Multiobjective Optimization of race car vehicle dynamics

Martin Mühlmeier

Audi Sport, Audi AG

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24 hours of Le Mans

> performed since 1923

> 200.000 spectators

> date: middle of june

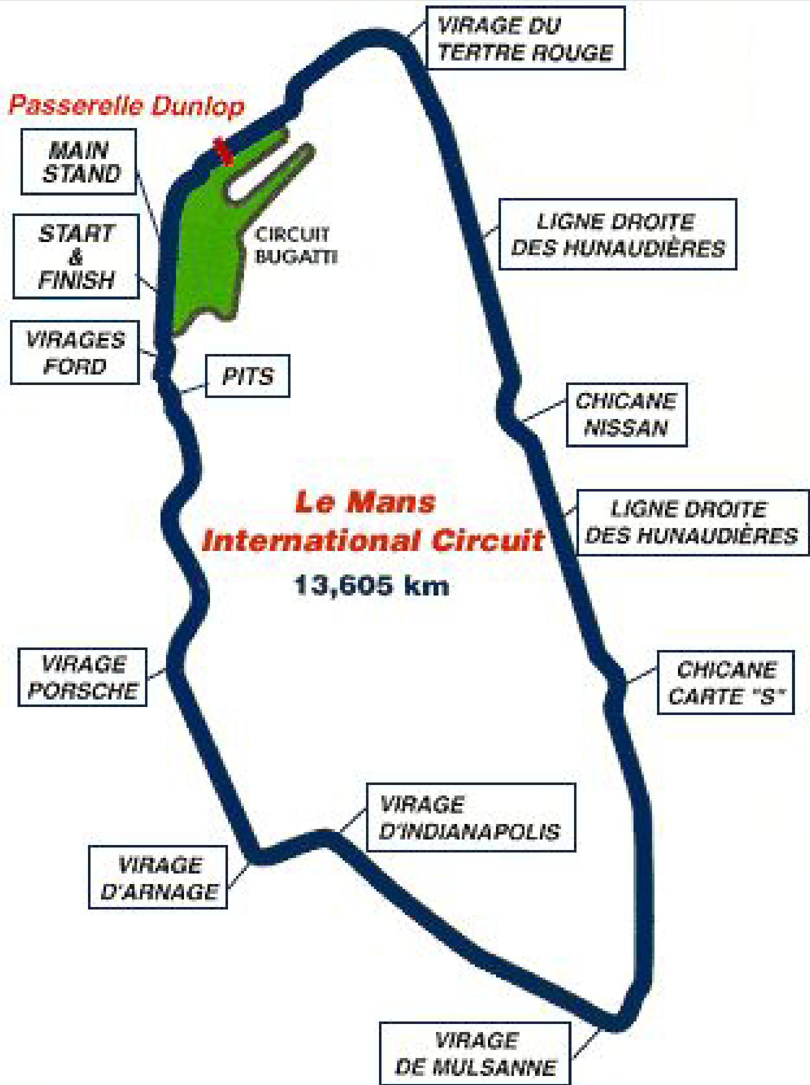
> 48 cars

> 5 classes: LMP, GTP, LMP675, GTS, GT

> 2-3 drivers per team

Le Mans race track

>length : 13,605 km
>vmax : > 330 km/h (Nissan-chicane)
>vmin : ~80 km/h (Arnage)
>average speed (qualy) : > 230 km/h
>average speed (24 h) : > 200 km/h
>distance (24 h) : > 5000 km



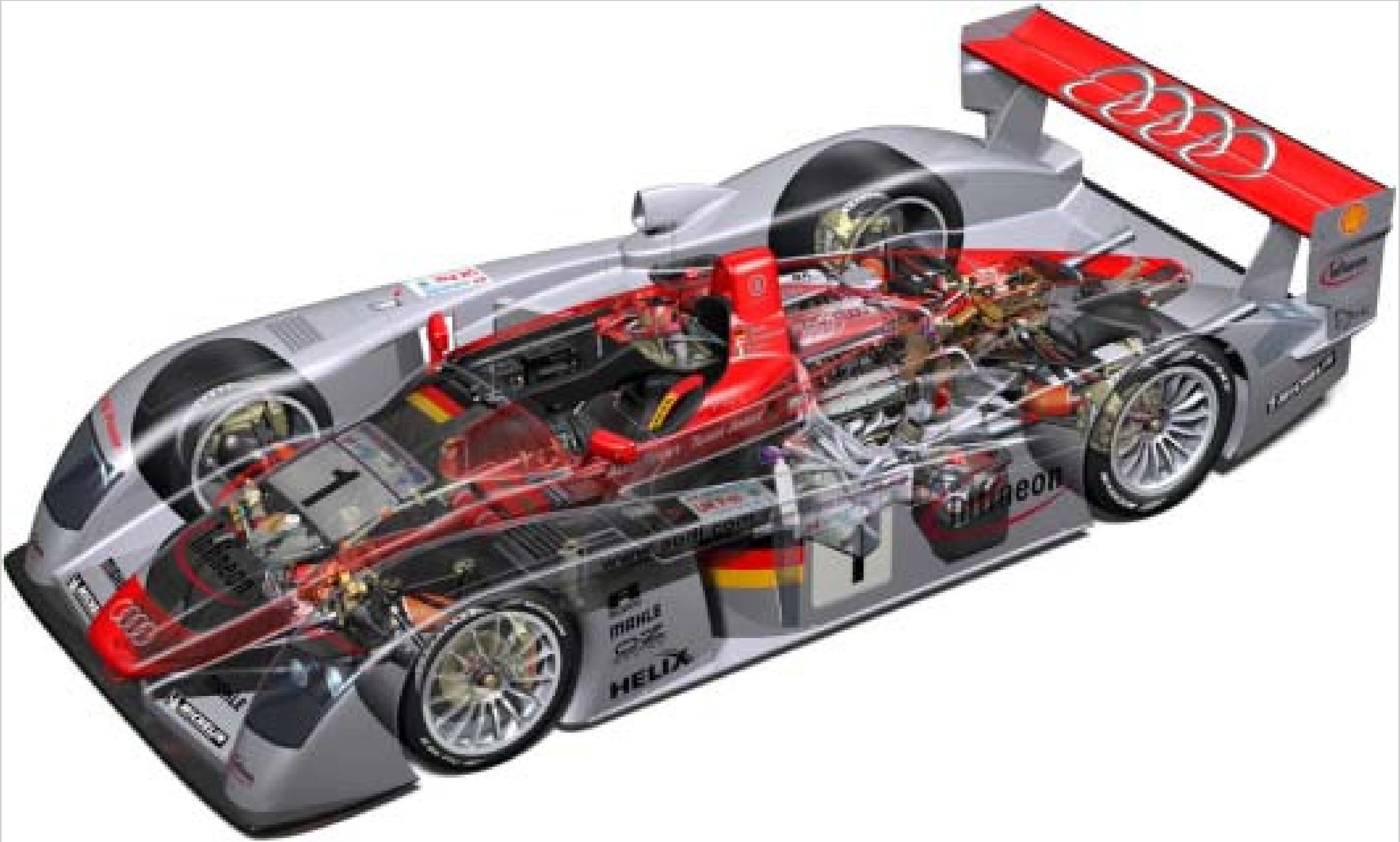
Le Mans prototype Audi R8

>Dimensions: 4650 x 2000 x 1020 mm, 900 kg

>Engine: 3.6 l, V8-Biturbo FSI, boost 1.67 bar, 610 HP, 750 Nm

>Dynamics : 0-100: 3.0 s; 0-200: 6.7 s; 0-300: 17.0 s; 300-0: 4.0 s/175 m; a_{xmax}=3 g; a_{ymax}=2.5 g, v_{max}=340 km/h

>Consumption: 46 l/100km



Hierarchy of simulation/optimization

Subject	**vertical dynamics**	**in-plane dynamics**	**global dynamics**
design paramters	spring, dampers	weight/aero/brake balance	both
objectives	eigenvalues, rms values	lap time, topspeed, consumption	lap time, topspeed, distance, sev. rms values
simulation model	Matlab/Simulink	EZ-Lap	ADAMS/Motorsport
domain	frequency+time	time	time
optimizer	Matlab	modeFrontier	modeFrontier

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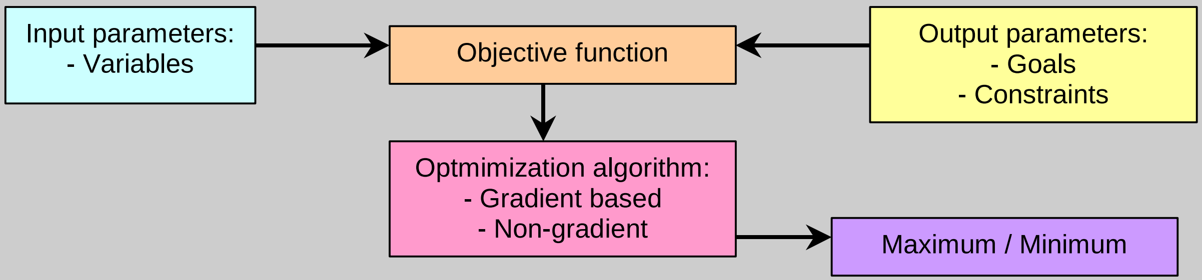
Optimization

> **Finding among several possible designs, the best one**

> **maximizing or minimizing a function**



> **Simple example**:

> Find a minimum of $F(x) = x^2-1$ with $|x| < 3$

> x is the <u>variable</u> (continuous)

> F(x) is the <u>objective function</u>

> $|x| < 3$ is a <u>constraint</u>

> the <u>goal</u> is to have a minimum

Optimization

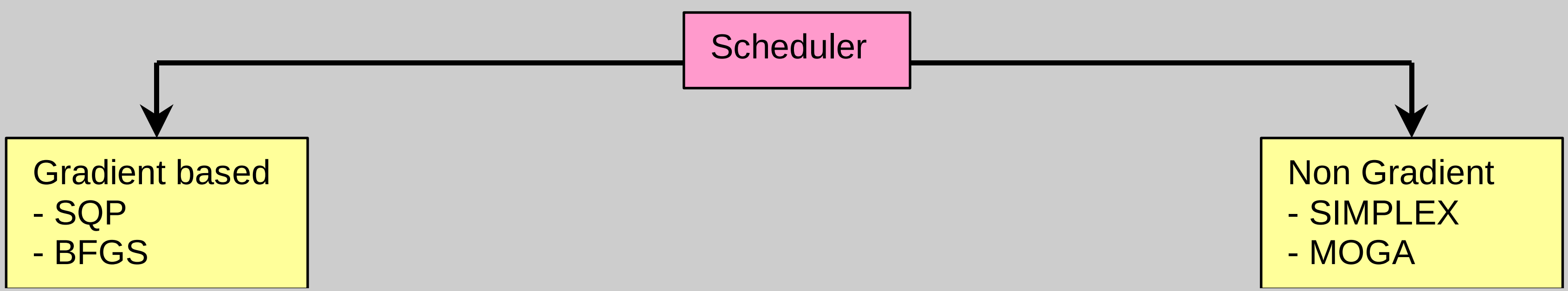
> **In a more general form:**

Find a minimum/maximum of $\vec{O} = (o_1, o_2, o_3, \ldots\ldots, o_m) = F(x_1, x_2, \ldots\ldots, x_n)$

