{opp}) \\ y(z, z_{opp}) \\ z \end{bmatrix}_{R_1}$$

Front axle

$$\vec{r}_{rel\ front\ axles} : \mapsto$$

$$(\vec{x}_1, \vec{y}_1, \vec{z}_1) \xrightarrow[\vec{z}_1]{\delta(z, y_n, z_{opp})} (\vec{x}_1', \vec{y}_1', \vec{z}_1) \xrightarrow[\vec{x}_1']{\varepsilon(z, y_n, z_{opp})} (\vec{x}_1', \vec{y}_2, \vec{z}_1'') \xrightarrow[\vec{y}_2]{\eta(z, y_n, z_{opp})} (\vec{x}_2, \vec{y}_2, \vec{z}_2)$$

Rear axle

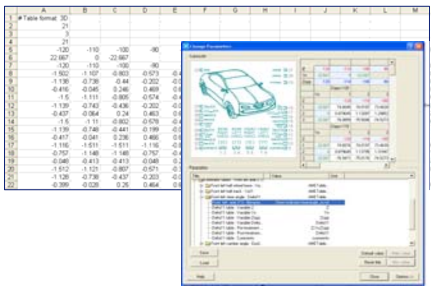
$$\vec{r}_{rel\ rear\ axles} : \mapsto$$

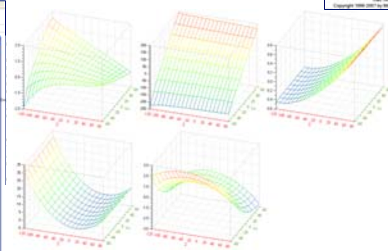
$$(\vec{x}_1, \vec{y}_1, \vec{z}_1) \xrightarrow[\vec{z}_1]{\delta(z, z_{opp})} (\vec{x}_1', \vec{y}_1', \vec{z}_1) \xrightarrow[\vec{x}_1']{\varepsilon(z, z_{opp})} (\vec{x}_1', \vec{y}_2, \vec{z}_1'') \xrightarrow[\vec{y}_2]{\eta(z, z_{opp})} (\vec{x}_2, \vec{y}_2, \vec{z}_2)$$

LMS ENGINEERING INNOVATION

Steps performed – 1 D Vehicle Modeling

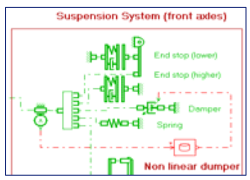
- The kinematics is translated in a look-up-table solution :

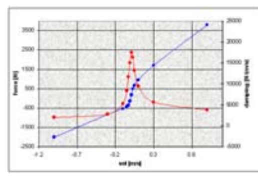




Wheel base, steer angle, self rotating angle, half track and castor angle at Zopp = cost = 0

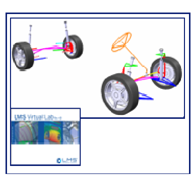
- Traduce spring damper characteristics from the multibody :

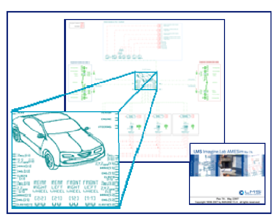




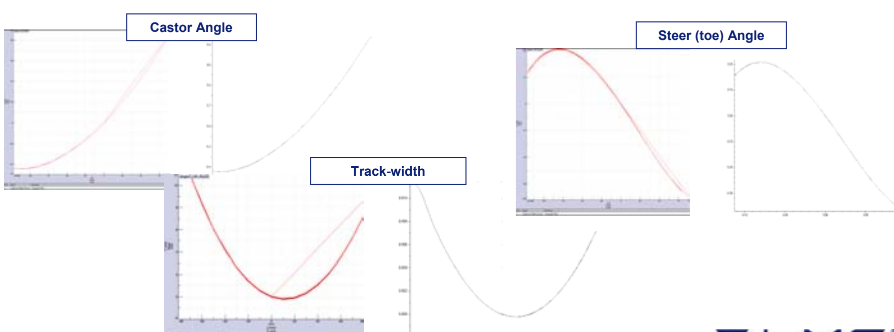
Steps performed – Correlation tests

- Tests performed with test rig event :

