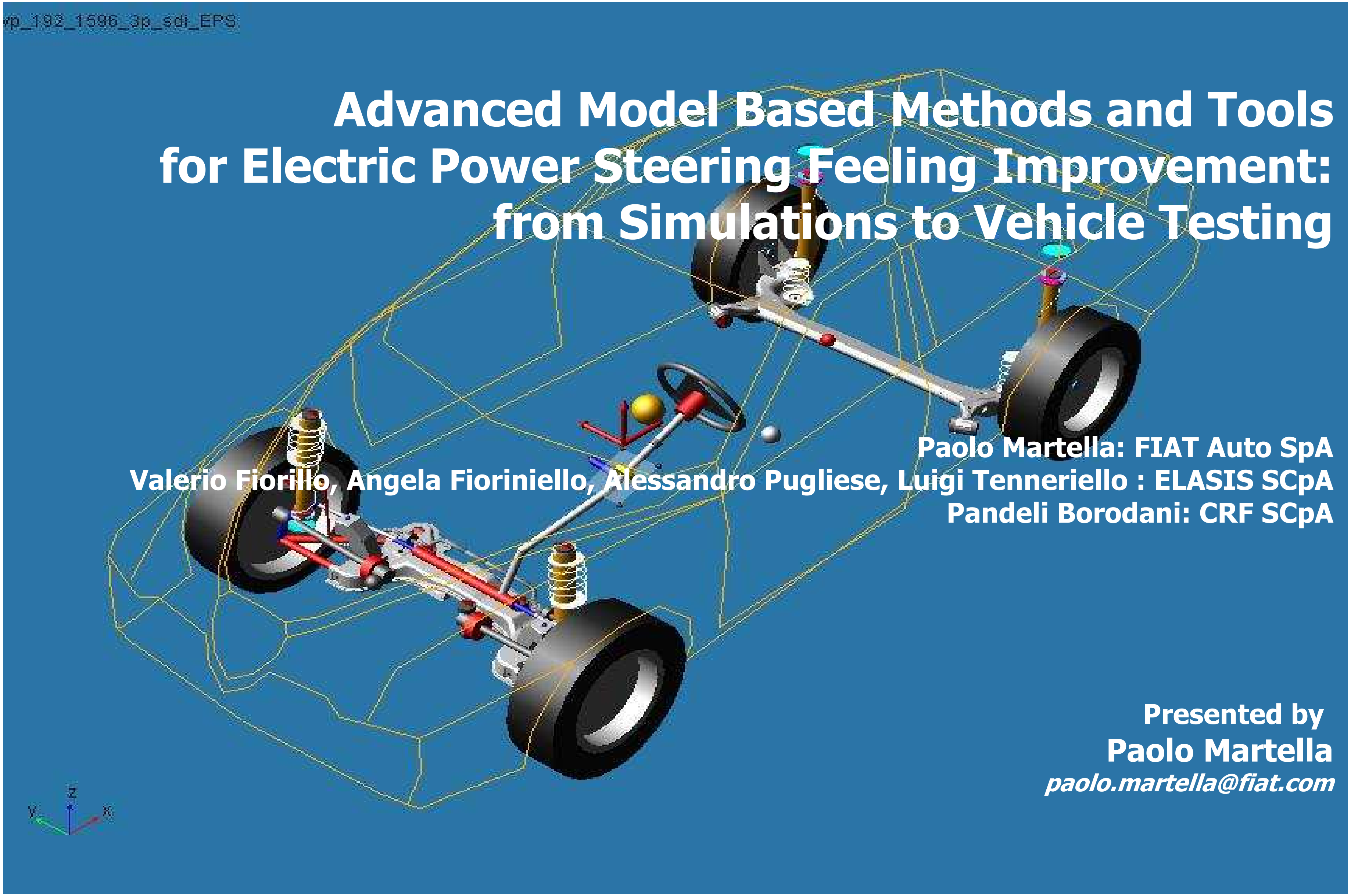

Advanced Model Based Methods and Tools for Electric Power Steering Feeling Improvement: from Simulations to Vehicle Testing

Paolo Martella: FIAT Auto SpA
Valerio Fiorillo, Angela Fioriniello, Alessandro Pugliese, Luigi Tenneriello : ELASIS SCpA
Pandeli Borodani: CRF SCpA

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Table of Contents

Objectives

Suggest modifications to current logics for assistance torque computation in the electric steering systems with the aim to increase the steering quality by:

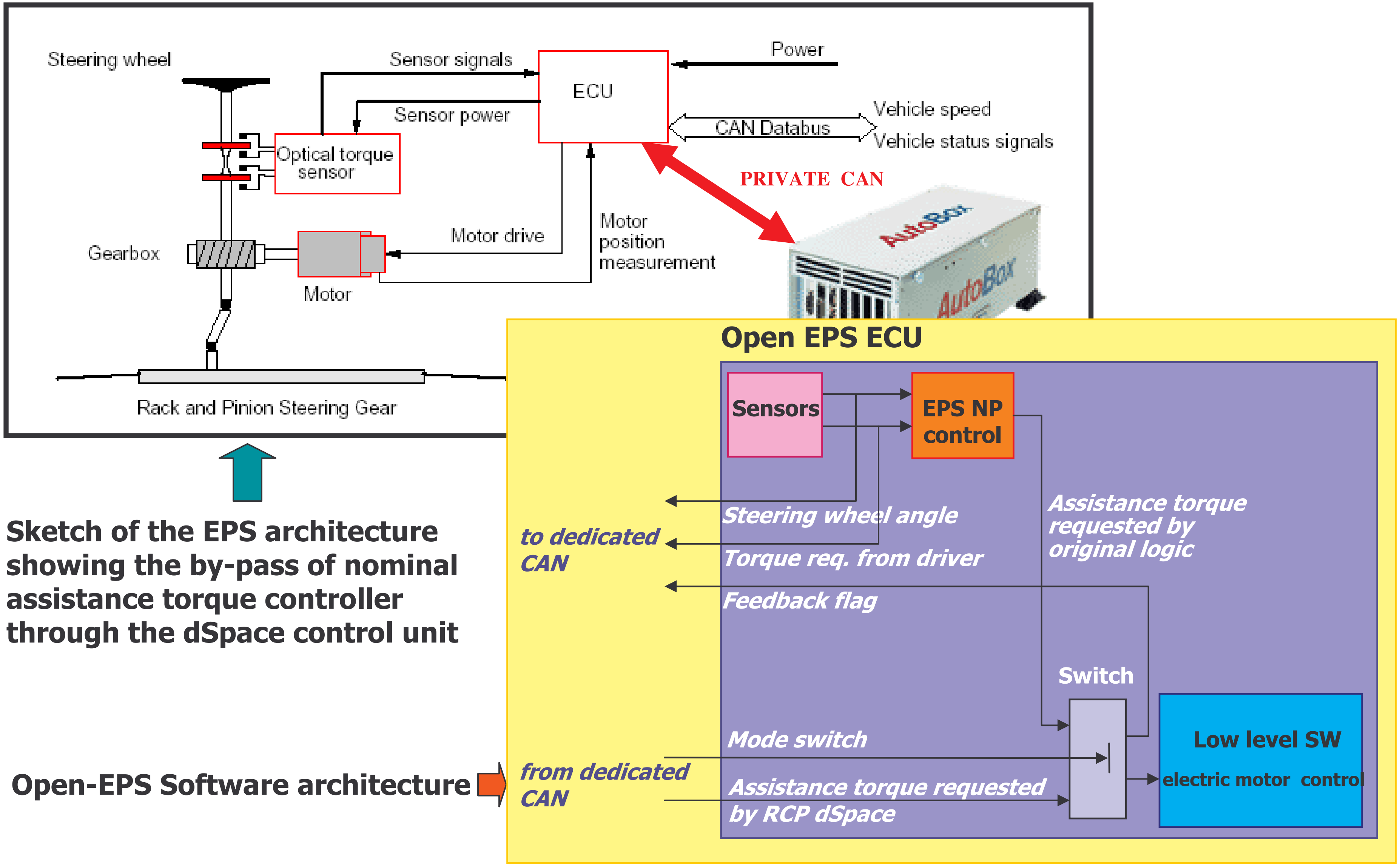
- exploring potential improvements with simple tuning of parameters through systematic sensitivity analysis
- determining areas to propose adjustments of the current control strategies
- introducing completely new contributions to assistance torque

in view of developing new control strategies for torque overlay to augment the safety feeling perceived by the driver and the global vehicle stability

Industrial Team

Fiat Auto SpA	Study Management, Control Strategies, Model Integration
Elasis SCpA	Test bench and prototype set-up, Modelisation, Sensitivity Analysis
CRF SCpA	Robustness Analysis

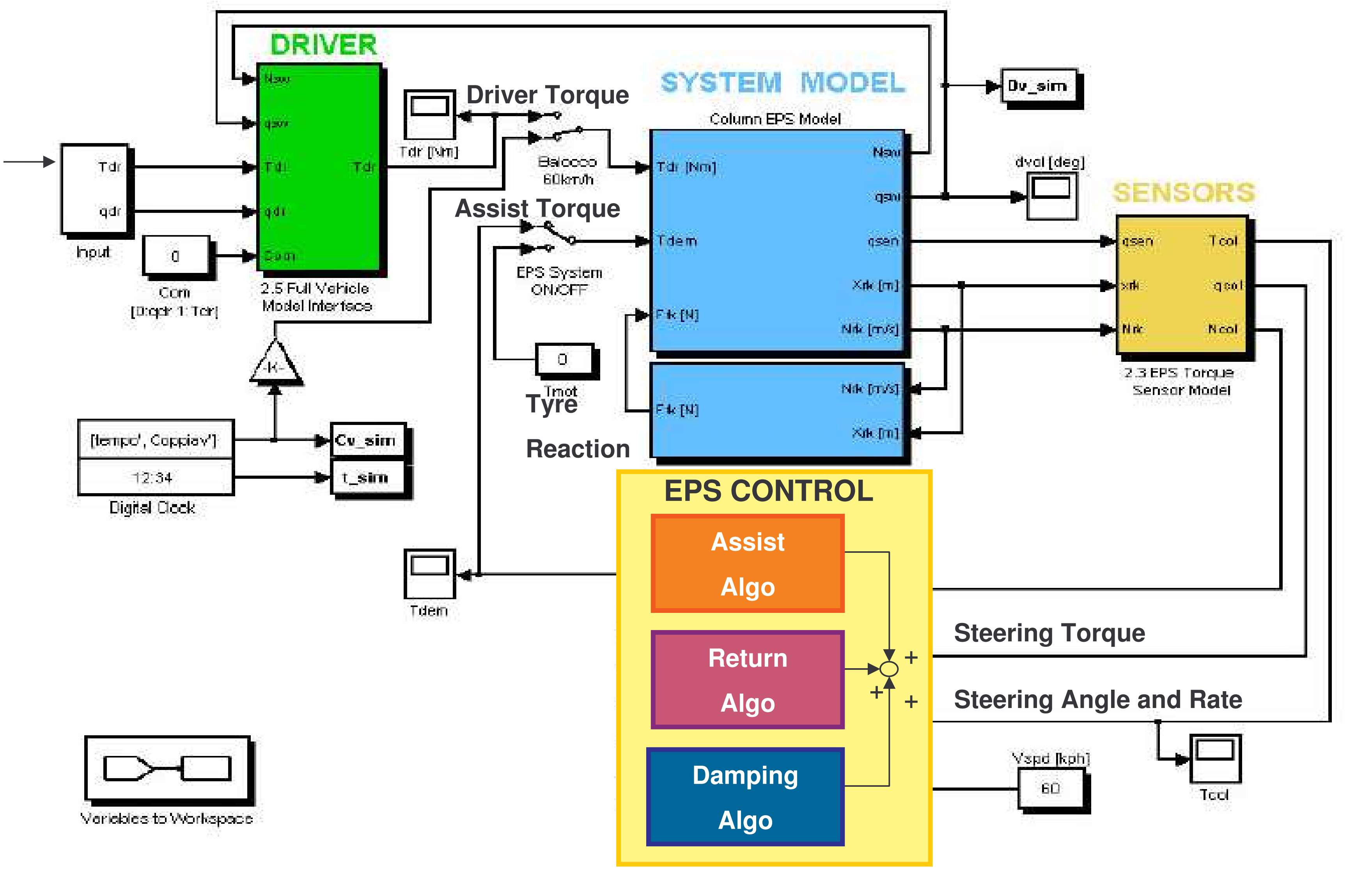
System H/W Architecture



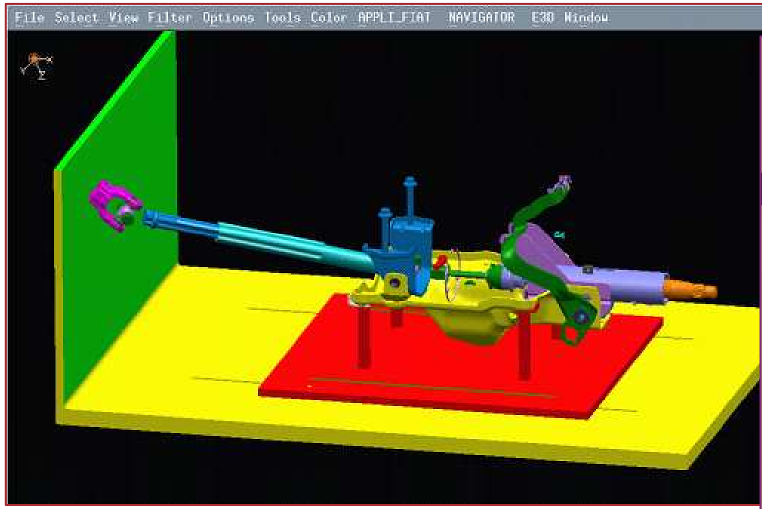
Sketch of the EPS architecture showing the by-pass of nominal assistance torque controller through the dSpace control unit