Constraints $G_i(x_1, \ldots\ldots, x_n) >$ or $<$ 0, i = 1:k

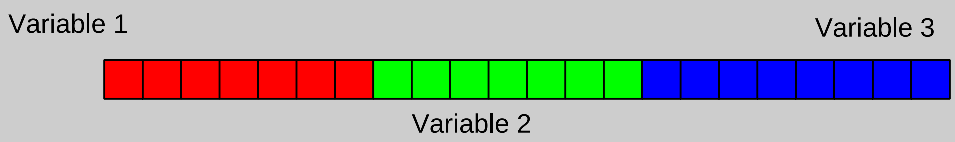
> **Both variables and goals are vectors, so there is a vectorial objective function and also a vector of constraints.**

> **The best design for one single objective could be the worse for another $\rightarrow$ weighting functions/Pareto fronts**

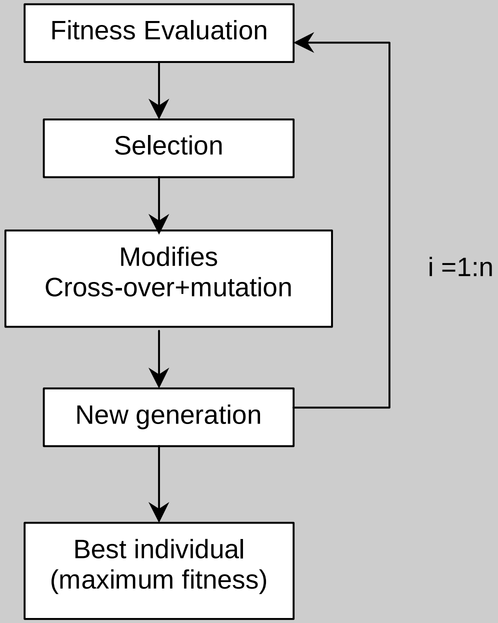


MOGA: Multi Objective Genetic Algorithm

> **Transforms problems in strings of bits, with every field representing a variable:**



> **After the creation of a first set of strings (first generation), it operates on strings in the following way:**

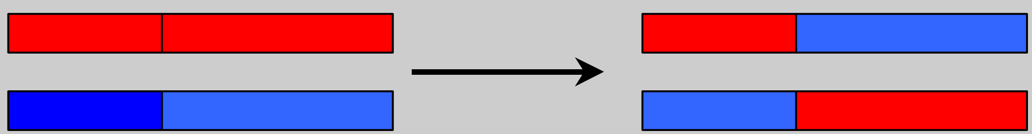


MOGA: Multi Objective Genetic Algorithm

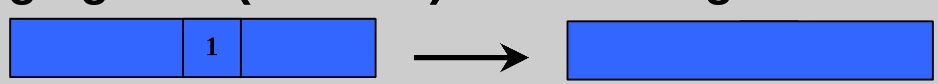
- Fitness is the calculated value of the objective, to be optimized
- Selection→ high fitness individuals are more likely to get on

$$P_{Sel} = \frac{FIT_i}{\sum_{i=1}^{m} FIT_i}$$

- Crossover→cutting strings and pasting their respective heads and tails



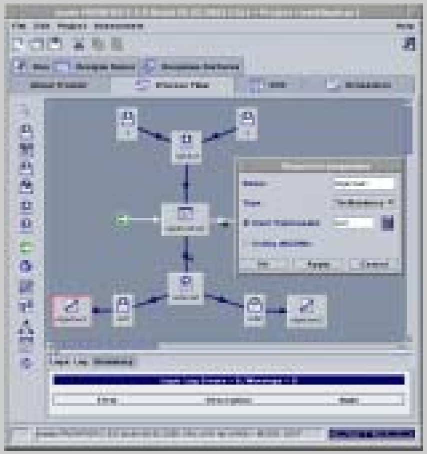
- Mutation→changing a bit (or more) in the string



- This allows to find the best individual ever, after going across a few generations.

ESTECO™ modeFRONTIER©

> **A software created and built in order to optimize any kind of design by means of:**
> **Process flow:** defining input and output variables, goals and constraints
> **DOE (Design On Experiment):** first set of input variables to be given to the application
> **Scheduler:** several possible choices among gradient and non gradient algorithms
> **Run:** a window where the analysis state is step by step updated
> **Design space:** there each calculated design is inserted into a table with in- and output parameters
> **Design charts:** possible plotting and viewing results in charts
> **MCDM (Multi Criteria Decision Making):** establishes priority between goals by means of weighting functions
> **Response functions:** interpolation between calculated values



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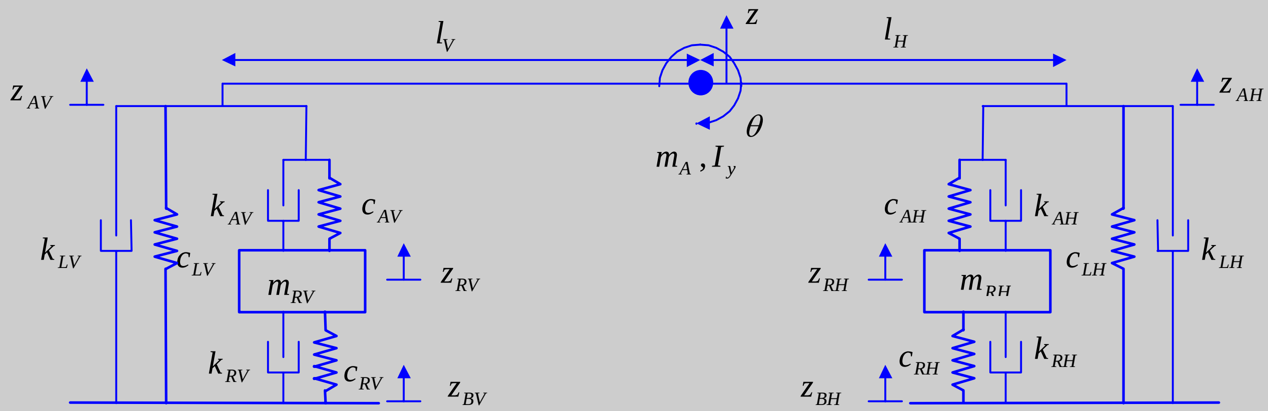
Matlab/Simulink model approach