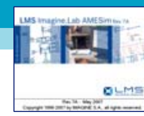




Figures shows 1D and 3D model representations are equivalent

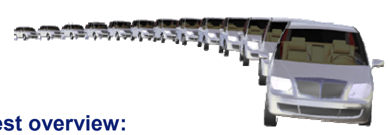


Simulation maneuver



ISO 7401: 2003 Step-steer:

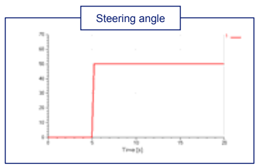
Road vehicles – Lateral transient response methods – Open loops tests

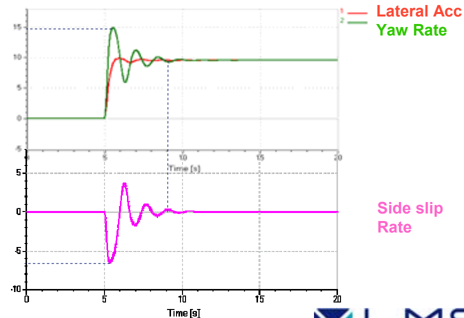


Input Domain	Test Method
Time Domain	Step Input
	Sinusoidal Input (one period) / Two pins slalom
Frequency Domain	Random Input
	Pulse Input
	Continuous Sinusoidal / Continuous Slalom

Test overview:

- Instant of step: 5 s
- Step steer lag: 0.25 s
- Max steering angle: 50 deg
- Speed: 27.8 m/s (100 km/h)





LMS ENGINEERING INNOVATION

Parameters definition in the Optimization process

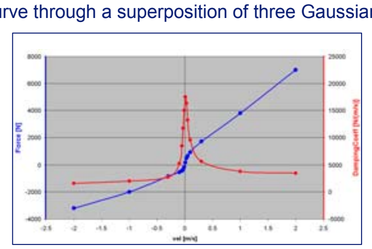
- Damping coefficient:

Parameterization of the damping coefficient's curve through a superposition of three Gaussian curves:

$$DampingCoeff_{F-R} = \sum_i A_i \cdot e^{\left[-\left(\frac{x-B_i}{C_i}\right)^2\right]}$$

Coefficients to be evaluated:

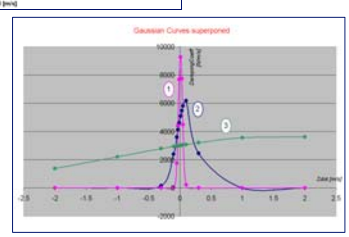
$A_{i,j}$ $B_{i,j}$ $C_{i,j}$* , with *i=1, 2, 3* and *j=Front, Rear



18

- Springs stiffness and preload: ***KSusp_F***, ***KSusp_R***, ***PreLoad_F***, ***PreLoad_R*** — 4

- Antiroll bars characteristics: ***K_Antiroll_F***, ***K_Antiroll_R*** — 2



LMS ENGINEERING INNOVATION

Parameters definition in the Optimization process

Kinematic curves

Parameterization of the kinematic curves has been done through a quadratic formulation:

$$ParametrizedCurve = X + CoeffShift + Coeff \cdot Z + CoeffQuad \cdot Z^2$$

Where ***X*** = Camber Angle, Toe Angle, Wheel Base, Half Track, Castor Angle

Z is the stroke

- Camber Angle coefficients
- Toe Angle coefficients
- Wheel Base coefficients
- Half Track coefficients
- Caster Angle coefficients

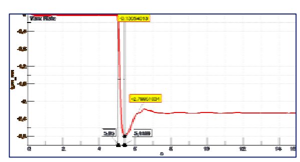
} for Front and Rear **30**

Those steps brought out a set of ***54 parameters***

Objective functions definition

Steady state yaw rate [1]: $1 - \dot{\psi}_{Steady}$

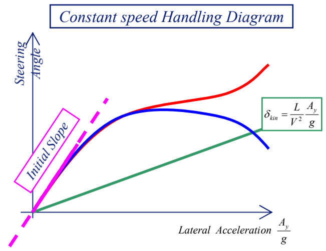
Yaw rate overshoot [1]: $\dfrac{\dot{\psi}_{Max} - \dot{\psi}_{Steady}}{\dot{\psi}_{Steady}}$