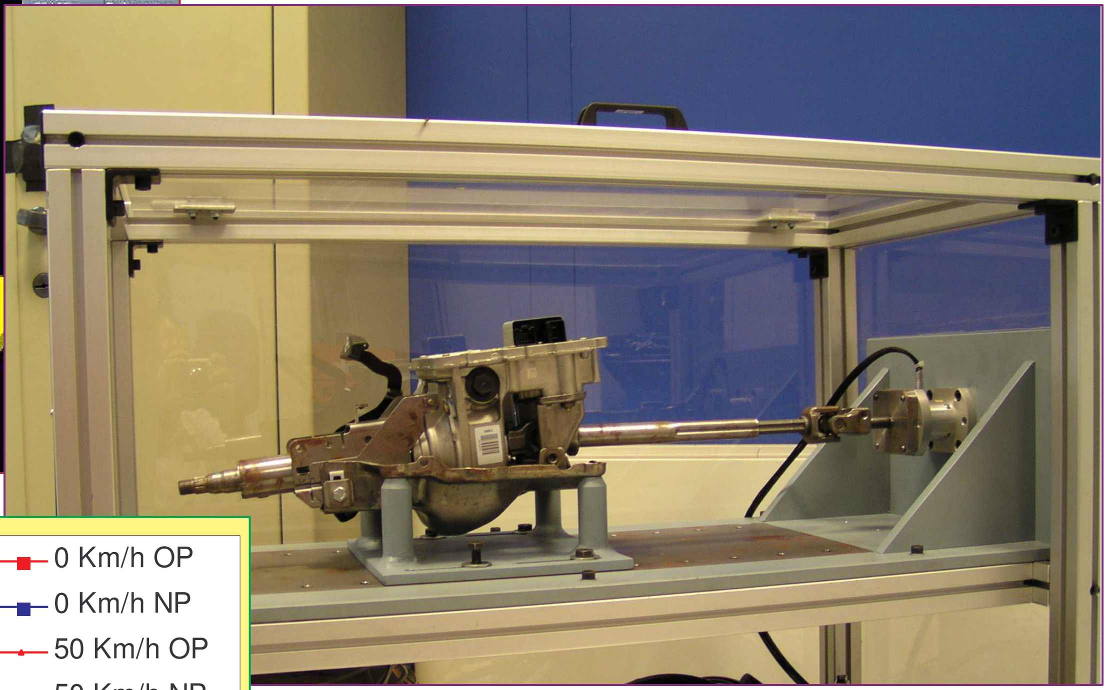
Open-EPS Software architecture

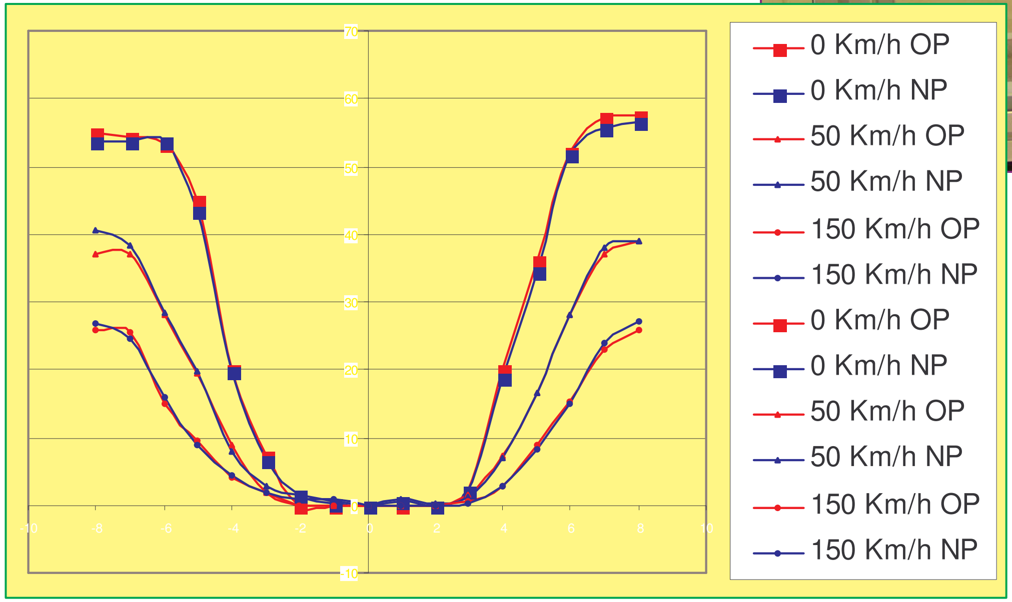
Control SW Architecture



Test Bench Set-Up and Measurements







A test bench has been designed and manufactured by Elasis. Before installation on the vehicle the Open EPS has been measured and compared with the Normal Production one

Vehicle Preparation

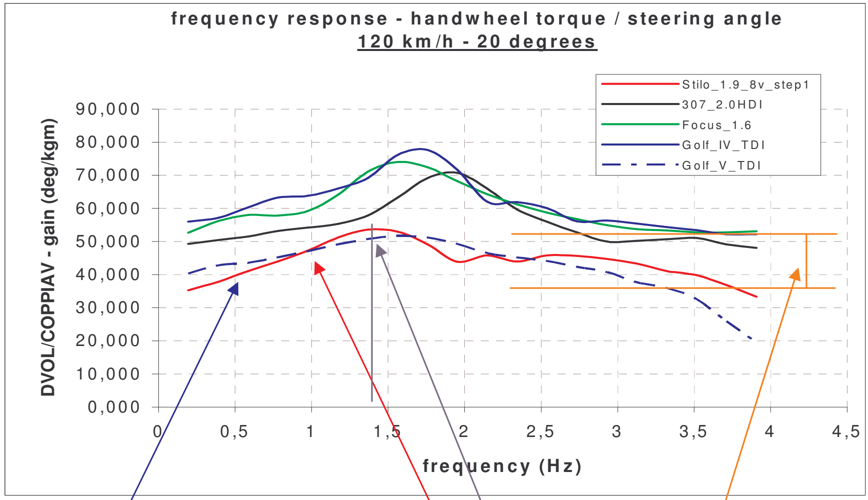
The Open EPS has been mounted onboard a **Fiat Stilo 1.9 JTD** and has been connected with the Rapid Control Prototyping System AutoBox dSpace.

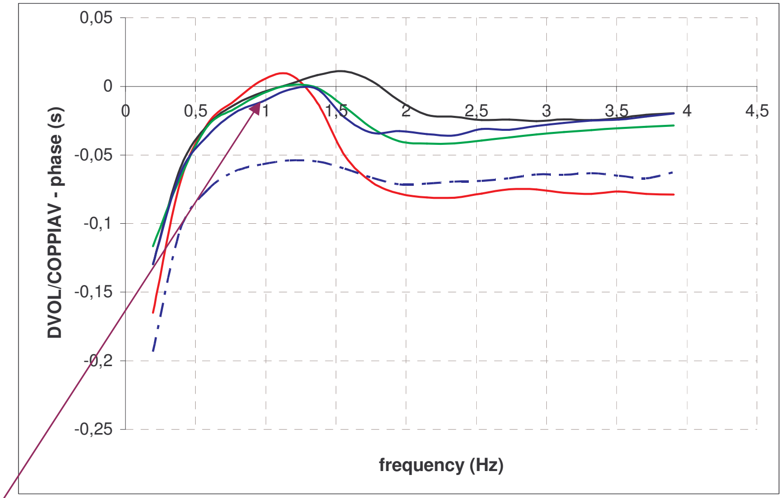
RCP System

User Interface

It has been verified, on the track, that the behaviour of the vehicle is identical to the case of Normal Production vehicle a part for the parking manoeuvres affected by the communication delay of the private CAN

Steer Angle/Driver Torque (D_{vol}/C_{vol}) frequency response

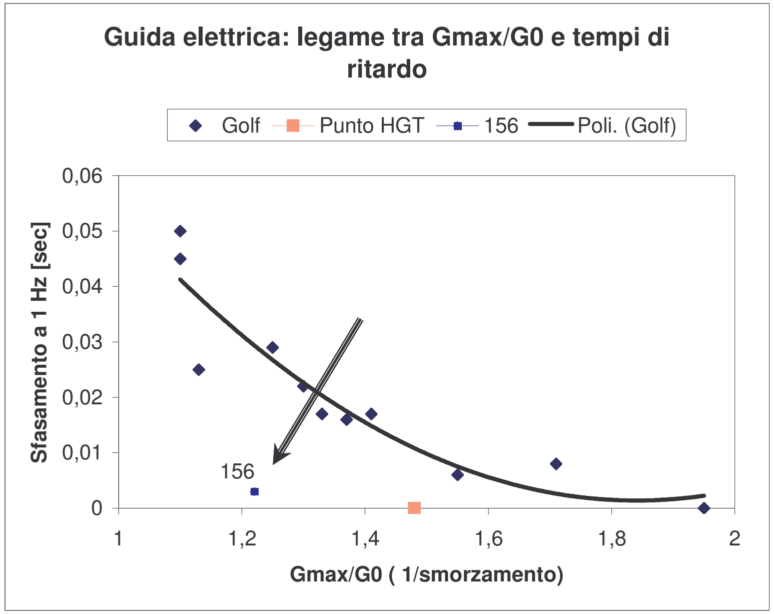




Evaluation of the relationship between damping and delay time measured for several vehicles

PARAMETER	UNIT
Magnitude of function Dvol/Cvol @ 1 Hz G(1)	[deg /kgm]
Magnitude of function Dvol/Cvol @ 0.5 Hz G(1)	[deg /kgm]
Peak Frequency in Magnitude of function Dvol/Cvol	[Hz]
Ratio Gmax/Go of Dvol/Cvol magnitudes at peak and DC **(damping)**	**[-]**
Delay between Cvol and Dvol at 1 Hz	**[s]**

The sweep manoeuvre gives a direct interpretation of the system behaviour in the frequency domain



IQS: a subjective-objective quality index

The IQS (by CRF) synthesises the steer performance by using objective parameters measured (or computed) in a number of significant manoeuvres:

- **0.2 Hz sinusoids @ 60 and 120 kph;**
- **step steer and release with several steer angles @ 100 kph;**
- **parking cycles @ low and null speeds**