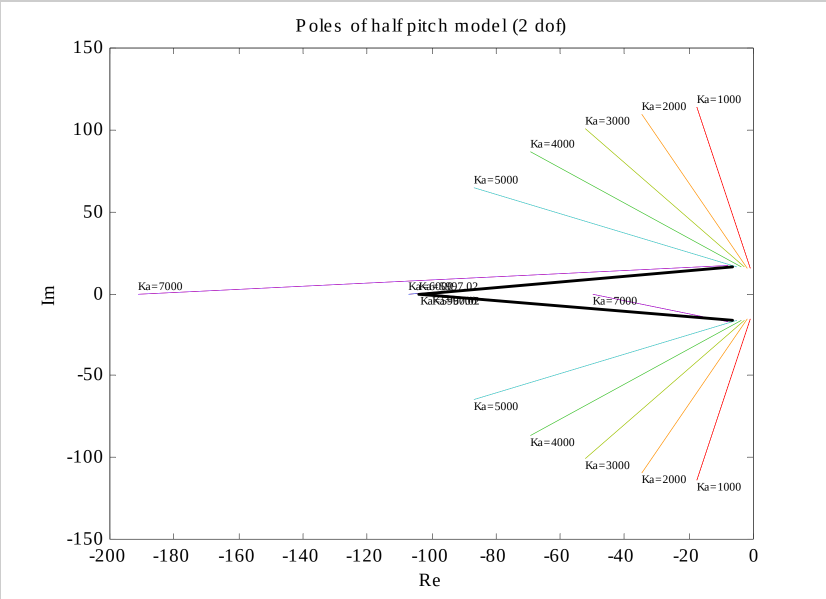


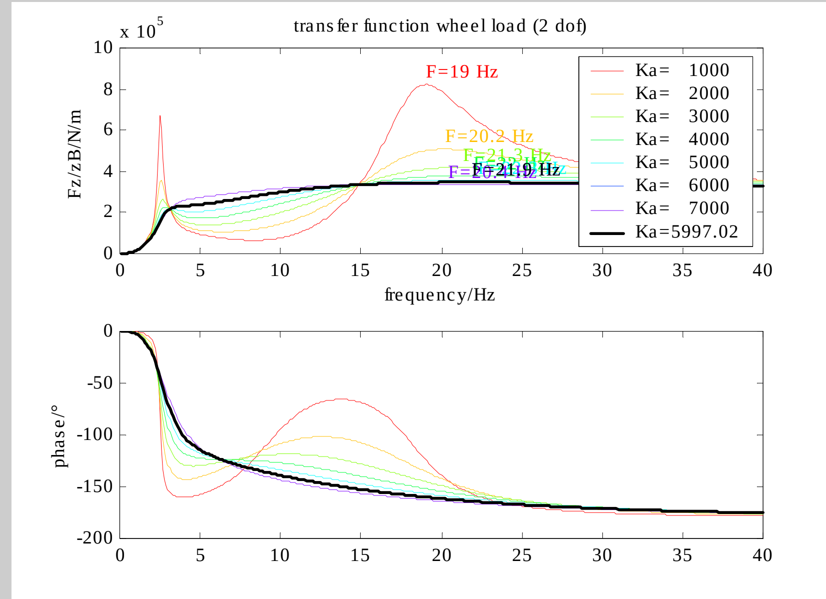
> 4 dof pitch model

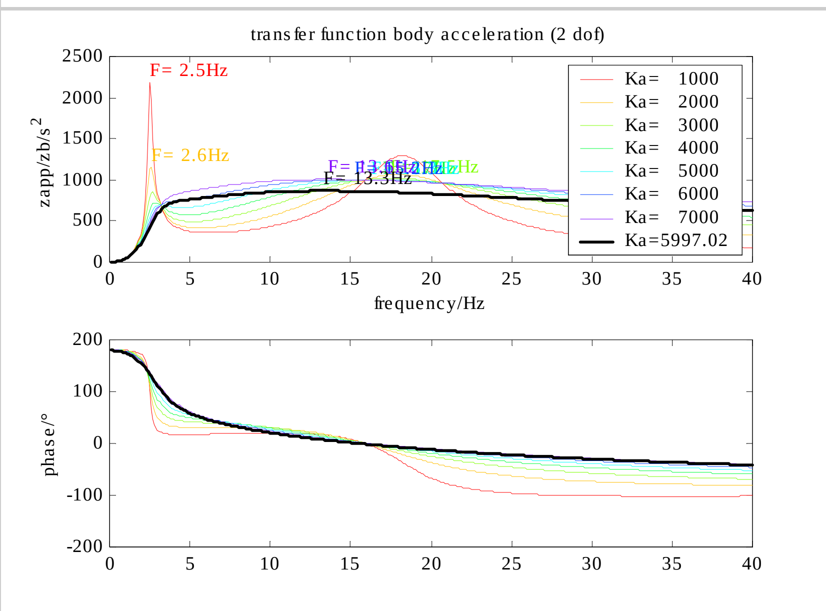
> Linear spring dampers

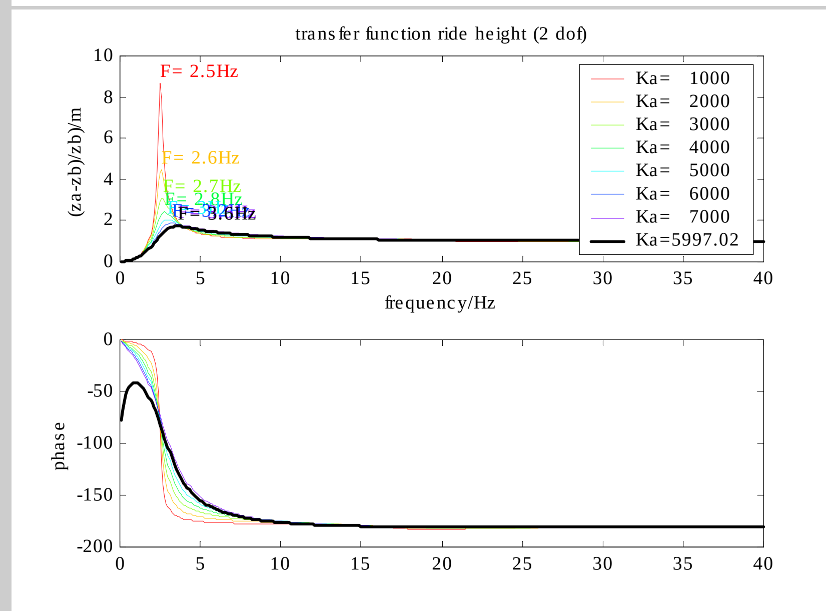
> Linear aero stiffness/(anti-)damping

Analysis in frequency domain (2 dof)





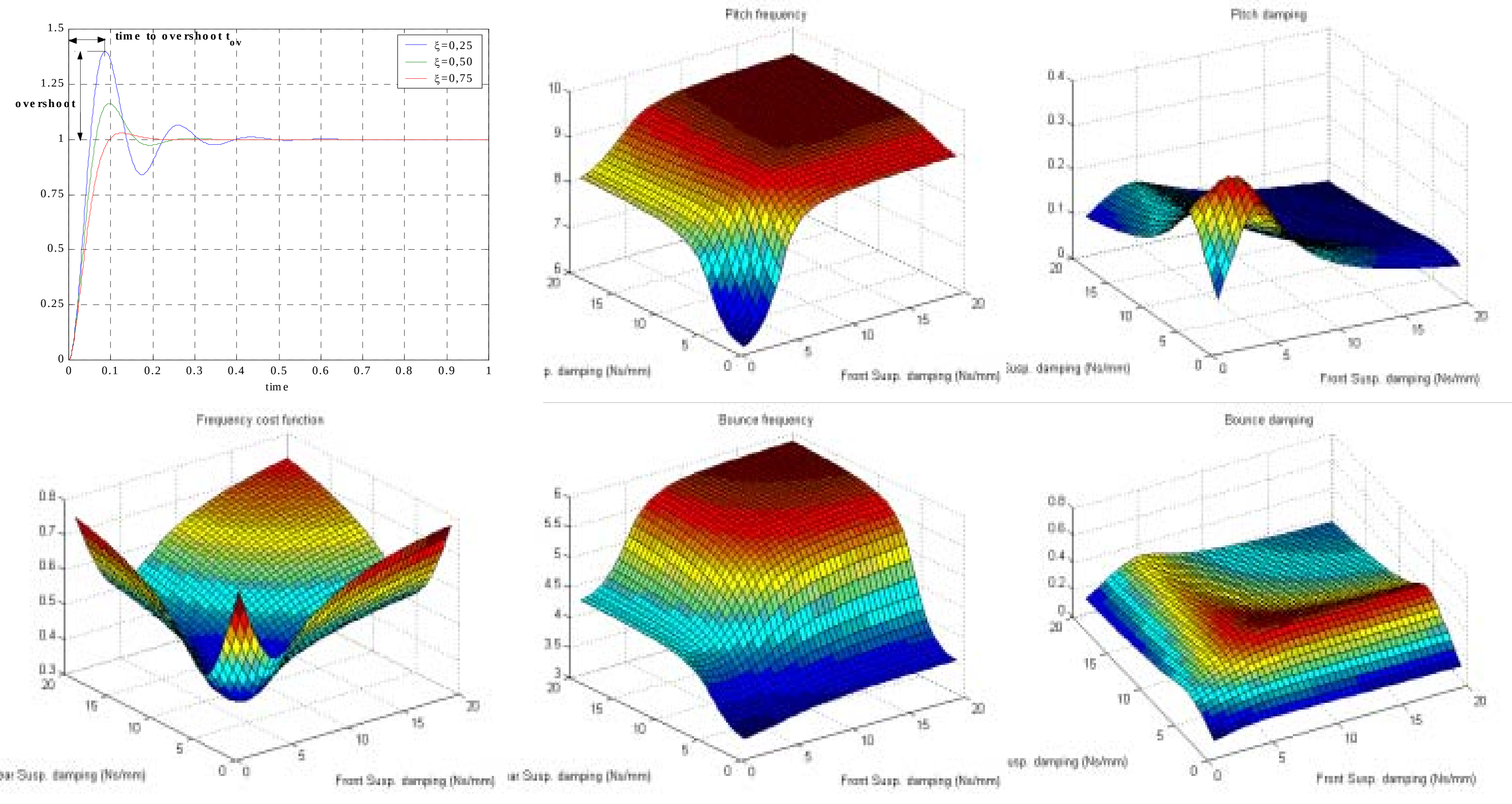




Analysis in frequency domain (4 dof)

> Optimization criterion:

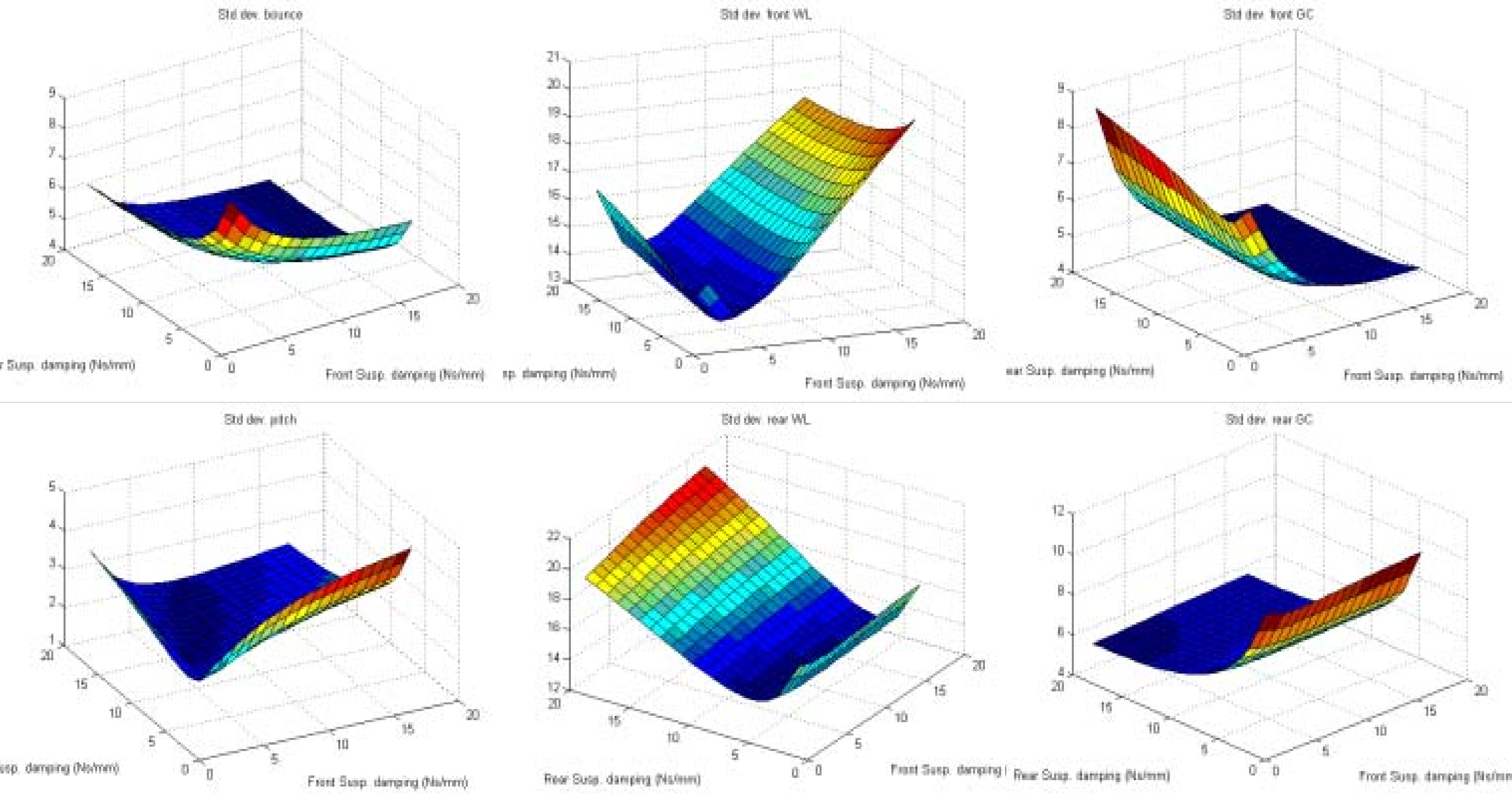
> $$C_f = \sqrt{\mathrm{k_{ov}} \cdot \mathrm{ov}^2 + k_{tov} \cdot t_{ov}^2}$$