Tβ Factor [1]: $T_{\dot{\psi}_{Max}} \cdot \beta_{Steady}$

Improving readiness & keeping tangential to path orientation

Constant speed Handling Diagram



Initial Understeer Gradient: $K_{opt} - K; \quad K = \dfrac{d(\delta_f)}{d\left(A_y / g\right)}$

Getting as close as possible to the target value

Final Understeer number: $\dfrac{A_{Rr,\max}}{A_{Fr,\max}} - 1$

To have a progressive steering control and not opposite: If >0 ⇨ final understeer

[1] Presentation extracted from:
Course of "Advances in Optimal Design of Mechanical Systems"
Giampiero Mastinu, Massimiliano Gobbi
Hyderabad – 22/26 March 1999

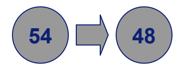
Optimization Process in Imagine.Lab AMESim

➢ *Full factorial DOE*

To identify the most important coefficients to be implemented in the dynamic optimization

Selection of the Factors and Responses $DampingCoeff_{F-R} = \sum_i A_i \cdot e^{\left[-\left(\frac{x-B_i}{C_i}\right)^2\right]}$

Effects\Responses	TB		OvershootPsiP		UndersteerInitGrad		UndersteerNumber		PsiPMin	
A1_F	0.00161	TRUE	-0.01926	TRUE	-0.01350	TRUE	-0.00070	TRUE	-0.00159	TRUE
A2_F	0.00143	TRUE	-0.01772	TRUE	-0.01261	TRUE	-0.00059	TRUE	-0.00133	TRUE
A3_F	0.00198	TRUE	-0.02022	TRUE	-0.01558	TRUE	-0.00048	FALSE	-0.00093	TRUE
B1_F	-0.00108	TRUE	0.00280	FALSE	0.00136	FALSE	0.00017	FALSE	0.00010	FALSE
B2_F	-0.00103	TRUE	0.00766	TRUE	0.00488	FALSE	0.00034	FALSE	0.00050	TRUE
B3_F	-0.00032	FALSE	0.00322	FALSE	0.00232	FALSE	0.00008	FALSE	0.00019	FALSE
C1_F	0.00734	TRUE	-0.06339	TRUE	-0.05482	TRUE	0.00100	TRUE	-0.00224	TRUE
C2_F	0.00863	TRUE	-0.05989	TRUE	-0.05350	TRUE	0.00088	TRUE	-0.00193	TRUE
C3_F	0.00657	TRUE	-0.03751	TRUE	-0.03395	TRUE	0.00112	TRUE	-0.00121	TRUE



➢ *Optimization algorithm*

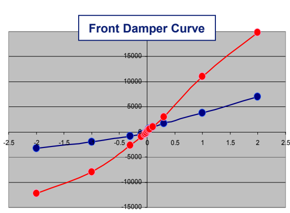
GA (Genetic Algorithm)

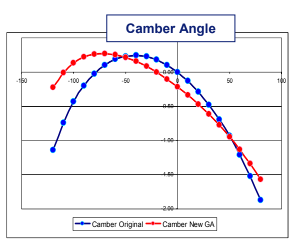
Note that there is **no need to use a Response Surface Model** (RSM), thanks to the speed of the simulation in AMESim !

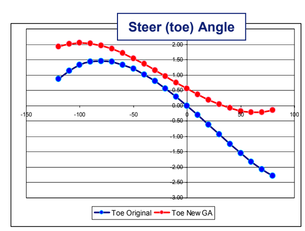
Results from GA Optimization - Component characteristics

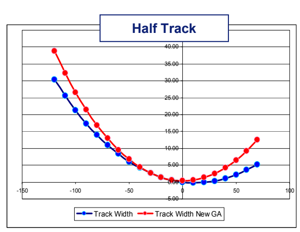
$$DampingCoeff_{F-R} = \sum_i A_i \cdot e^{\left[-\left(\frac{x-B_i}{C_i}\right)^2\right]}$$