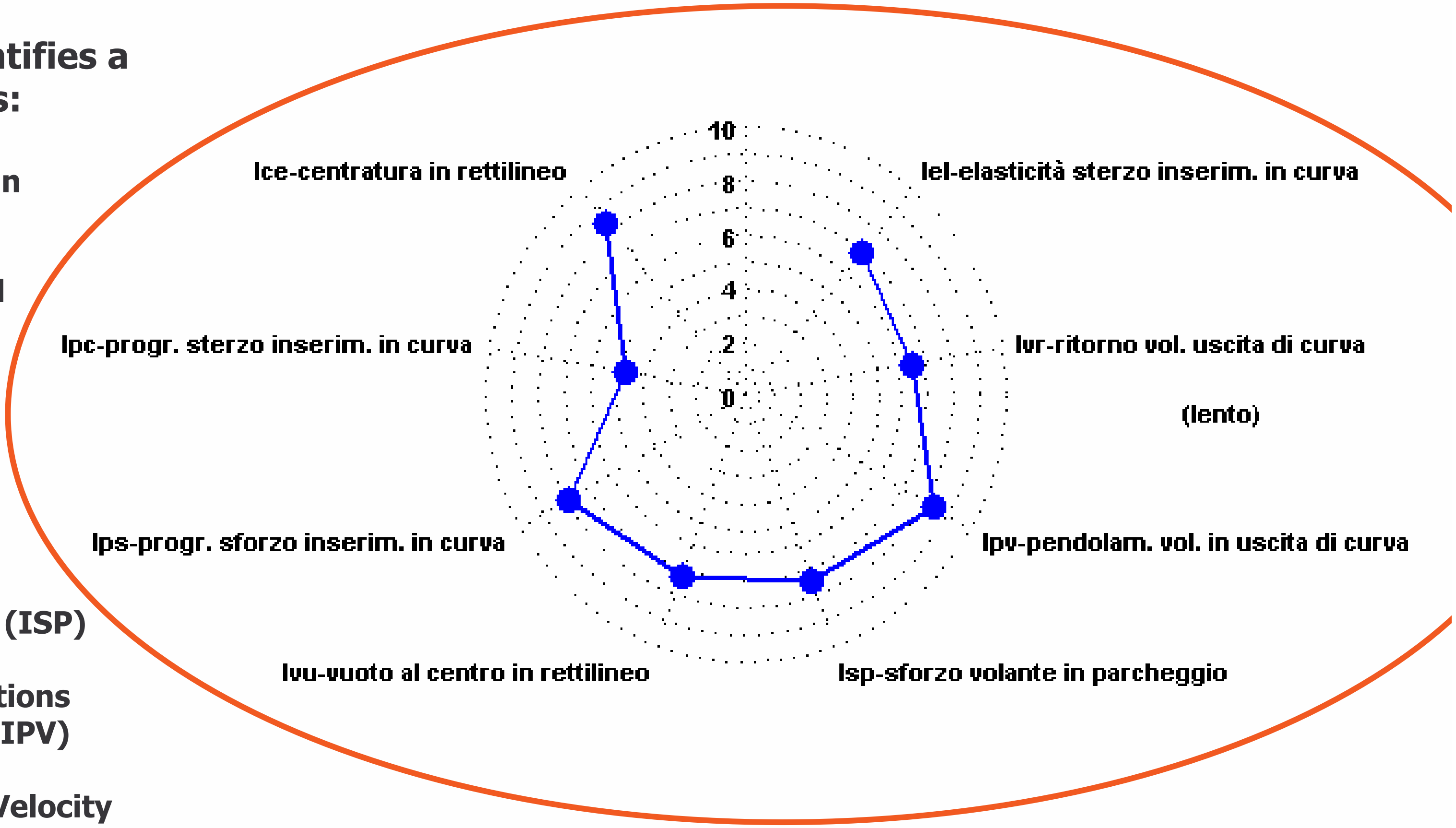
Parametri oggettivi	IEL	IVR	IPV	ISP	IVU	IPS	IPC	ICE	
TAU40									STEERIN PAD
KDVOL [deg/g]									
CVMAX [kgm]						■			
KBETA [deg/g]									
mVB2/VB1 [1/g]		■							STEP STEER 100 kph
qVB2 [g]		■							
qTDVOL1 [s]		■							
mDVOL2/DVOL1 [1/g]			■						
qDVOL2/DVOL1									
mDVOL2 [deg/g]			■						
qDVOL2 [deg]			■						
CDmi [kgm/deg]								■	SINUSOI 120 kph
CDarea [Kgm*Deg]								■	
DAm [Deg/g]								■	
CDmi [kgm/deg]					■		■		SINUSOI 60 kph
CDcv0 [kgm]					■				
PDarea [Deg*Deg/s]							■		
CAmi [kgm/g]	■					■			
CDarea [kgm*Deg]							■		
CAarea [kgm*g]						■			
CAcv0 [kgm]	■								
CDcv0BV [kgm]				■					PARKING
CDcv0DF [kgm]				■					

IQS Radar

The procedure identifies a set of 8 sub-indices:

- **Torque Deadband in Straight Path (ICE)**
- **Handwheel Control Graduality (IPC)**
- **Handwheel Torque Graduality (IPS)**
- **Center Feel (IVU)**
- **Steering Torque in Parking Manoeuvre (ISP)**
- **Handwheel Oscillations after Corner. Man. (IPV)**
- **Handwheel Align. Velocity after Corner. Man. (IVR)**
- **Handwheel Elasticity (IEL)**

and a global quality index of the steering (IQS)

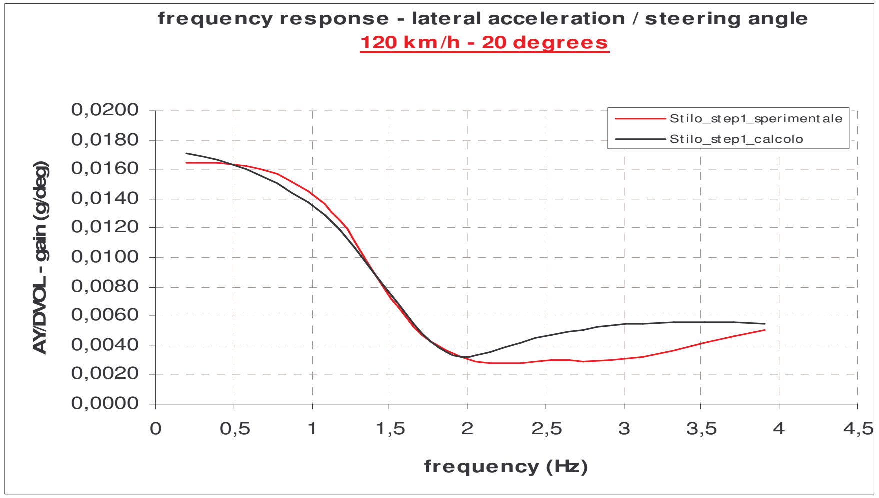


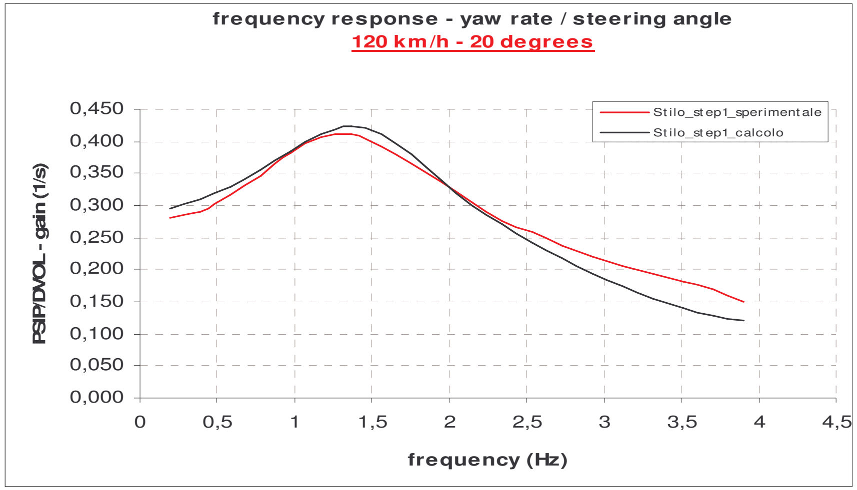
IQS – Measured Steering Quality: 7.9

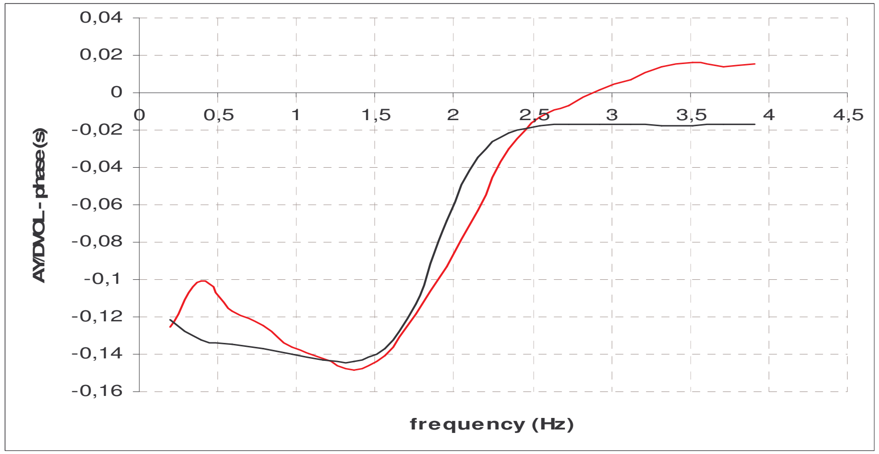
Fiat Stilo, 1.9 JTD, Step 1

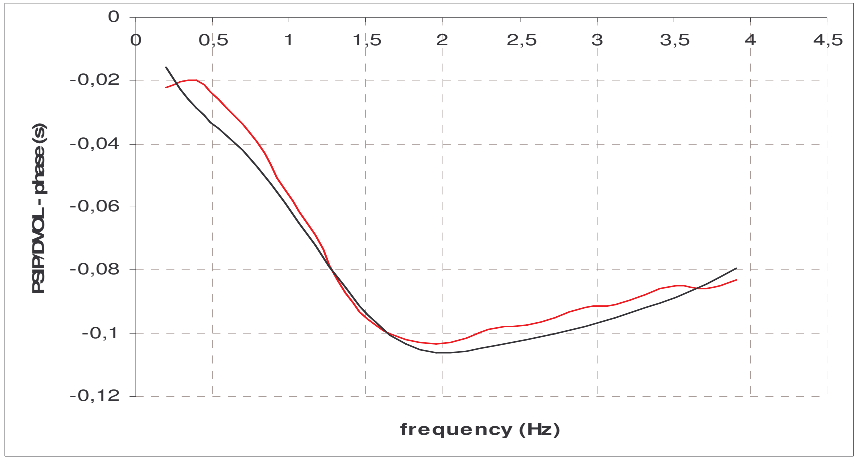
Balocco September 2004-March 2005

Steer-Vehicle Model integration and fitting on track tests


frequency response - lateral acceleration / steering angle
120 km/h - 20 degrees

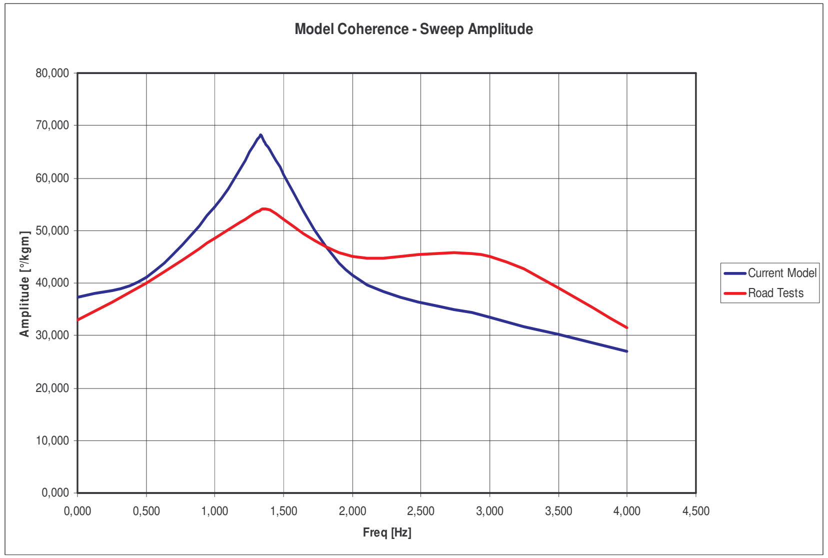

frequency response - yaw rate / steering angle
120 km/h - 20 degrees

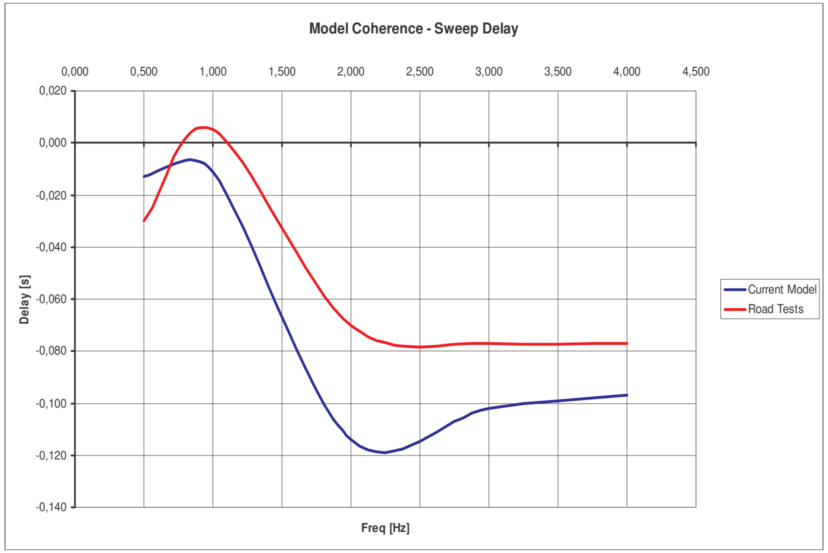




Starting from the stand-alone steering system model, the integration with the vehicle model has been pursued, aiming to fit model and vehicle performances in handling and mentioned metrics