Analysis in time domain

> Optimization criterion:

> $C_t = \Sigma k_{stdd_i} \cdot stdd_i^{r_i}$



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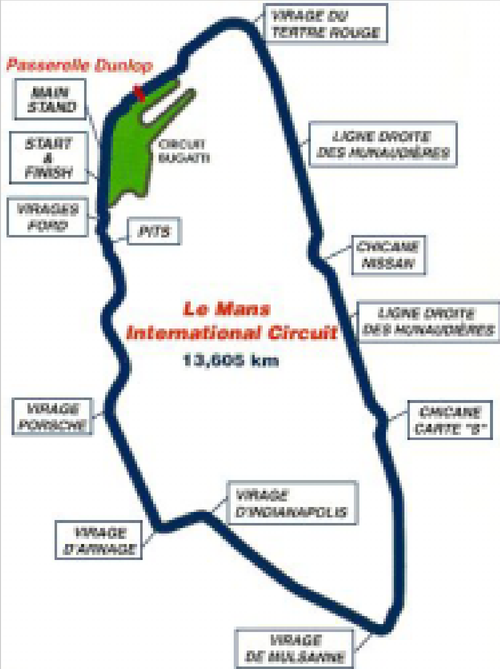
EZ-Lap model approach

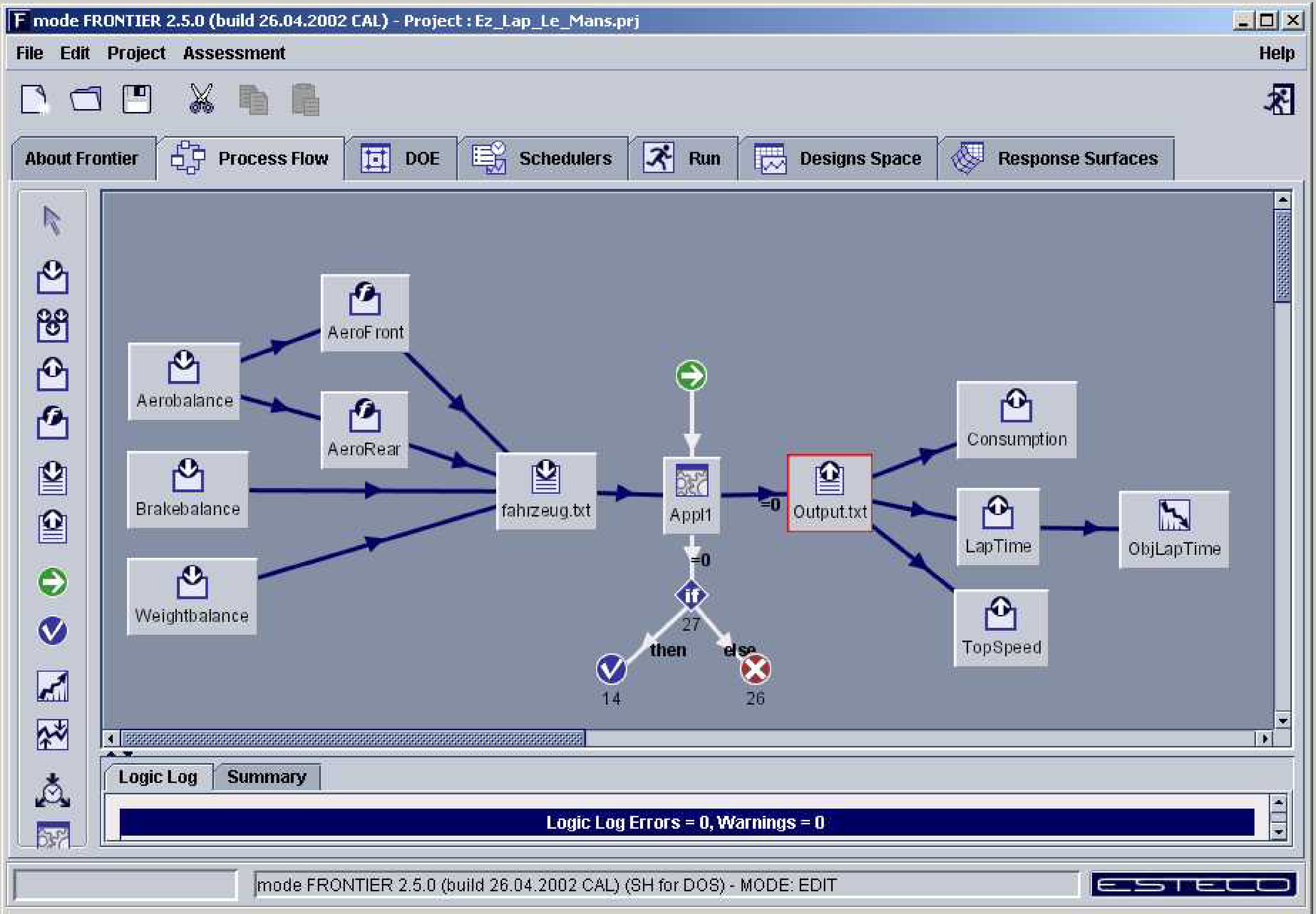
> Nonlinear aerodynamics
> Nonlinear kinematics, springs
> Engine maps, drivetrain w. max. 3 diffs
> Tyre Michelin-Pacejka
> Track in 3D, some GPS
> All eigenvalues zero → static equillibrium
> Forward/backward sim.→less iterations



EZ-Lap: design variables & objectives

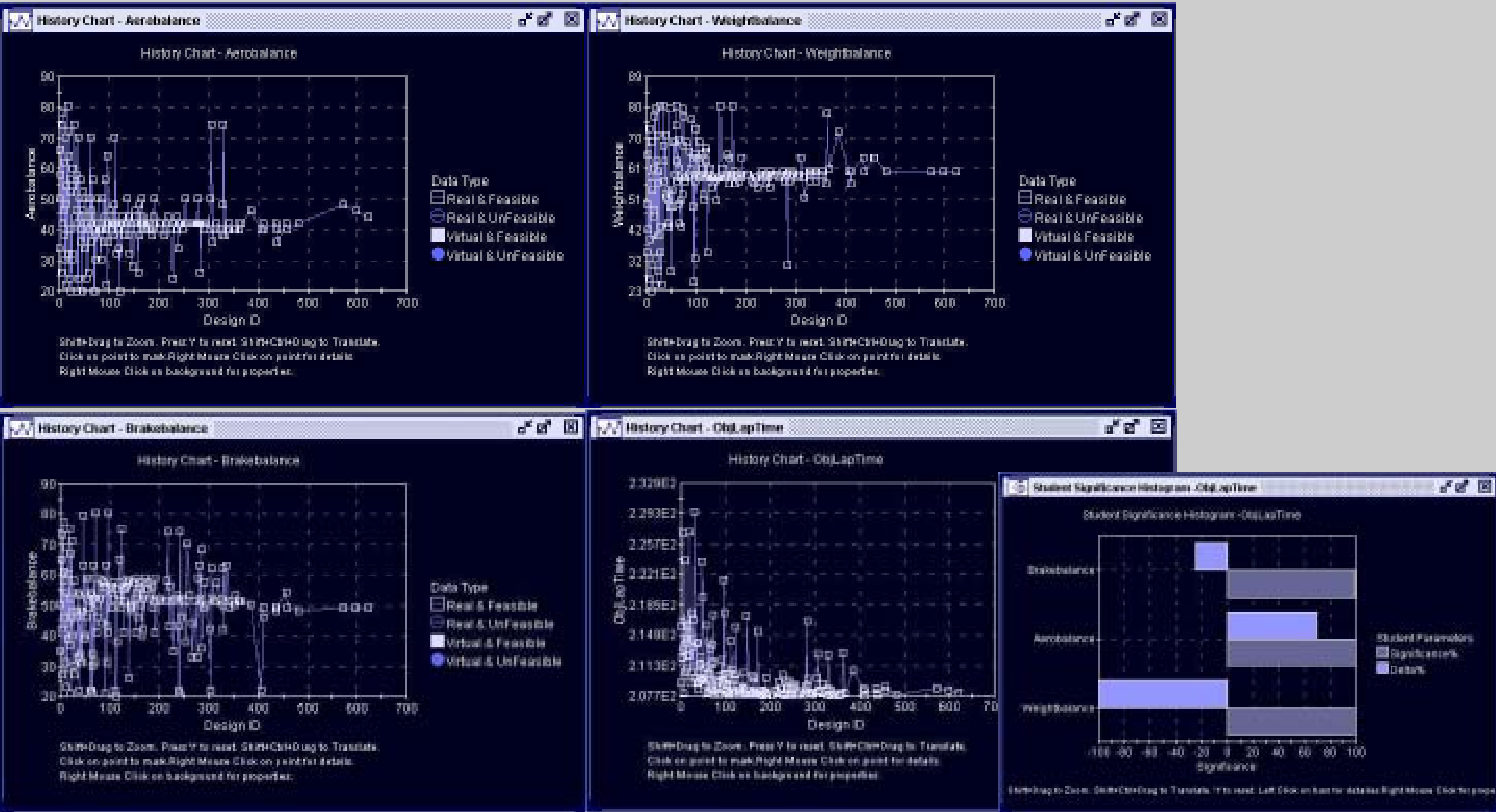
- Design variables:
  - Aero balance
  - Weight balance
  - Brake balance
- Objective:
  - lap time