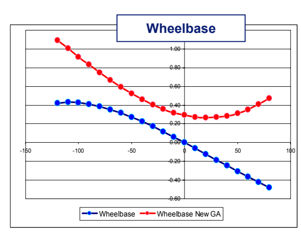
A	B	C
6950	0.01022	0.03700
8790	0.1015	3.47200
3670	1.624	1.23000





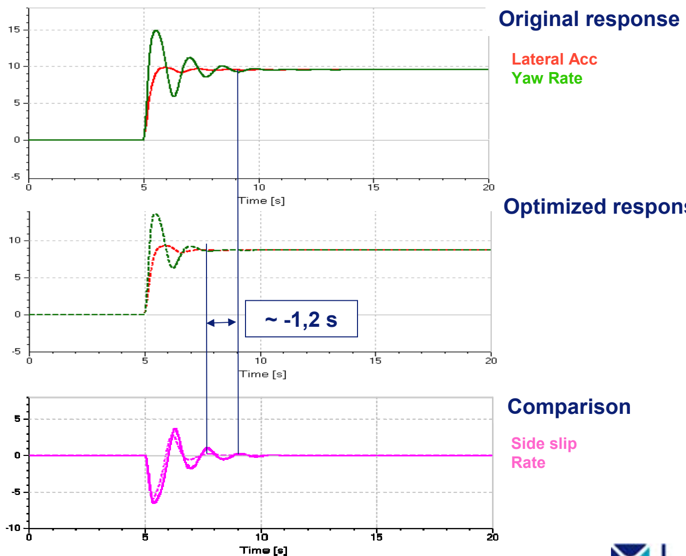






— Original
— Optimized

Results from GA Optimization - Dynamic response



Final geometrical Optimization in Virtual.Lab MOTION

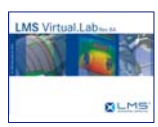
Sensitivity Analysis

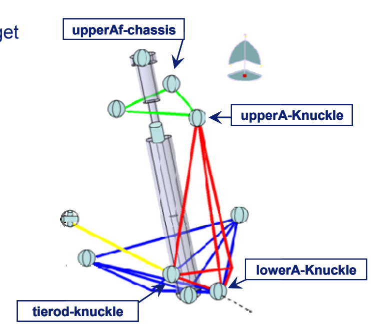
Feeding the model with the target curves a cost function to be minimized must be figured out :

$$RMS = \sqrt{\frac{1}{t_{e-t_i}} \int_{t_i}^{t_e} e^2 \; dt}$$

where **e** is the error between target and desired actual curves of :

- **Camber**
- **Toe**
- **Wheelbase**
- **Half track**



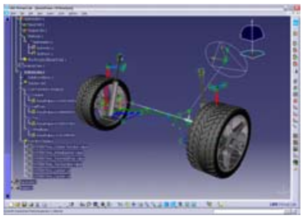


Hard Points sensitivity

	X	Y	Z
lowerAf-chassis	↓	↑	↑
lowerAr-chassis	↓	↓	↓
lowerA-lowerdumper	↑	↓	↓
lowerA-knucle	↑↑	↑↑	↑↑
upperAf-chassis	↑↑	↑↑	↓
upperAr-chassis	↑	↓	↓
upperA-knukle	↑↑	↑↑	↑↑
tierod-knucle	↑↑	↑	↑↑
wheelcenter	↑↑	↑	↓
toe_camber_AxisPoint	↑	↑	↑↑
upperdumper-chassis	↓	↓	↓
tierod-rack	↓	↓	↓

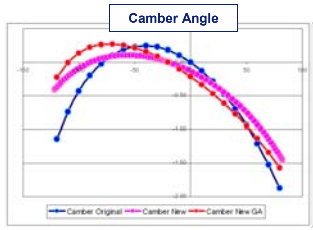
↑↑ high effect
↑ medium effect
↓ low effect

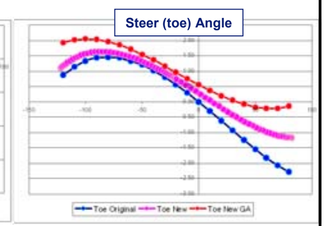
Final geometrical Optimization in Virtual.Lab MOTION