Steer-Vehicle Model integration and fitting on track tests

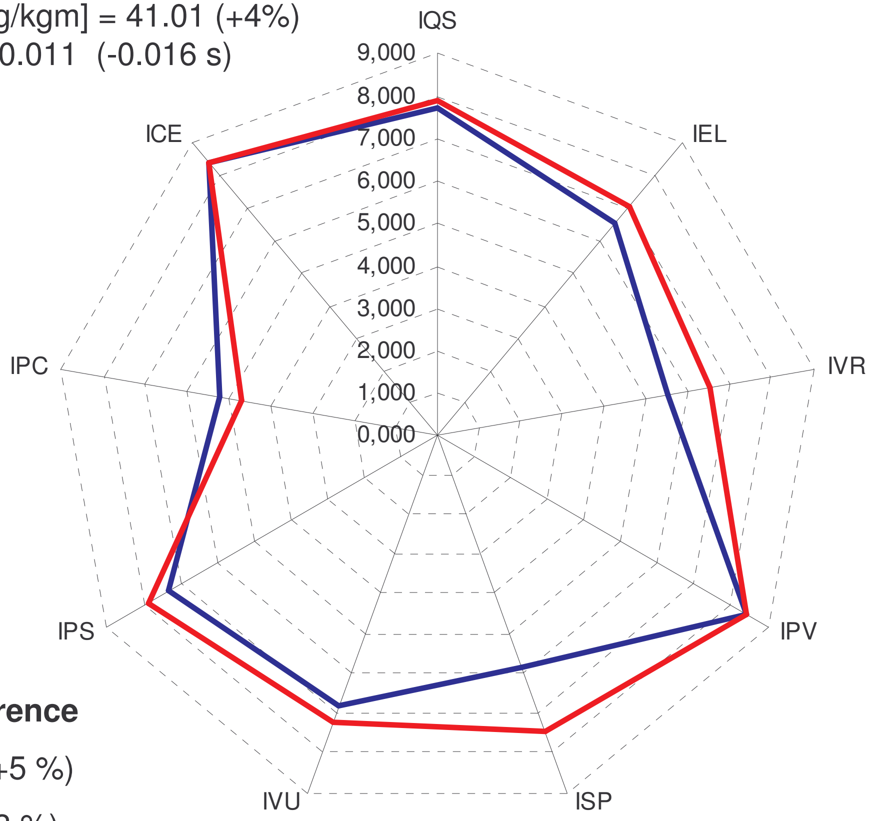




Sweep Coherence

f(Gmax) [Hz] = 1.33 (+1.5%)
Gmax/G0 [] = 1.83 (+12%)
G(0) [deg/kgm] = 37.26 (+12 %)
G(0.5) [deg/kgm] = 41.01 (+4%)
tr(1) [s] = -0.011 (-0.016 s)

Model Coherence - IQS



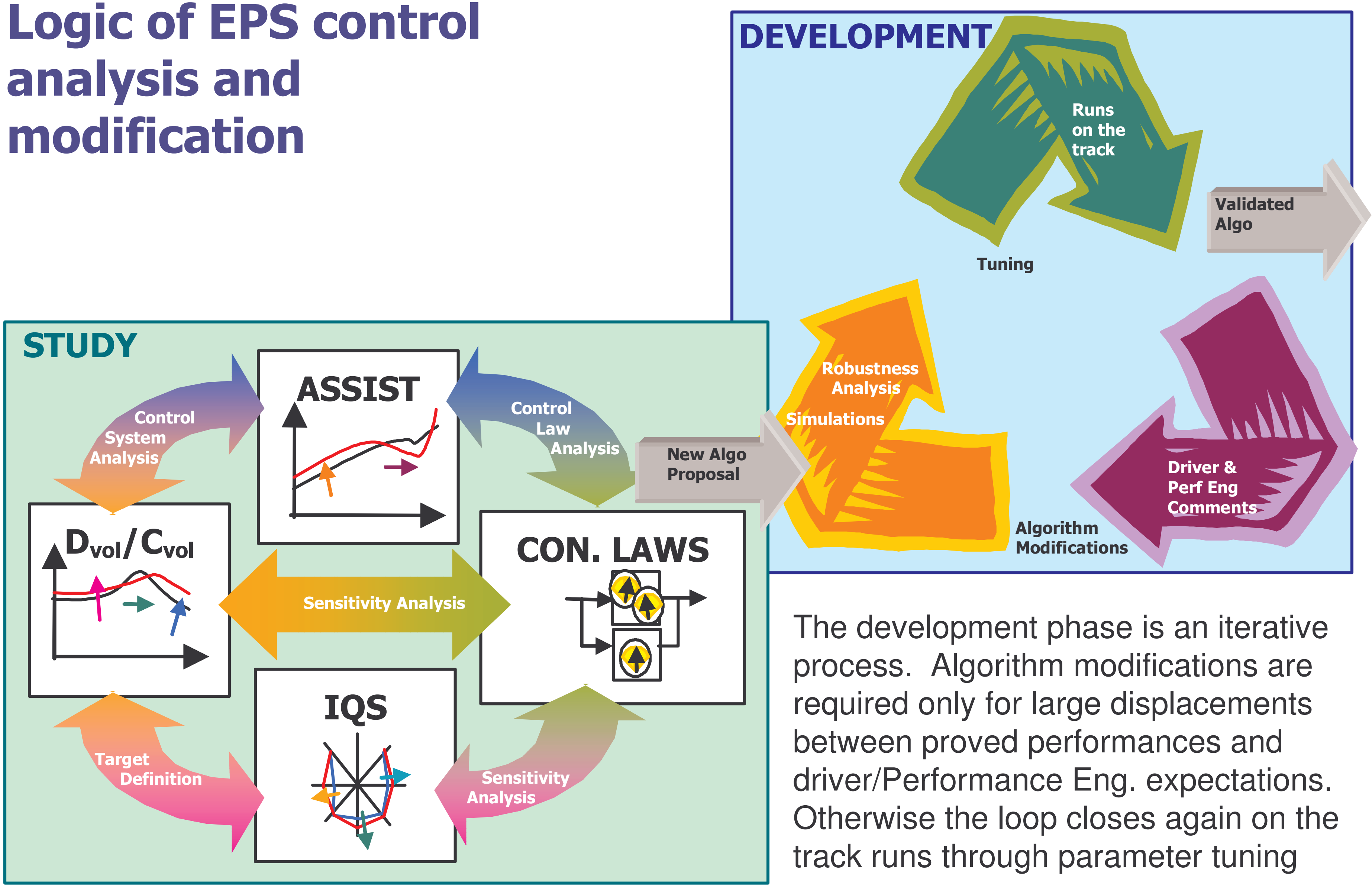
IQS Coherence

IPZ: 6.6 (+5 %)

ISS: 7.7 (-3 %)

IQS: 7.7 (-3 %)

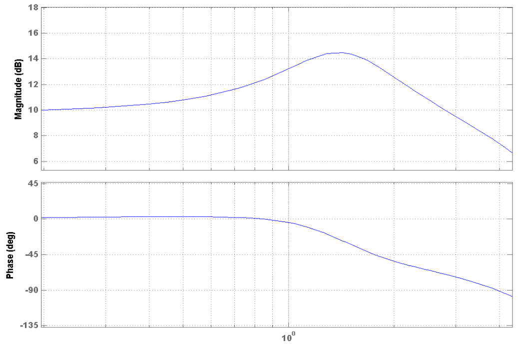
Logic of EPS control analysis and modification



The development phase is an iterative process. Algorithm modifications are required only for large displacements between proved performances and driver/Performance Eng. expectations. Otherwise the loop closes again on the track runs through parameter tuning

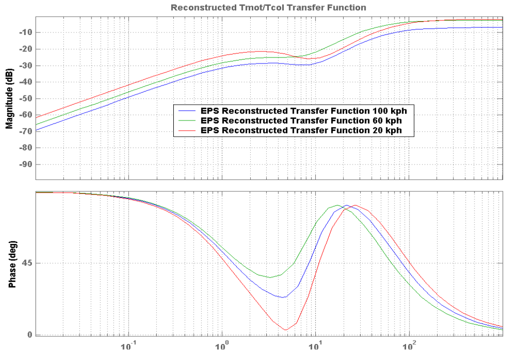
Control Analysis and Assist Shaping

1) Identify curve representative of the actual **Dvol/Cvol in Bode (TFtarget)**



2) Define **Elementary Transfer Functions** of the system (steer and road)

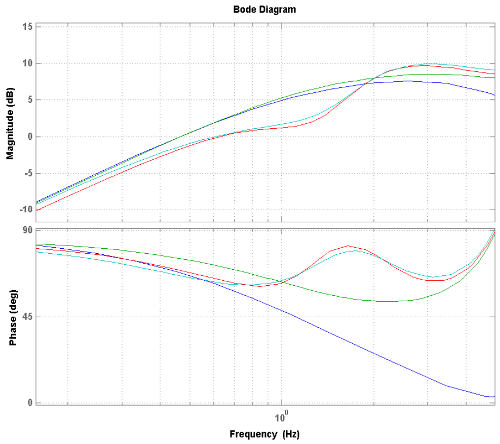
3) Compute the Transfer Function **TFeps**= Tdem/Tsen as function of the actual **TFtarget**



4) Verify the coherence of **computed assistance** with **actual assistance**

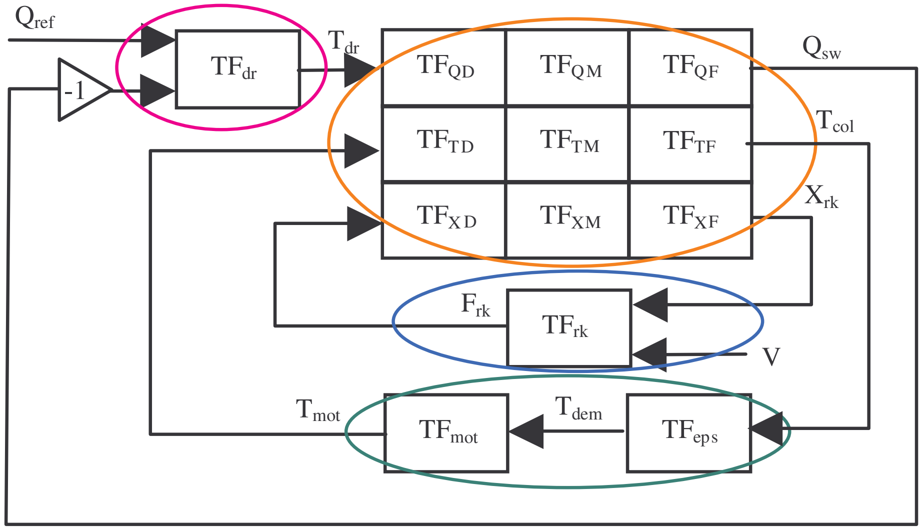
5) Define the curve representative of desired $\mathbf{TFtarget_{des}}$ =$\mathbf{Dvol/Cvol_{des}}$ in **Bode**

6) Compute the Transfer Function $\mathbf{TFeps_{des}}$= $\mathrm{Tdem_{des}}$/Tsen as function of the $\mathbf{TFtarget_{des}}$

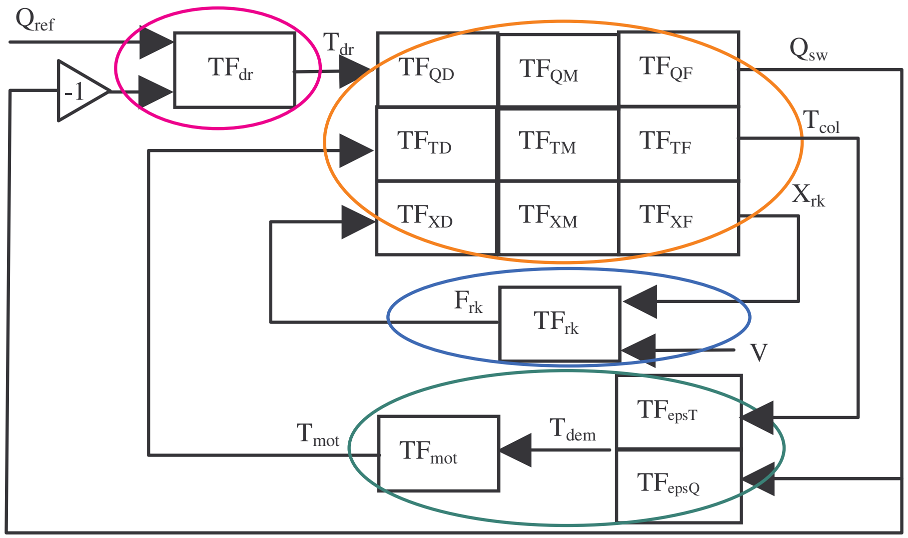


7) Reproduce the compensation filter able to modify **TFeps** in $\mathbf{TFeps_{des}}$

Block Structures for Assist Shaping Calculation



○Driver ○Mechanical Sys ○Road & Vehicle ○Assistance & Motor



○Driver ○Mechanical Sys ○Road & Vehicle ○Assistance & Motor

$TF_{eps}=Num_{eps}*(Den_{eps})^{-1}$

where:

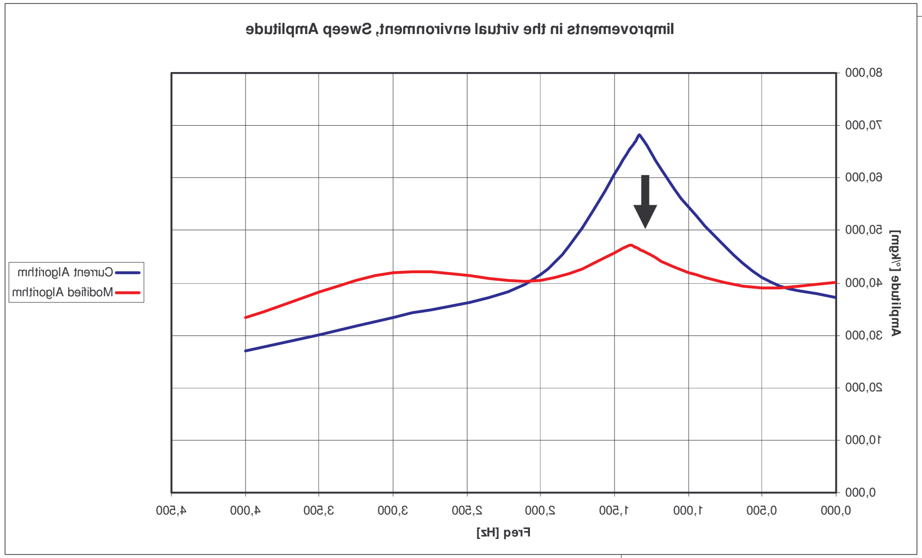
$Num_{eps}\ (-TF_{TargetReq}*(1-TF_{XF}*TF_{rk})-TF_{QD})*(1-TF_{XF}*TF_{rk})$
$Den_{eps}=(-TF_{TargetReq}*(1-TF_{XF}*TF_{rk})-TF_{QD})*$
$(TF_{TM}*(1-TF_{XF}*TF_{rk})+TF_{TF}*TF_{rk}*TF_{XM})+$
$TF_{QM}*(TF_{TD}*(1-TF_{XF}*TF_{rk})+TF_{TF}*TF_{rk}*TF_{XD}).$

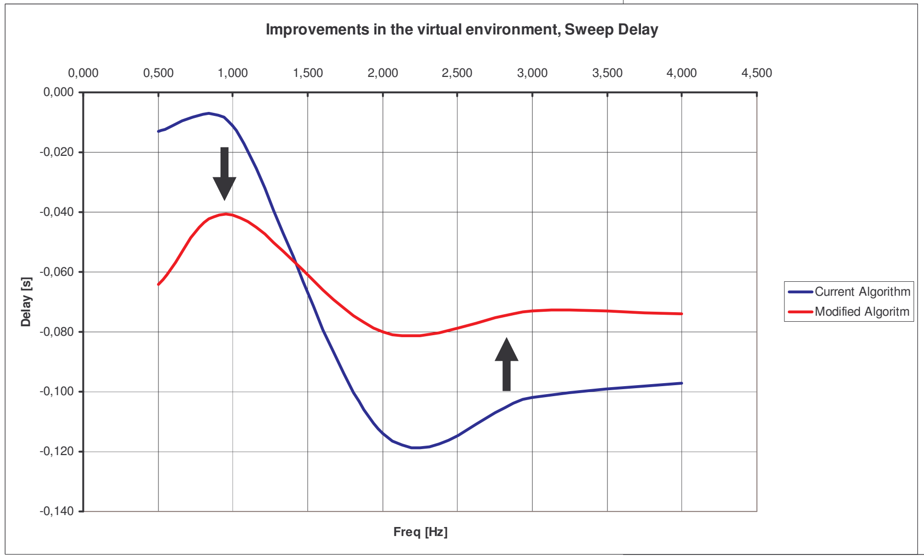
$TF_{epsQ}= TF_{TargetDen}*(TF_{Target}*TF_{Target1Req}^{-1} -1)*$
$(TF_{QM})^{-1}*(1-TF_{XF}*TF_{RK})^{-1}$

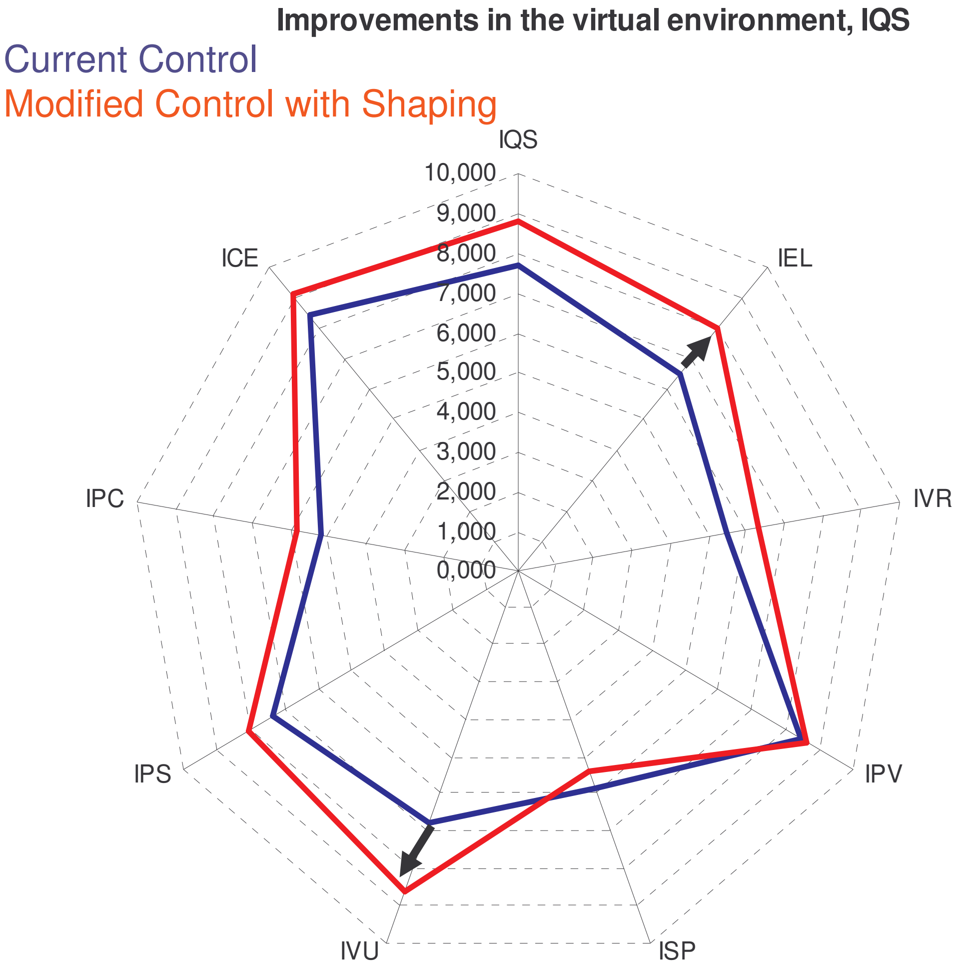
where:

$TF_{Target}=-TF_{TargetNum}*TF_{TargetDen}^{-1}$
$TF_{TargetNum}=TF_{QD}*((1-TF_{TM}*TF_{epsT})*$
$(1-TF_{XF}*TF_{rk})-TF_{TF}*TF_{rk}*TF_{XM}*TF_{epsT})+$
$TF_{QM}*TF_{epsT}*$
$(TF_{TD}*(1-TF_{XF}*TF_{rk})+TF_{TF}*TF_{RK}*TF_{XD})$
$TF_{TargetDen}=((1-TF_{TM}*TF_{epsT})*(1-TF_{XF}*TF_{rk})-$
$TF_{TF}*TF_{rk}*TF_{XM}*TF_{epsT})*(1-TF_{XF}*TF_{rk})$

Effects of Assist Shaping in the Virtual Environment



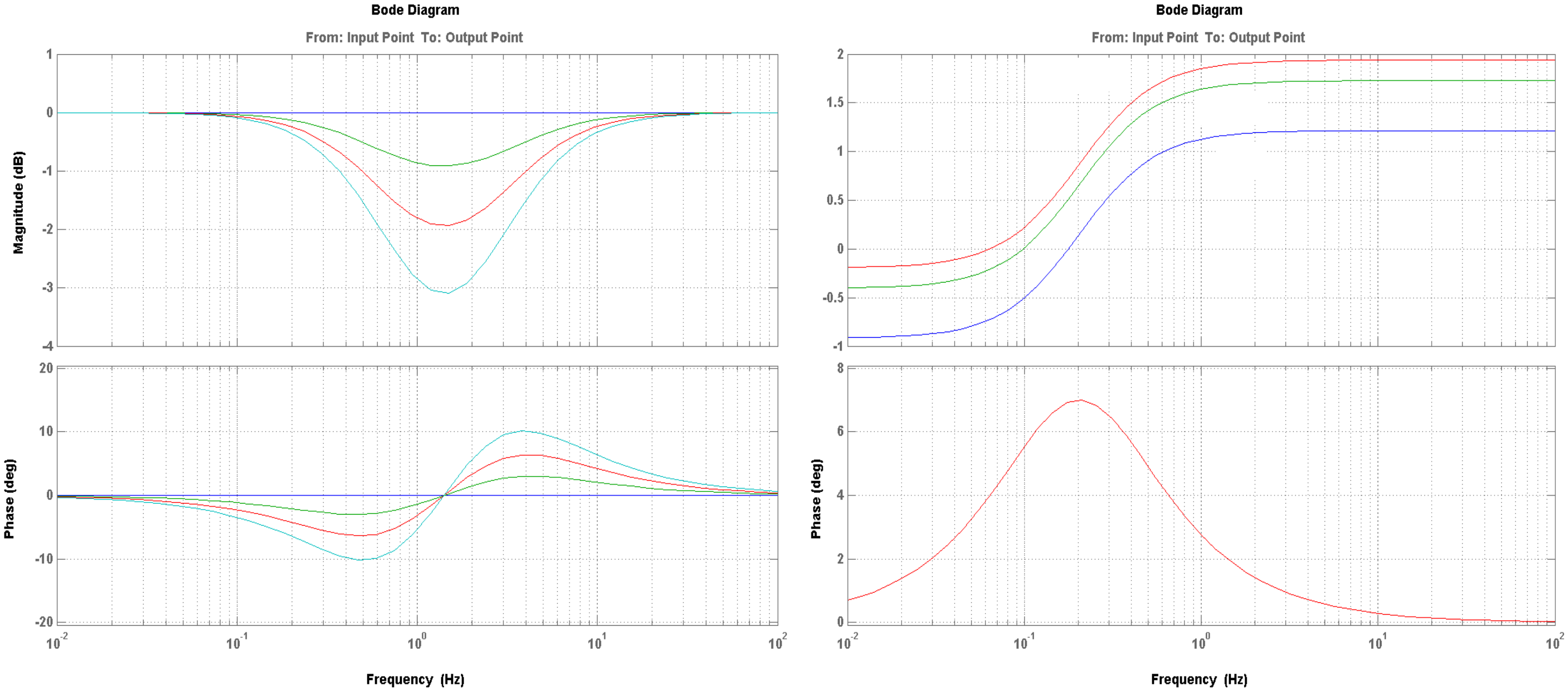




Local Interventions on Assist through Shaping Functions

Option 1: Torque Shaping devoted to reduction of ration Gmax/Go

Option 2: Torque Shaping devoted to phase-lead at low frequency



Other Proposed Assist Functions

Alternative Self Centering

It applies a torque based on measured steering angle and rate looking at the peculiar signs of these objects if and only if:

- *Measured Driving Torque,*
- *Estimated Reaction Force from the road* **are lower than prescribed thresholds**

and

- *Measured Steering Angle* **is larger than a prescribed deadband**

Leading idea:

Estimation of reaction Force from the road is possible using the available information of the torque commanded to the motor at previous step **inside a fixed gains Kalman observer**

Longitudinal Acceleration Feedback

The longitudinal acceleration feedback is aimed to correct the steer assistance in the cases of cornering manoeuvres in power-on and power-off, to make the steering system feeling uniform, independently from the vehicle acceleration, and to improve the vehicle stability in braking.

Leading idea:

The assist torque contribution is then determined **by applying a scaling factor**, depending on the longitudinal acceleration estimation, **to the boost torque**

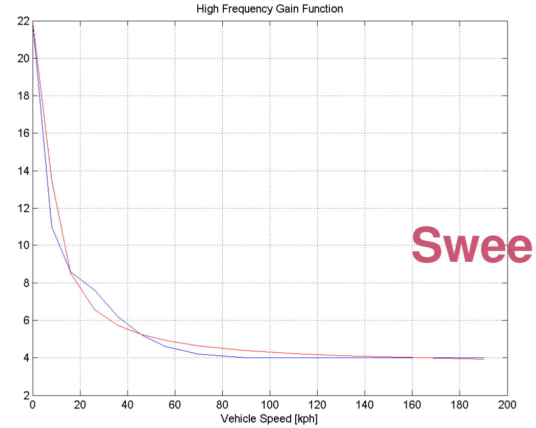
Inertia Compensation

The module aims to eliminate the braking effect for the assist torque related to rotor acceleration

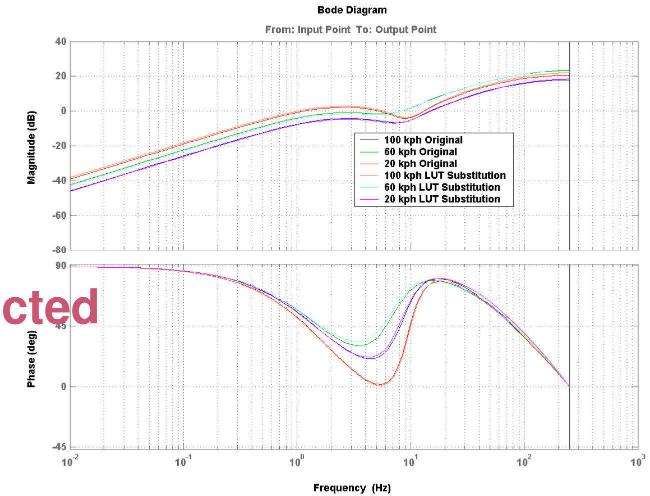
Sensitivity analysis: Method

Criterion

The number of control parameters has been reduced by about a factor 3 to permit easier analysis