EZ-Lap/modeFrontier: process flow



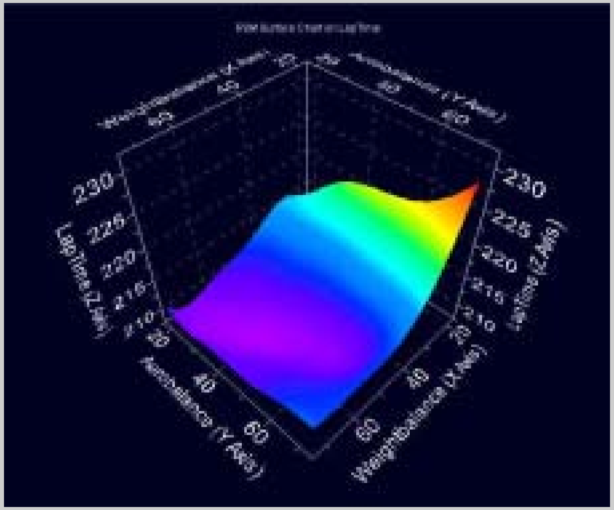
EZ-Lap: aero/weight/brake balance

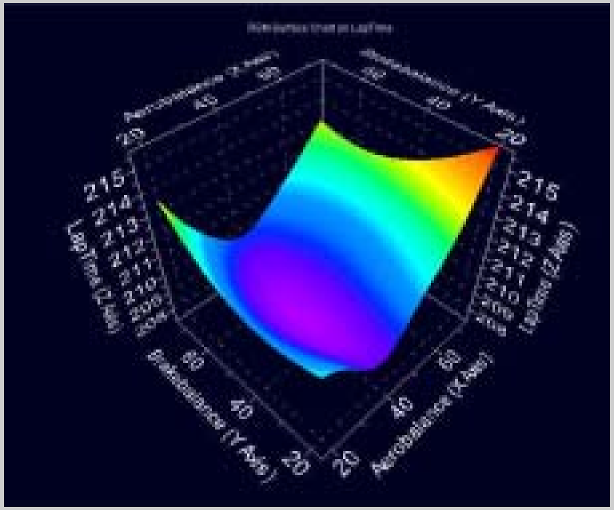
> Le Mans: History charts



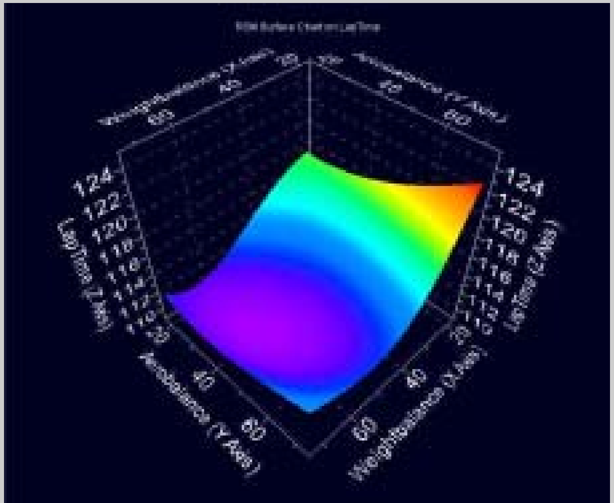
EZ-Lap: aero/weight/brake balance

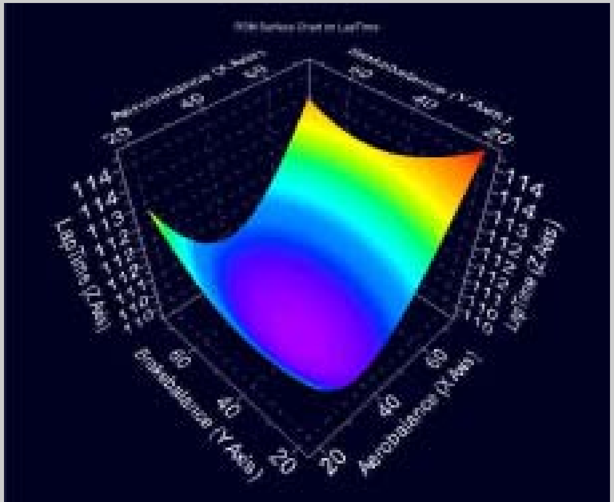
> Le Mans: surface plots designs/objectives





> Sebring: surface plots designs/objectives





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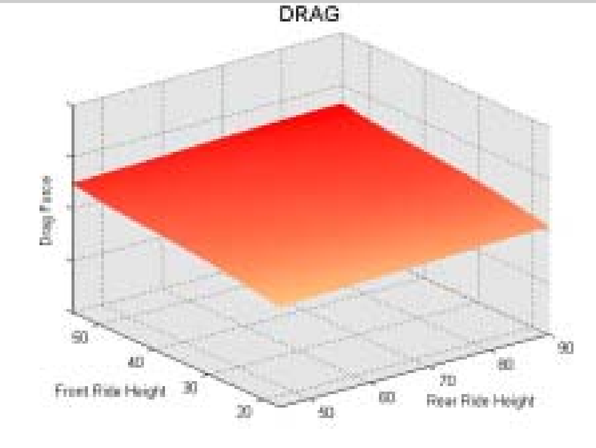
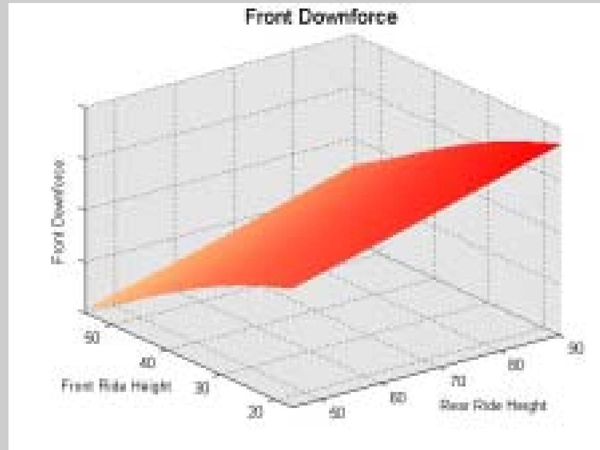
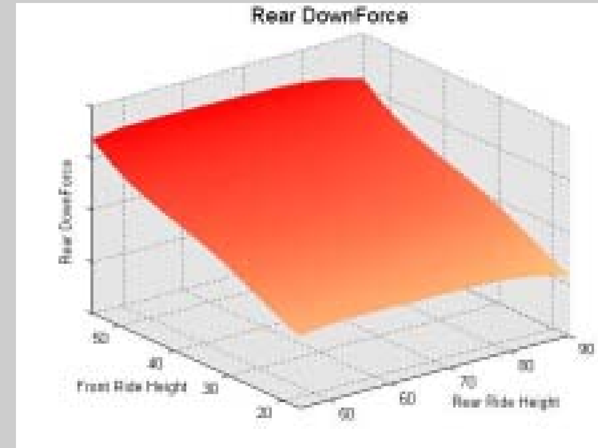
ADAMS model approach

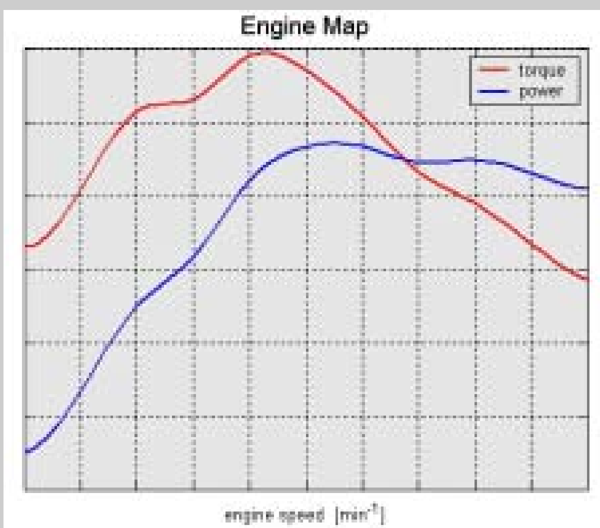
- > Aerodynamics
- > Suspension
- > Engine, drivetrain
- > Tyre Michelin-Pacejka
- > 3D-Road
- > Driver model

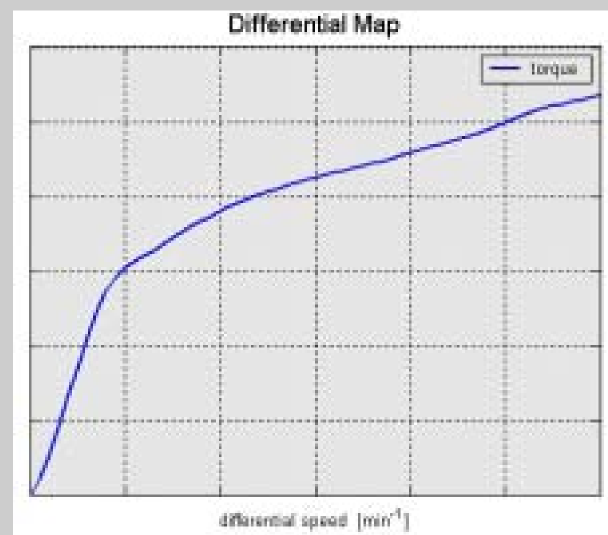
Aerodynamics/drivetrain











Suspension

>Double wishbones (kinematic mode)