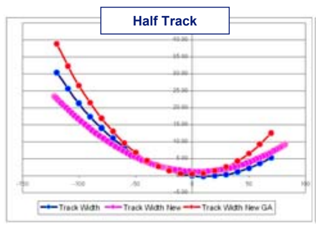


Hard Points variations

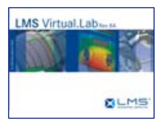
	X	Y	Z
lowerAf-chassis			
lowerAr-chassis			
lowerA-lowerdumper			
lowerA-knucle	-15.0	15.0	15.0
upperAf-chassis	-5.0	17.0	
upperAr-chassis			
upperA-knukle	-6.4	-6.8	-10.3
tierod-knucle	-2.7		5.3
wheelcenter	4.2		
toe_camber_AxisPoint			0.1
upperdumper-chassis			
tierod-rack			







— Original AMESim
— Optimized AMESim = Target VL.MOTION
— Optimized VL.Motion



LMS ENGINEERING INNOVATION

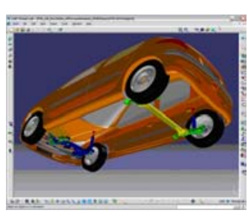
Further investigations

- **Adding elasto-kinematic contribution**

$$d_{rel\ BLSASTOCIN} = d_{rel\ BLAS} + d_{rel\ CIN}\ :\quad \begin{cases} x_{rel\ BLSASTOCIN} = x_{rel\ BLAS} + x_{rel\ CIN} \\ y_{rel\ BLSASTOCIN} = y_{rel\ BLAS} + y_{rel\ CIN} \end{cases}$$

$$r_{rel\ BLSASTOCIN} = r_{rel\ BLAS} + r_{rel\ CIN}\ :\quad \begin{cases} \delta_{rel\ BLSASTOCIN} = \delta_{rel\ BLAS} + \delta_{rel\ CIN} \\ \varepsilon_{rel\ BLSASTOCIN} = \varepsilon_{rel\ BLAS} + \varepsilon_{rel\ CIN} \\ \eta_{rel\ BLSASTOCIN} = \eta_{rel\ BLAS} + \eta_{rel\ CIN} \end{cases}$$

- **Implementation of flexible parts (subframes, trimmed body, …)**



- **Full Multi-attribute Optimization (Ride-comfort & Handling)**

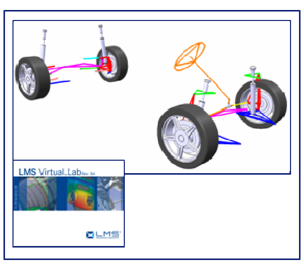
LMS ENGINEERING INNOVATION

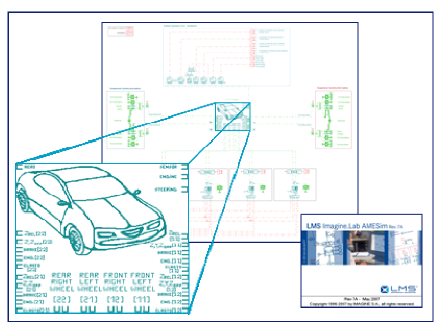
Conclusions

- A **reverse engineering methodology** in Concept Stage of new vehicle development has been shown
- Show-case has been applied to **kinematics of the front suspension** to optimize handling in the ISO step-steer maneuver
- Methodology can be extended to **complete front and rear K&C characteristics including flexible parts and full multi-attribute optimization for Ride-comfort & Handling** maneuvers
- Integration of **LMS Virtual.Lab/Motion®** and **Imagine.Lab AMESim®** offers **a unique automated solution for the complete simulation study and optimization in chassis and full vehicle performance domain**

LMS ENGINEERING INNOVATION

VEHICLE DYNAMICS EXPO 2008
6,7,8 MAY 2008 STUTTGART MESSE | STUTTGART | GERMANY





Thanks for your attention !

Ir. Valerio CIBRARIO Vertical Business Unit Manager, Automotive Solutions, C&S – LMS Italiana
Dr. Ir. Joris DE CUYPER Product Line Manager Virtual.Lab MOTION – LMS International
Ir. Marco GUBITOSA Research Engineer – LMS International

LMS ENGINEERING INNOVATION