Assistance is slightly affected



Sweep and IQS are slightly affected

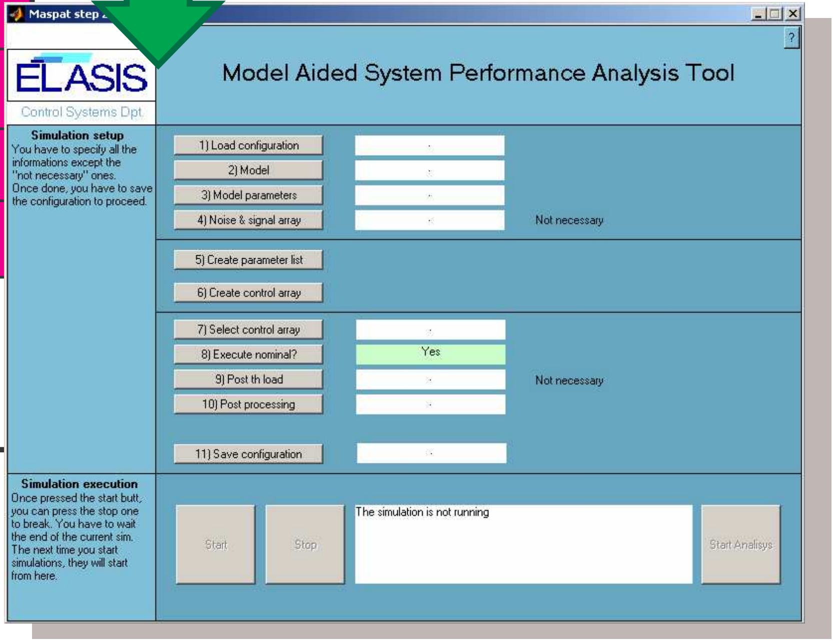
Current Control Performance	Reduced Control Performance
Torque Deadband in Straight Path (ICE): 8.4	**Torque Deadband in Straight Path (ICE): 8.4**
Handwheel Control Graduality (IPC): 5.2	**Handwheel Control Graduality (IPC): 5.2**
Handwheel Torque Graduality (IPS): 7.3	**Handwheel Torque Graduality (IPS): 7.3**
Center Feel (IVU): 6.8	**Center Feel (IVU): 6.5**
Steering Torque in Parking Manoeuvre (ISP): 5.8	**Steering Torque in Parking Manoeuvre (ISP): 6.0**
Handwheel Oscillations after Corner. Man. (IPV) : 8.4	**Handwheel Oscillations after Corner. Man. (IPV) : 8.4**
Handwheel Align. Velocity after Corner. Man. (IVR) : 5.5	**Handwheel Align. Velocity after Corner. Man. (IVR) : 5.6**
Handwheel Elasticity (IEL): 6.5	**Handwheel Elasticity (IEL): 6.3**
Response Precision (IPZ): 6.6	**Response Precision (IPZ): 6.6**
Sincerity Feeling (ISS): 7.7	**Sincerity Feeling (ISS): 7.5**
Steering Quality Index (IQS): 7.7	**Steering Quality Index (IQS): 7.5**

METHOD VALIDATED

Sensitivity analysis: Mechanisation

The correlation between **quality indices**, **control parameters** and test **manoeuvres**, permits the planning of a sort of “MonteCarlo” simulation campaign to verify the influence on performances of each parameter (in the reduced control system) and the **potential improvements obtainable without changes of the state-of-art control structure**

	Sincerity Feel	**Response Precision**	**Parking Effort**	**Steer Release**	**Syntesis Eval**
CORE ALGO	🟪	🟪	🟪	🟨	🟪
TORQ DAMP	🟪	🟪	🟨	🟨	🟪
YAW DAMP	🟨	🟨	🟨	🟪	🟪
SELF CENT	🟪	🟨	🟪	🟪	🟪
STAB CON	🟪	🟪	🟪	🟪	🟪
REF SIM	Sin 60 kph Pad R,L 3 runs	Sin120 kph 1 Run	Park Cycles 0 & 5 kph 2 Runs	Step Steer 100 kph 6 Runs	20° Sweep 120 kph 1 Run



Simulation setup
You have to specify all the informations except the "not necessary" ones. Once done, you have to save the configuration to proceed.

1) Load configuration
2) Model
3) Model parameters
4) Noise & signal array — Not necessary
5) Create parameter list
6) Create control array
7) Select control array
8) Execute nominal? — Yes
9) Post th load — Not necessary
10) Post processing
11) Save configuration

Simulation execution
Once pressed the start butt, you can press the stop one to break. You have to wait the end of the current sim. The next time you start simulations, they will start from here.

The simulation is not running

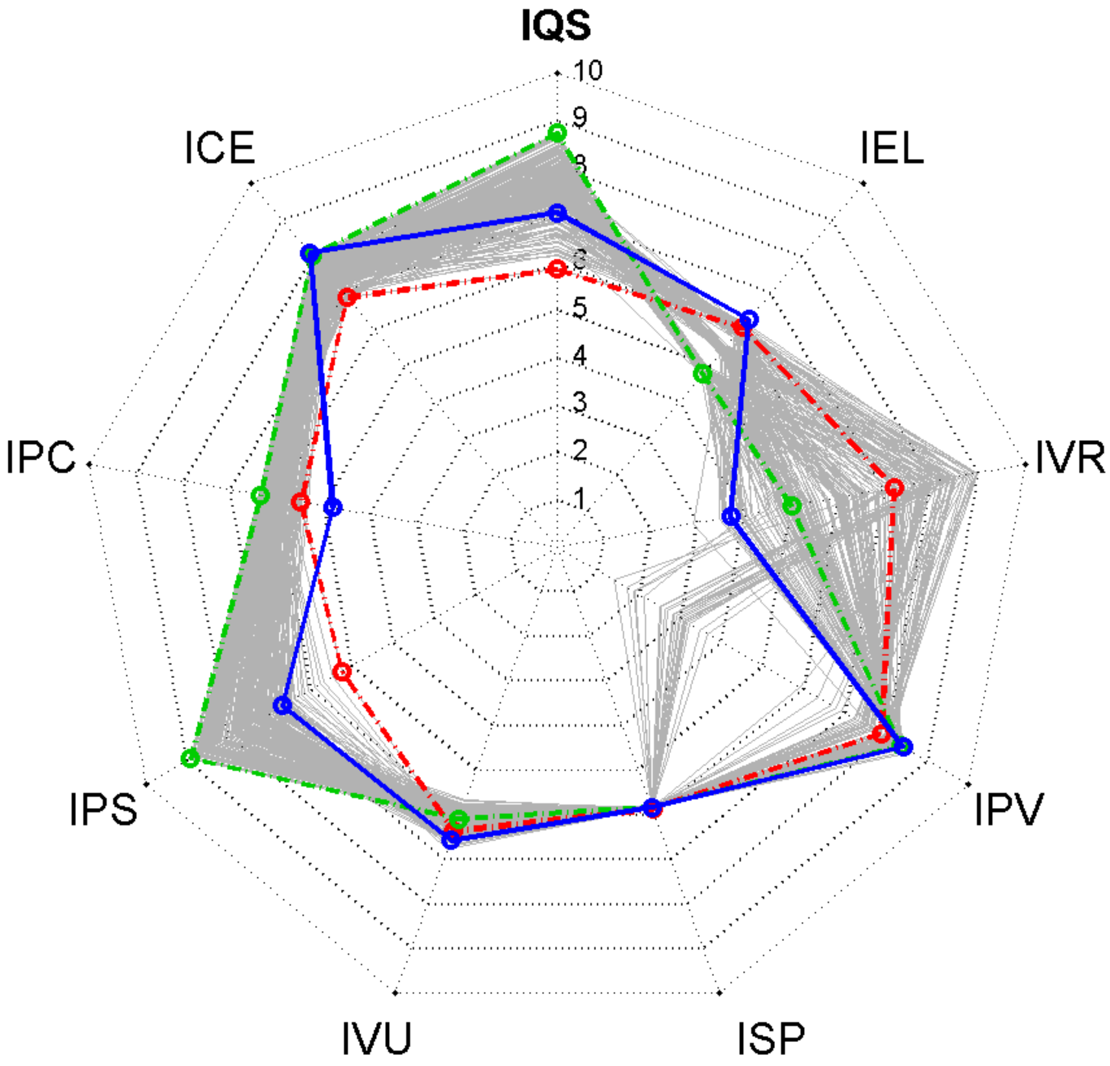
A SW tool has been designed and realised for the **automatic execution and analysis of a large number of simulations**

Sensitivity Analysis: Synthesis of Results

The works has been executed in two steps

1) The first step has been devoted to **define the influence of single parameters on the performances**.
   Ten parameters having the largest influence have been selected

2) The second step has considered the effect of the **contemporary variation of parameters belonging to several SW modules**. The combination giving the most promising improvements has been proved in the vehicle during preliminary and final test sessions



Sensitivity analysis: Impact on IQS

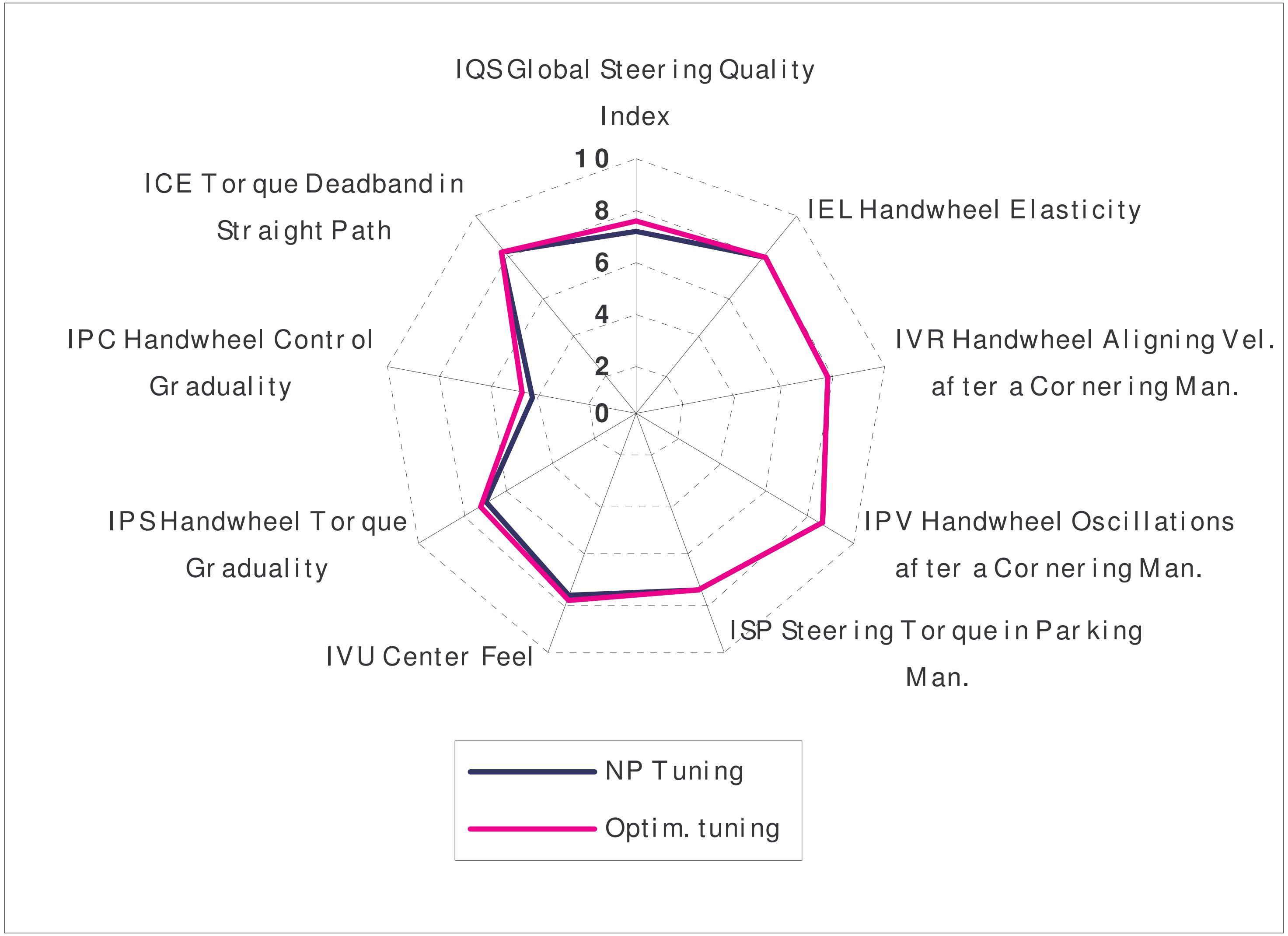
Calibration “168” (optimal Sweep)

Improvement of the torque graduality in the bending manoeuvres with medium/narrow radius