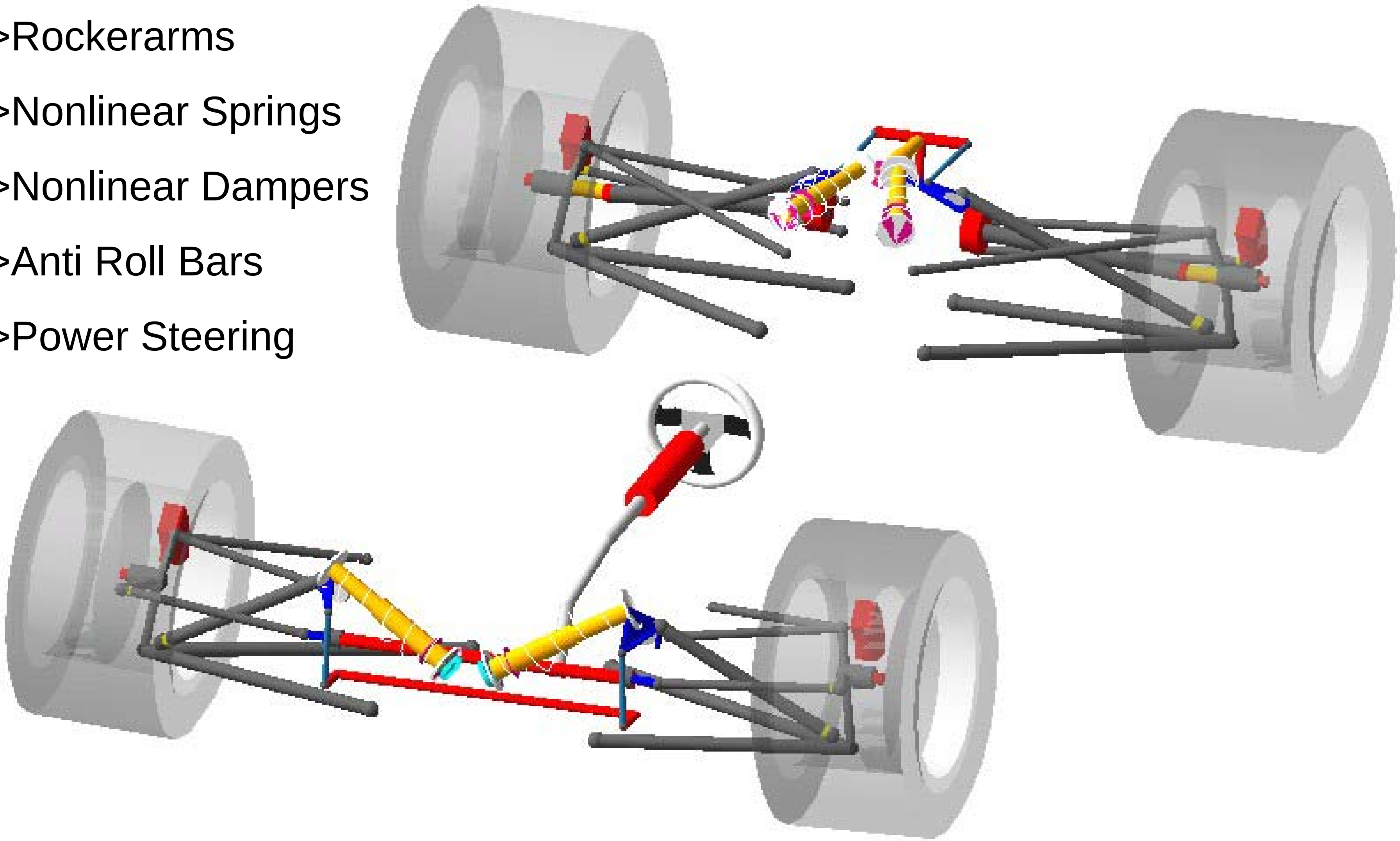
>Rockerarms

>Nonlinear Springs

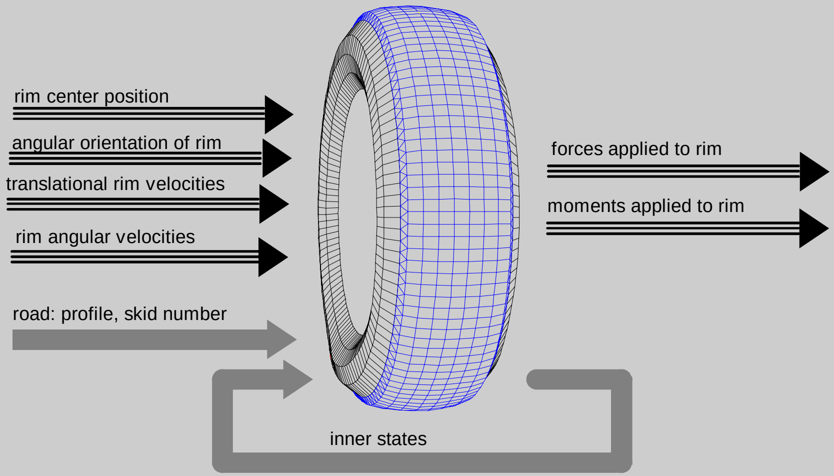
>Nonlinear Dampers

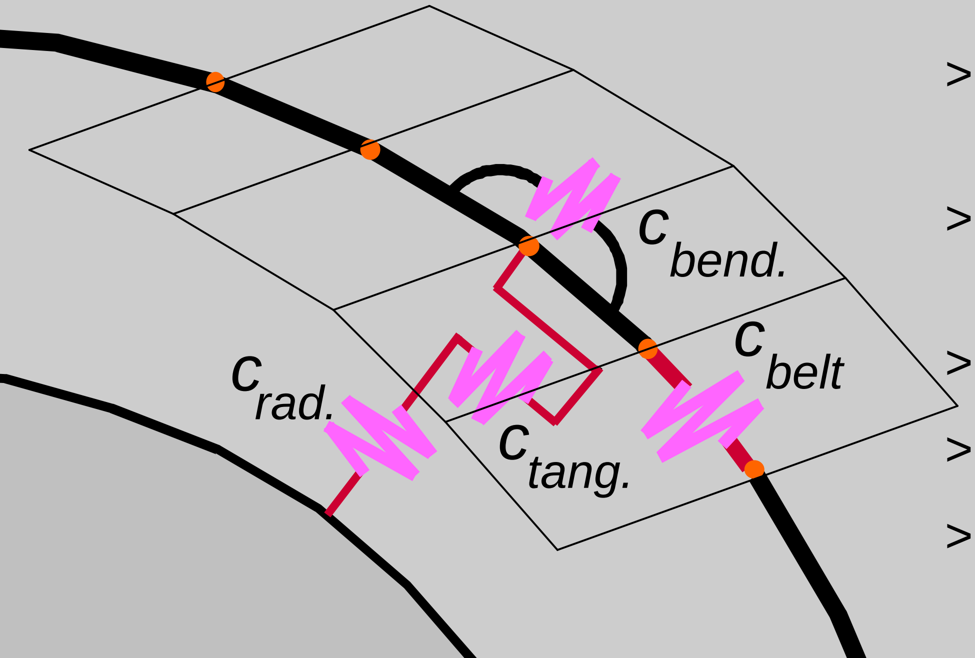
>Anti Roll Bars

>Power Steering



FTire

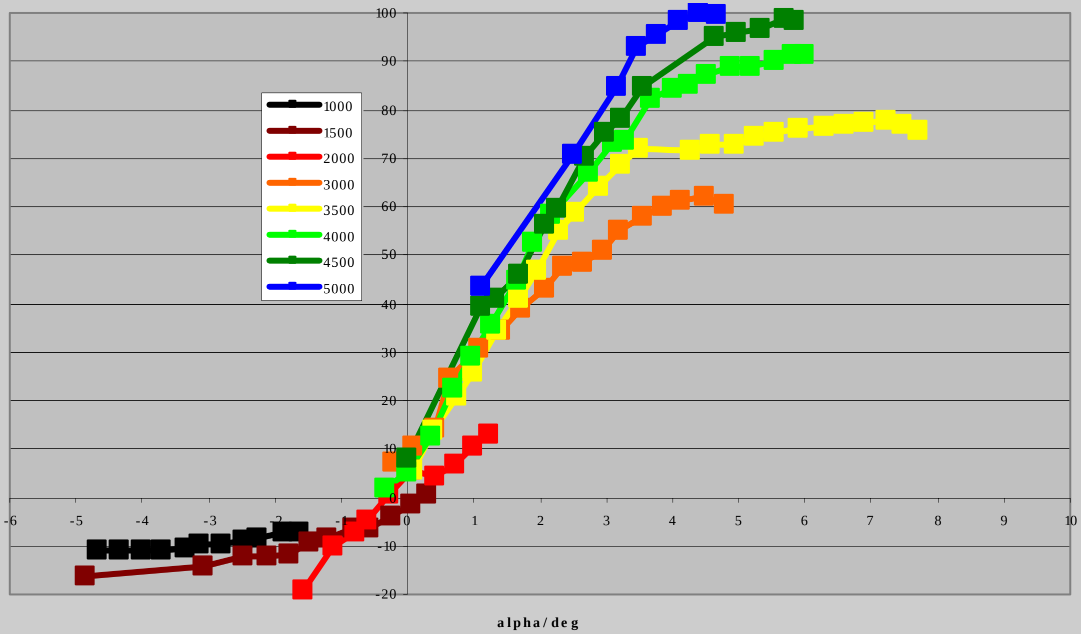




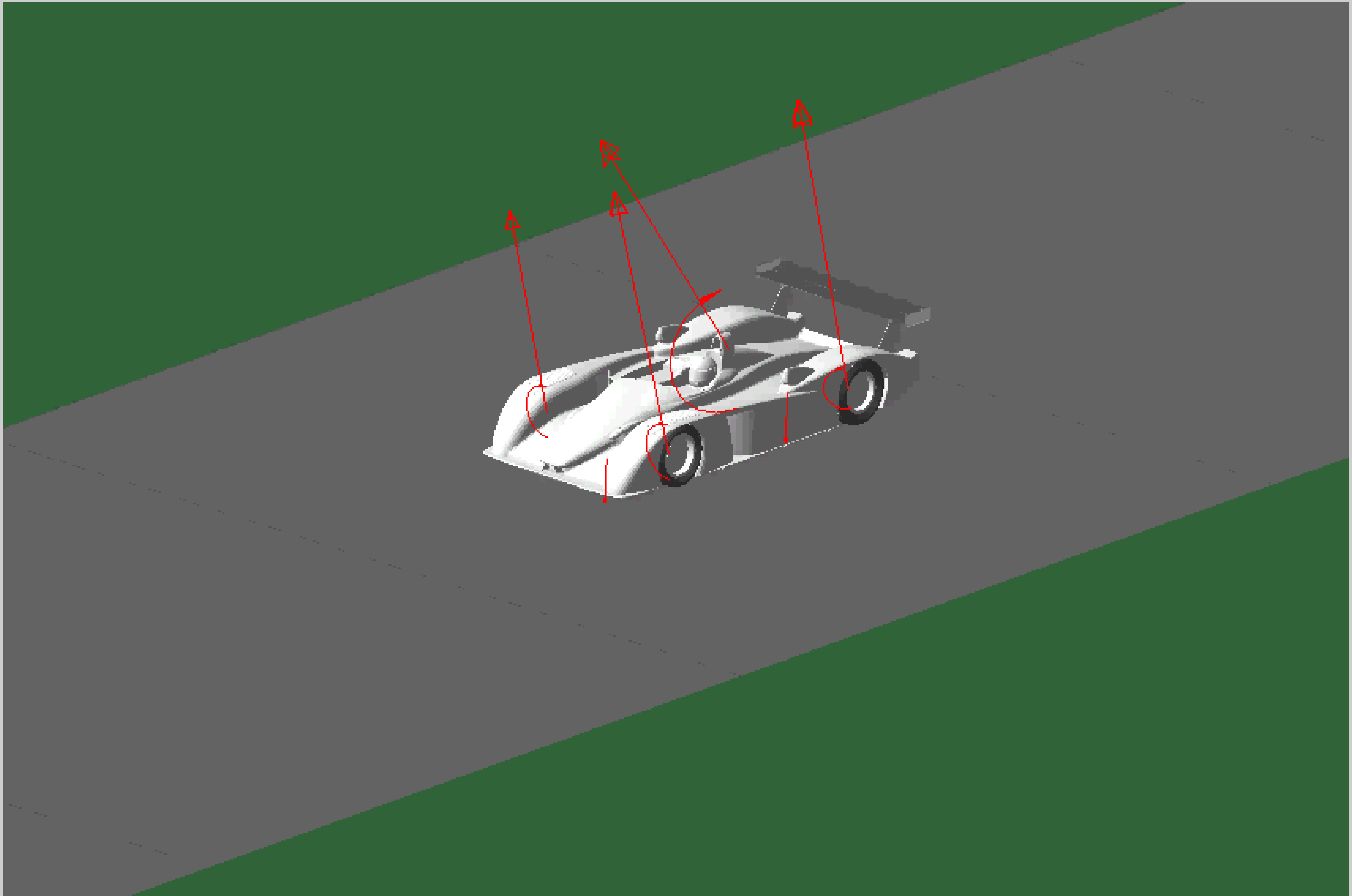
- > Lateral stiffness
- > Dynamic radial stiffness
- > Bending stiffness ‘in-plane’ and ‘out-of-plane’
- > Torsional stiffness between two elements
- > Torsional stiffness between element and rim
- > Damping
- > Belt preload due to internal pressure
- > Valid < 120 Hz, no limitation to wave length of obstacles