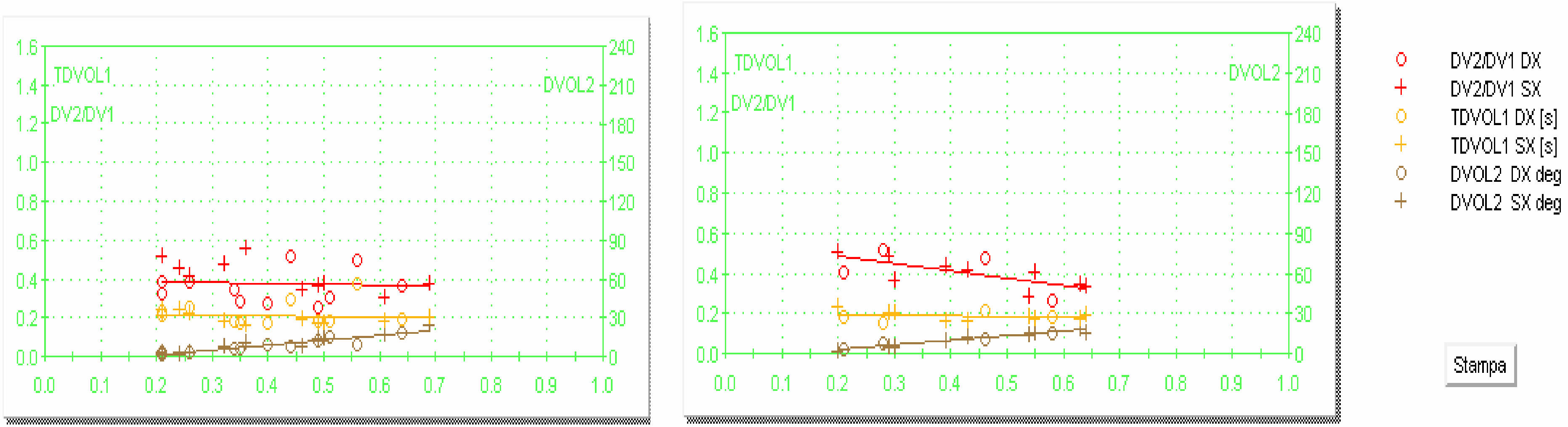
Better elasticity (torque graduality for small angular variations)

Smoother but not braked centering

Nardò (LE)
November 2005



Sensitivity analysis: Impact on step steer and release



mTDVOL1 [s/g] = **- 0.017**
qTDVOL1 [s] = 0.208

mDV2/DV1 [1/g] = **- 0.059**
qDV2/DV1 = 0.378

mDVOL2 [º/g] = **37.75**
qDVOL2 [º] = 9.01

mTDVOL1 [s/g] = **- 0.012**
qTDVOL1 [s] = 0.185

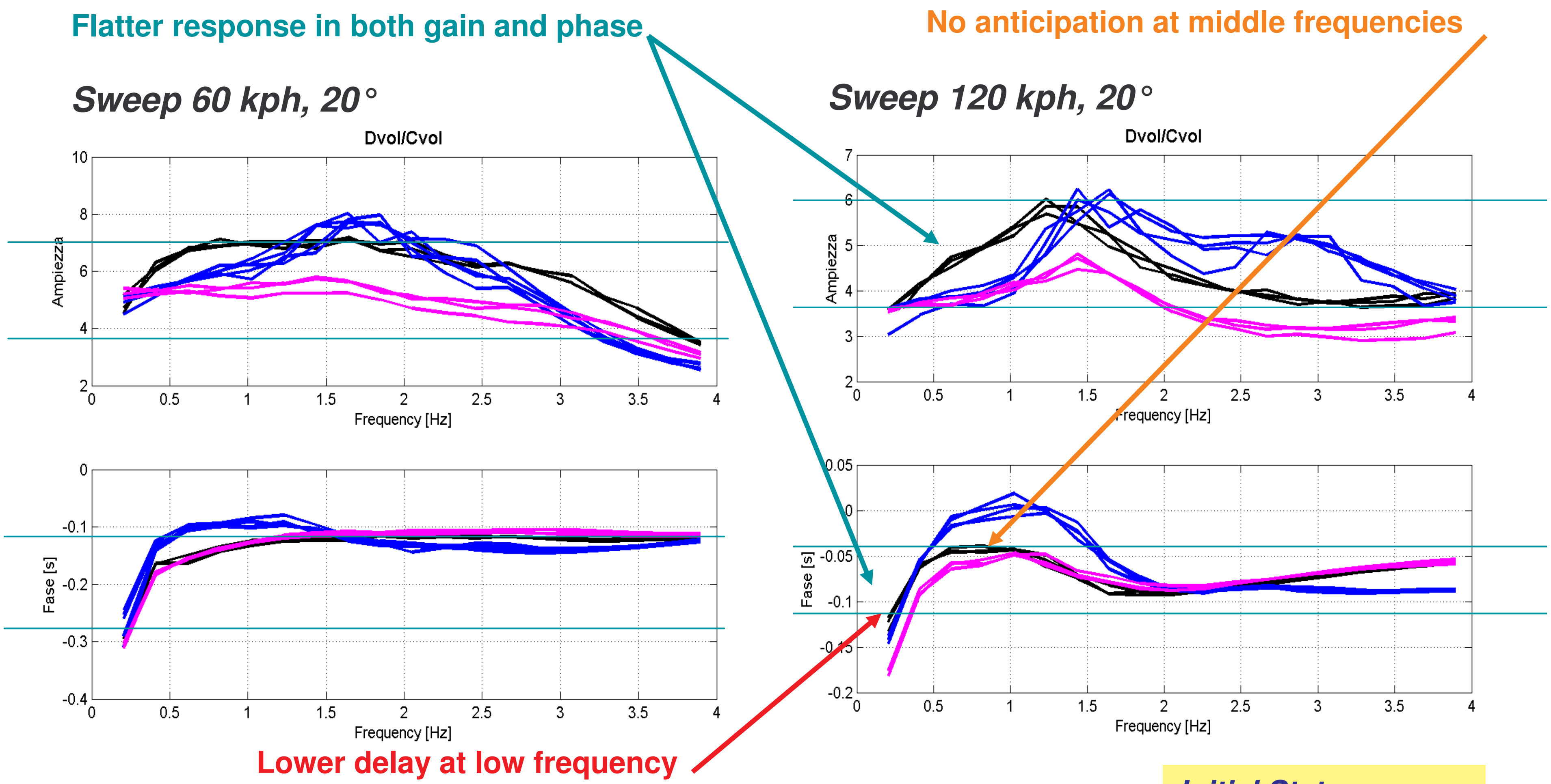
mDV2/DV1 [1/g] = **- 0.379**
qDV2/DV1 = 0.410

mDVOL2 [º/g] = **33.93**
qDVOL2 [º] = 9.49

Nardò (LE)
November 2005

NOTE: mDVOL2 (-10%), mDVOL2/DVOL1 (-0.379 instead that -0.059) and qTDVOL1 (-11%). In consideration that qDVOL2 is affected by a negligible increment (+5%) these parameters gives the indication of a return more damped and faster in the same time.

Final Results on the Track: Sweep Manoeuvres



Flatter response in both gain and phase

No anticipation at middle frequencies

Sweep 60 kph, 20°

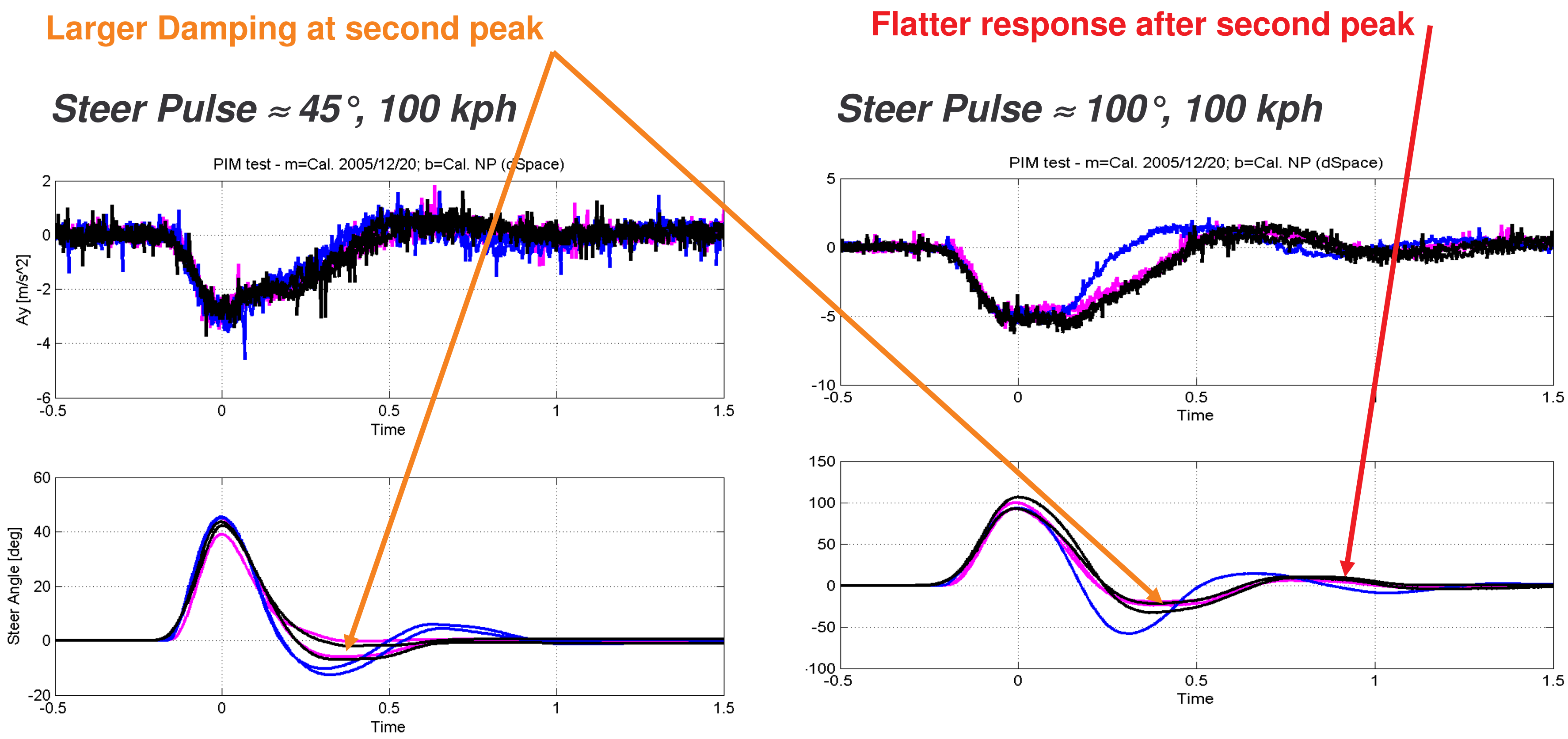
Sweep 120 kph, 20°

Lower delay at low frequency

Initial Status
Intermediate Status
Final Status

Balocco (VC)
December 2005

Final Results on the Track: Steer Pulses


Larger Damping at second peak

Flatter response after second peak

Steer Pulse ≈ 45°, 100 kph

Steer Pulse ≈ 100°, 100 kph

Initial Status
Intermediate Status
Final Status

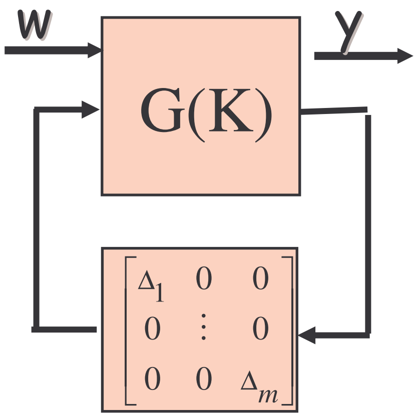
Balocco (VC)
December 2005

Theoretical Background

- Methodological approach analysing **performance and robustness** contemporary
- **“structured” uncertainty** model representation is preferred, because less conservative
- After the individuation of the parameters set having the largest influence on the system performance, relevant to each calibration, this analysis may be useful to indicate **margins for performance improvements** when they vary contemporary

Theorem: Consider the structured perturbation:

$$\Pi_s^p = \left\{ \Delta^p = diag[\Delta \ , \Delta_o] : \Delta \in \Pi_s , \| \Delta_o \|_\infty \le 1 \ \right\}$$

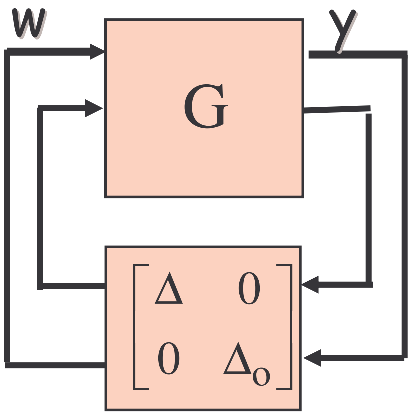


The loop possesses robust performance if only if:

- G (augmented controlled plant) is stable
- $\mu_{\Pi_s^p} [G(\omega)] < 1 \quad \forall \omega$

Robust Performance

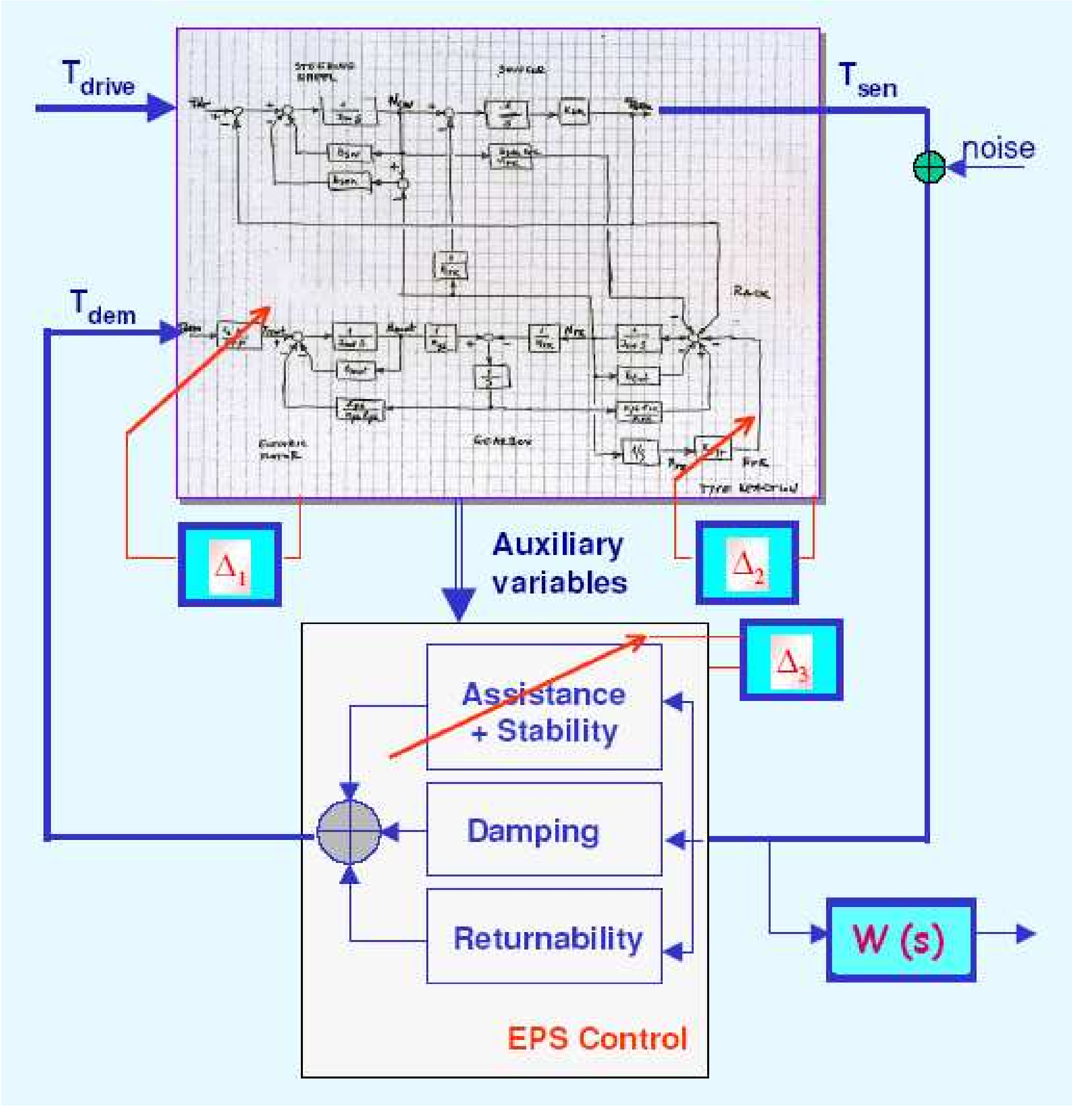
Robust Stability for 'augmented' perturbation



$\Delta \in \Pi_s$

$\| \Delta_o \| \le 1$

Building the Augmented Controlled Plant

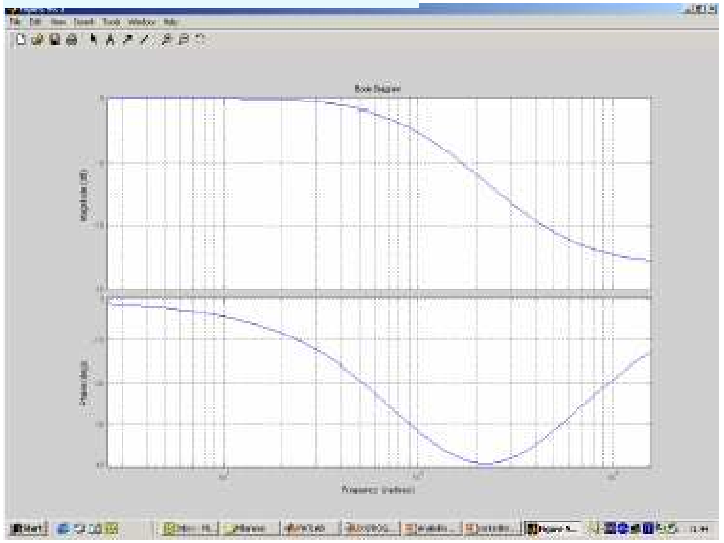


Structured Uncertainties

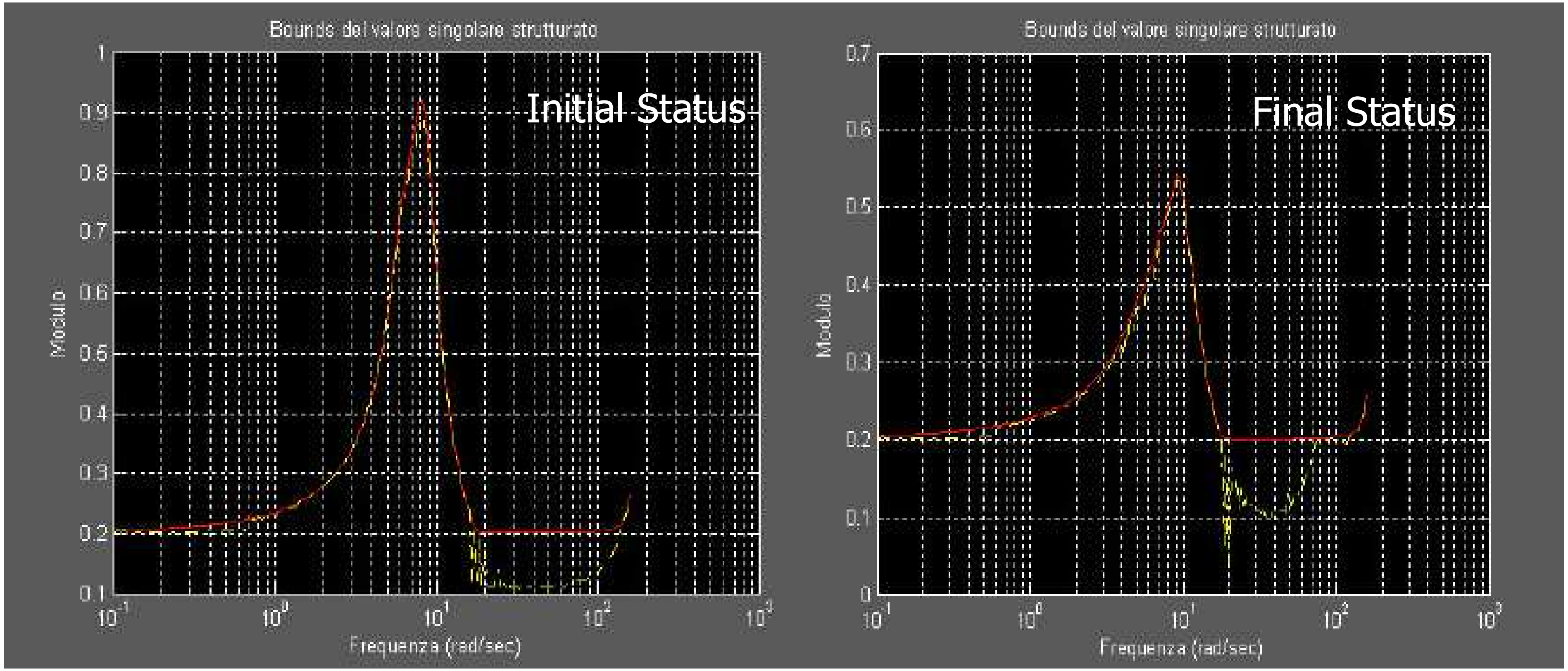
$\lvert \delta_1 \rvert \leq 0.2$	(20 %)	On the motor bandwidth
$\lvert \delta_2 \rvert \leq 0.2$	(20 %)	On the tyre reaction force
$\lvert \delta_3 \rvert \leq 0.1$	(10 %)	On the Assist torque

Weight Functions

$W_5^{-1}(s) = 1.3$	On the Sensitivity Tsen/noise
$W_4^{-1}(s) = \dfrac{0.2222 \cdot (s + 472.5)}{s + 105}$	On the Comp. Sens. Tsen/Tdr



μ Analysis without noise limitation constraint



pkupper = 0.9201

pklow = 0.8926

omegapklow = 8.1954

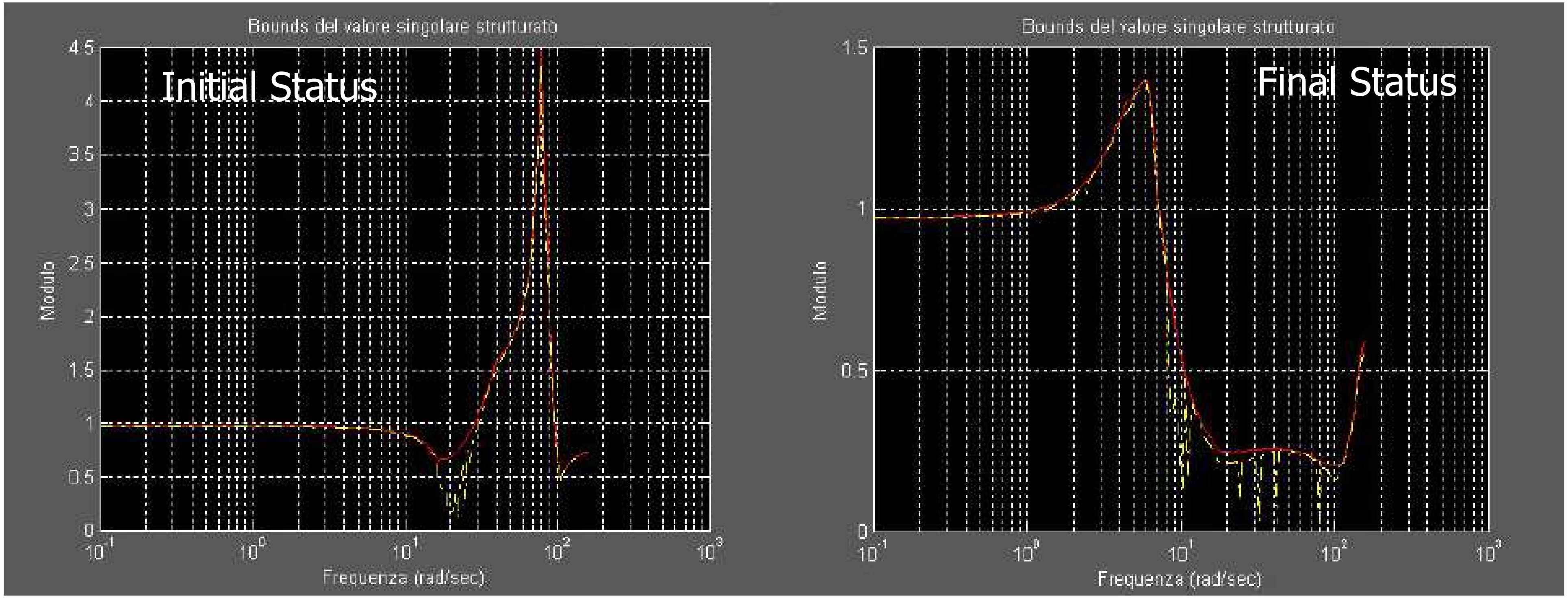
Proposed modifications increases the stability margin mainly due to the Inertia Compensation block

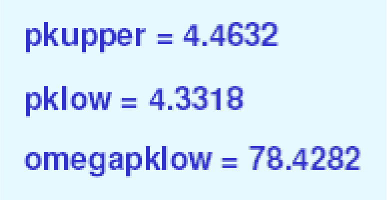
pkupper = 0.5404

pklow = 0.5357

omegapklow = 9.1582

μ Analysis with noise limitation constraint





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pkupper = 4.4632

pklow = 4.3318

omegapklow = 78.4282
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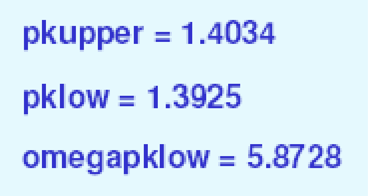
New control implies very larger noise rejection at high frequency (less vibrations) at the cost of a possible slight degradation at low frequency



```
pkupper = 1.4034

pklow = 1.3925

omegapklow = 5.8728
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