Tyre measurements on race track

Normalizd side force Tyre Michelin front left; parameter wheel load



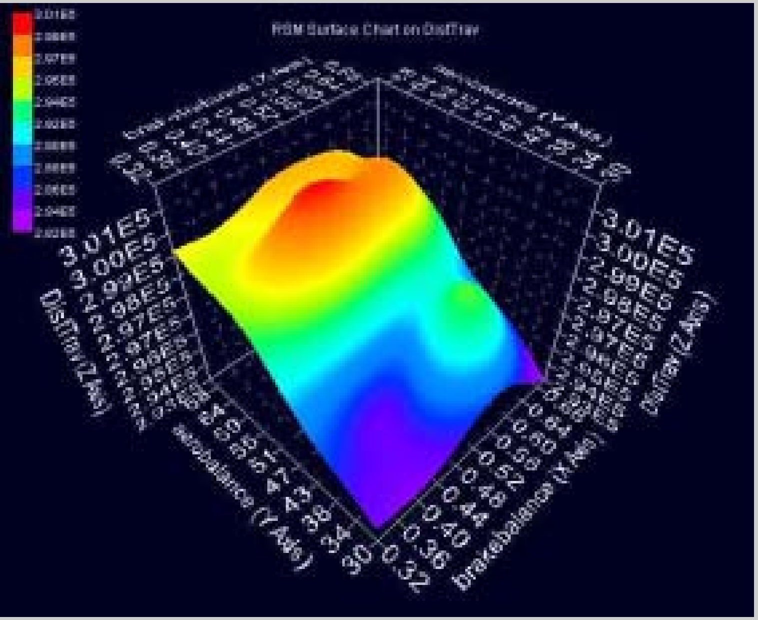
ADAMS: simulation manoeuvre



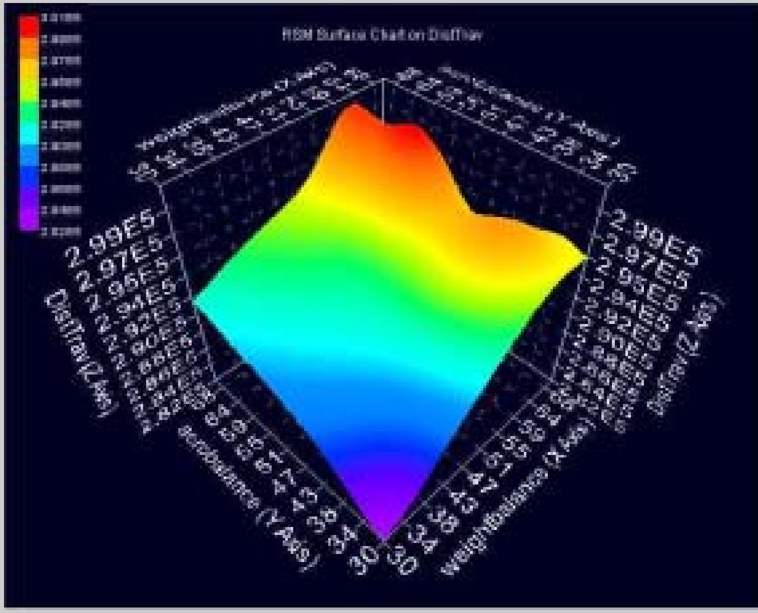
ADAMS: design variables/objectives

- Design variables:
  - 1. Aero/weight/brake balance
  - 2. Dampers: low/high speed (150/1000 mm/s) coefficients
- Objectives:
  - 1. Distance travel/final speed
  - 2. Standard deviations wheel loads front/rear, yaw speed

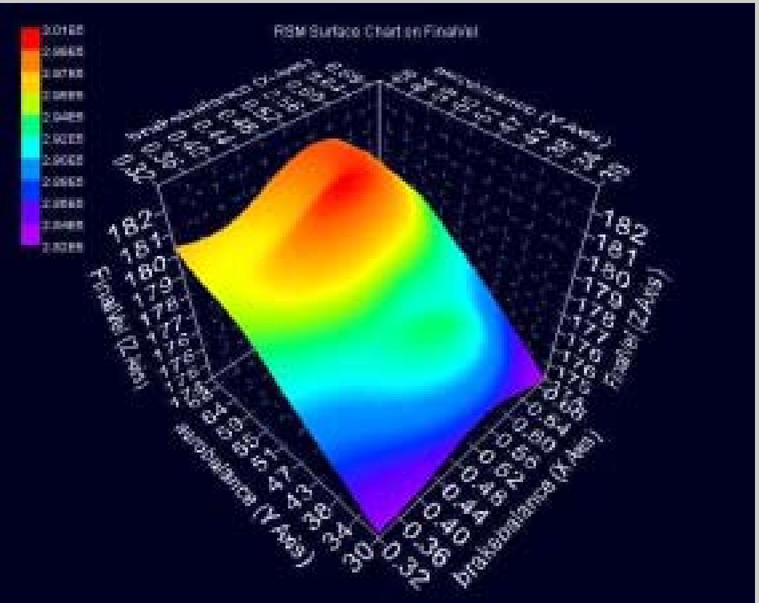
ADAMS: optimization of in-plane dynamics

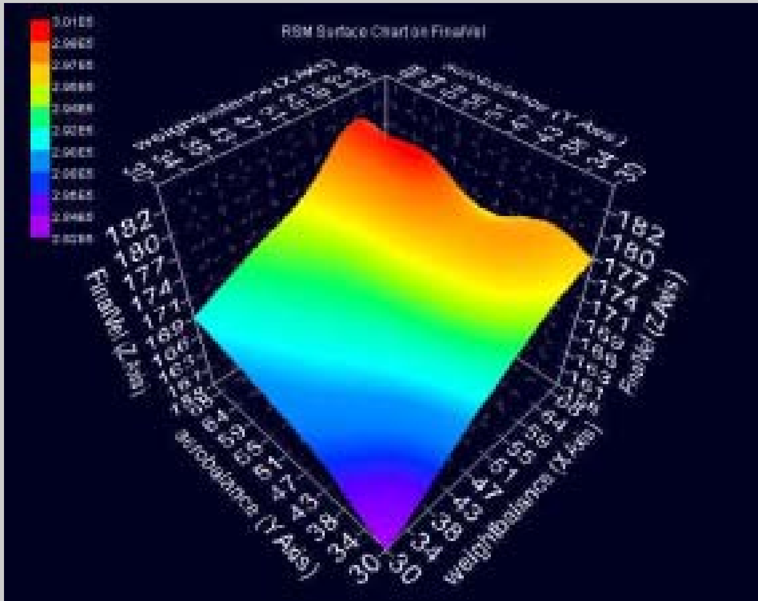


Designs: weight, aero, brake balances



Objective: distance travel



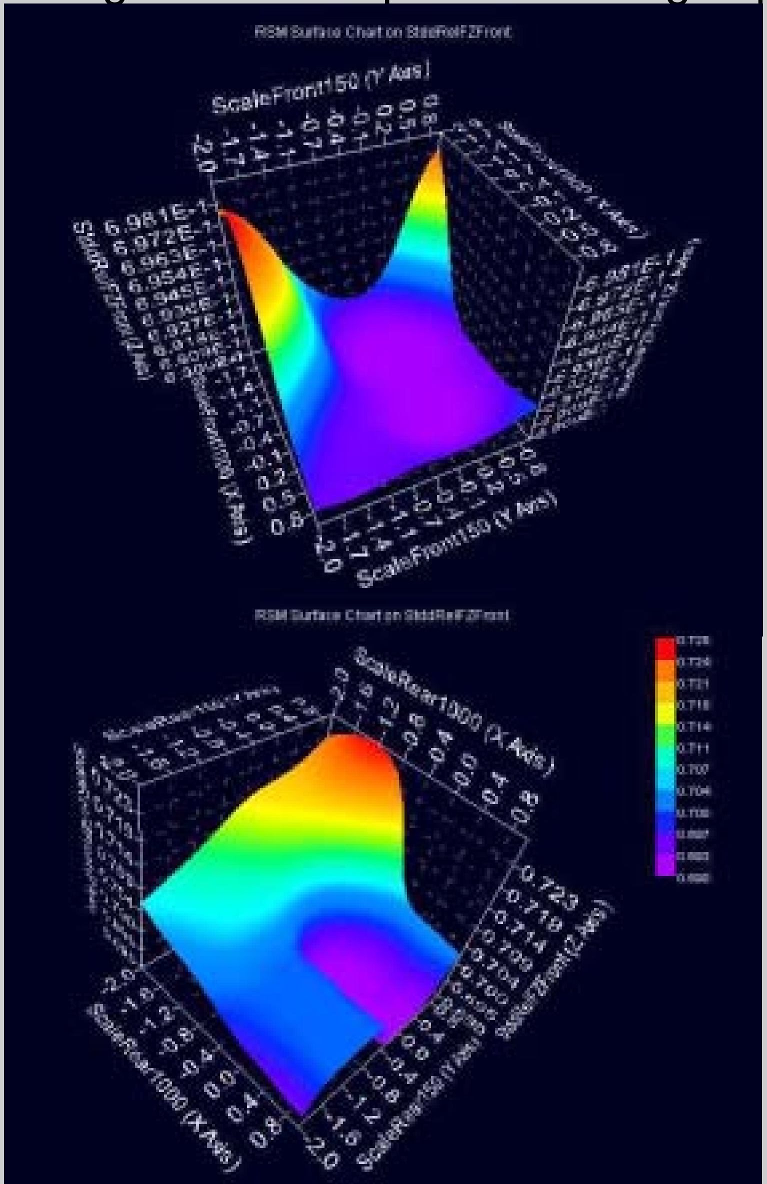


Objective:

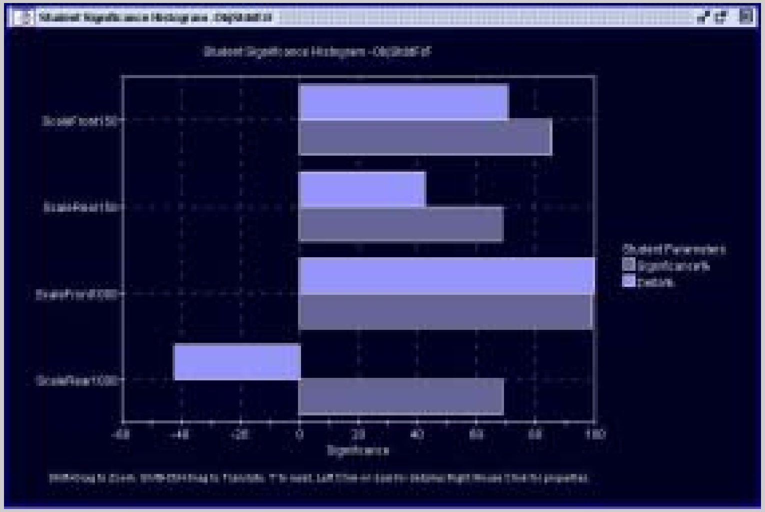
final velocity

ADAMS: optimization of vertical dynamics

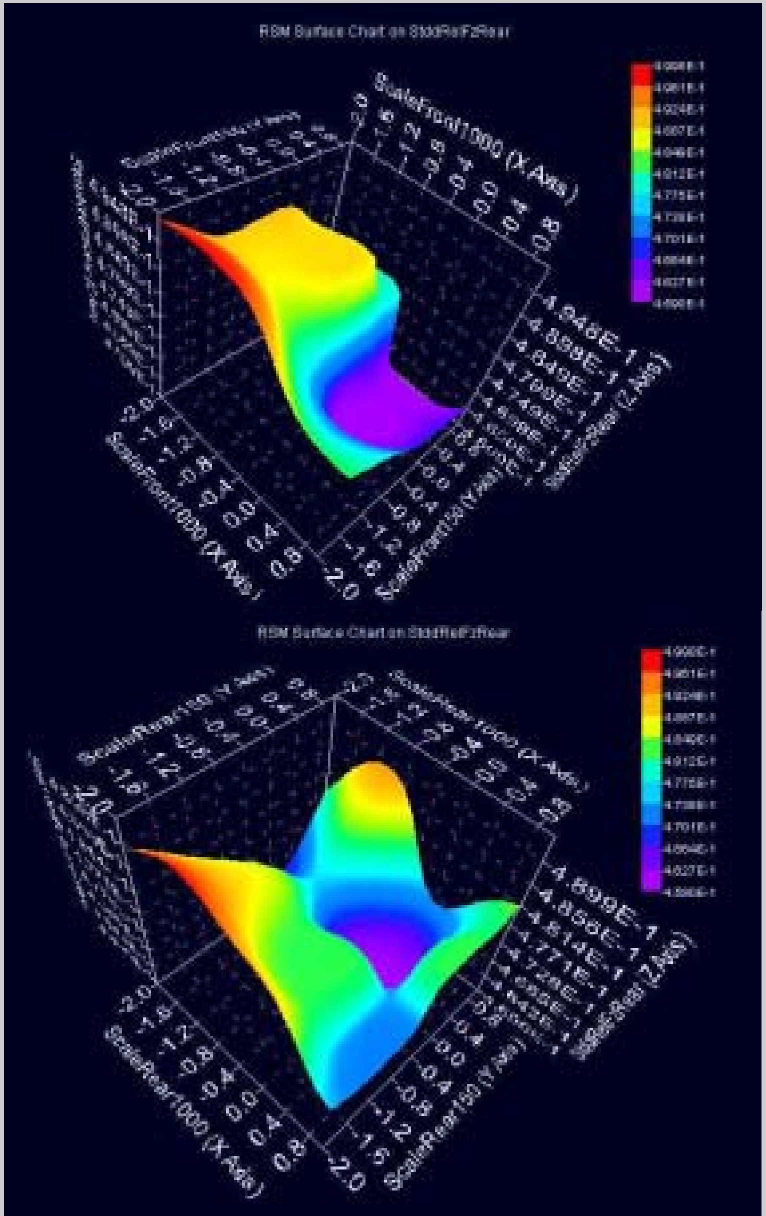
Designs: scale exponent low/high speed damping forces front/rear



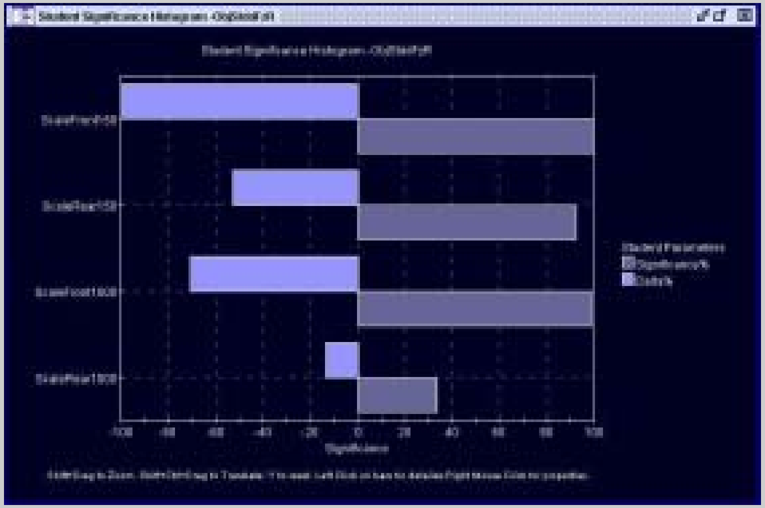
Objective: standard deviation wheel load front



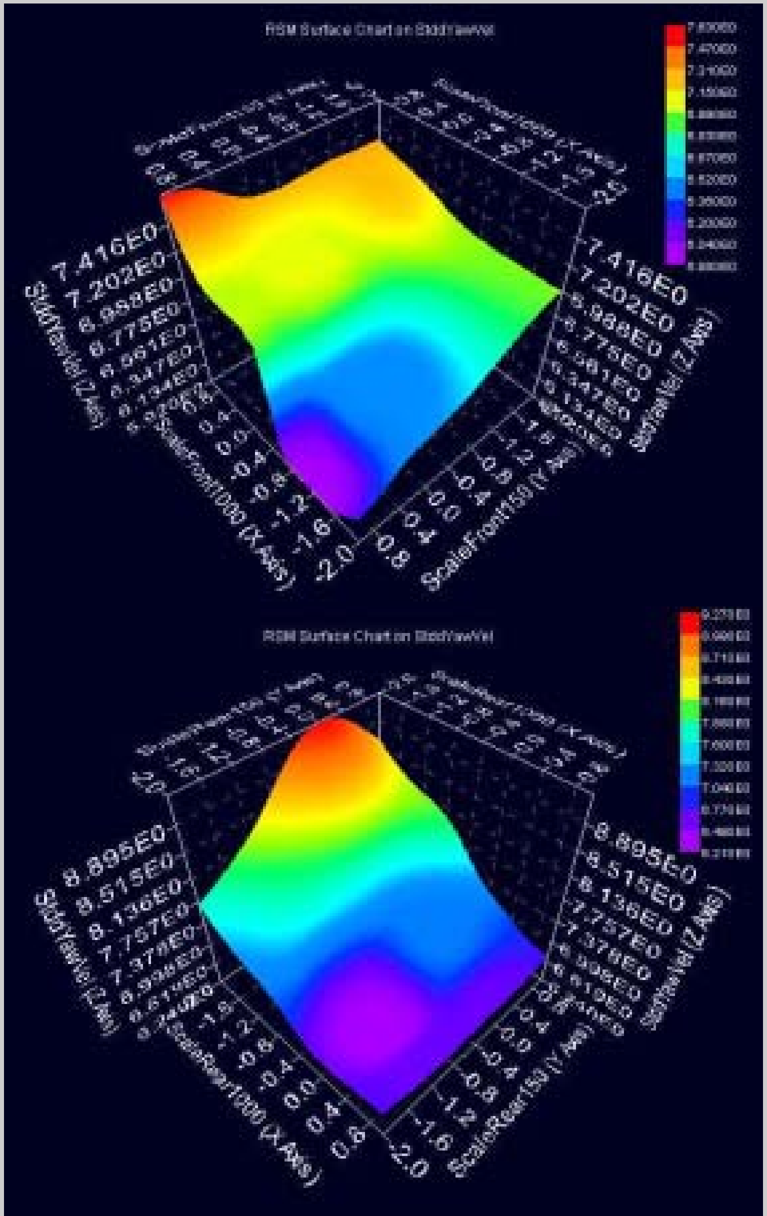
ADAMS: optimization of vertical dynamics



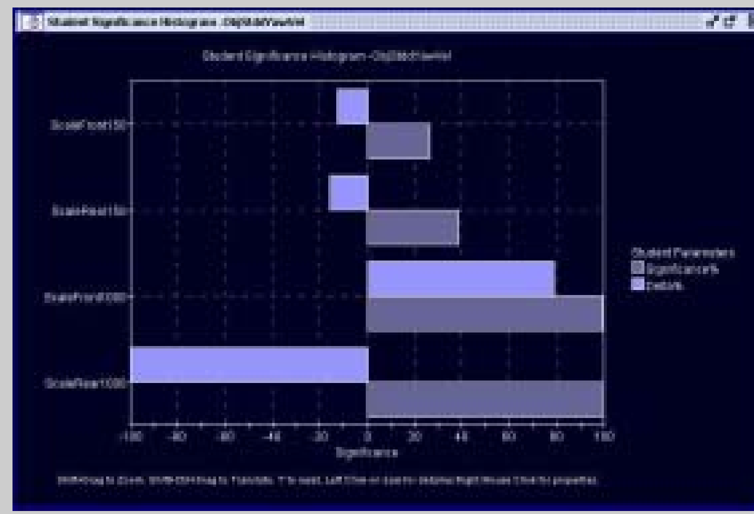
Objective: standard deviation wheel load rear



ADAMS: optimization of vertical dynamics



Objective: standard deviation yaw velocity



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> Optimization of vertical dynamics in Matlab/Simulink
> Optimization of in-plane dynamics with EZ-lap/ modeFrontier
> Multiobjective optimization of global vehicle dynamics in ADAMS/modeFrontier
> Conclusions

Conclusions

- Simple model approaches are designed to describe certain single aspects of the complex system
- Simple models allow to investigate full design space to identify global properties
- More complex models require to reduce design space e.g. automatically by MOGA, but give more detailed results
- Results from simpler models can serve as start values for the optimization with the more complex models
- Optimizations with simpler models concerning vertical dynamics and in-plane-dynamics find a range in the design space not too far away from the optimization with the complex model
- Required improvements: convergence of closed loop ADAMS mavoeuvres with driver controler