VEHICLE SENSITIVITY TO TYRE CHARACTERISTICS BOTH IN OPEN AND CLOSED LOOP MANOEUVRES

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1 - Introduction

The vehicle sensitivity to Tyre characteristics is strongly dependant on the working conditions, i.e. the manoeuvre: this influence can be investigated with suitable open-loop manoeuvres. Moreover, in case of closed-loop manoeuvres (concept closer to the way of driving of “common” drivers) the driving style can strongly influence the sensitivity to tyre differences as well. Herewith a detailed virtual investigation with ADAMS/Car with Driver Lite (included in ADAMS/Car 10.0) is presented. Firstly, a detailed investigation about a wide range of Open-Loop manoeuvres allows to detect in an “analytic” way the conditions where the vehicle is most sensitive to the tyres; secondly, some Closed-Loop manoeuvres clearly show how the driving style can strongly modify the sensitivity to the tyre characteristics as well, with results easy to explain with the basis of the conclusions of the “analytic” open-loop analysis.

2 - Definition of virtual Design Of Experiments - Manoeuvres and Tyre variations

A virtual Design of Experiments (varying both the Manoeuvre and the Tyre Characteristics) has been defined on the basis of a full-validated vehicle-tyre model. The tyre was characterised both for Steady-State and Transient phase following Pirelli procedure. Some examples of validation of full vehicle behaviour and of the Tyre transient characterisation are reported in Fig. 2.1 e 2.2.

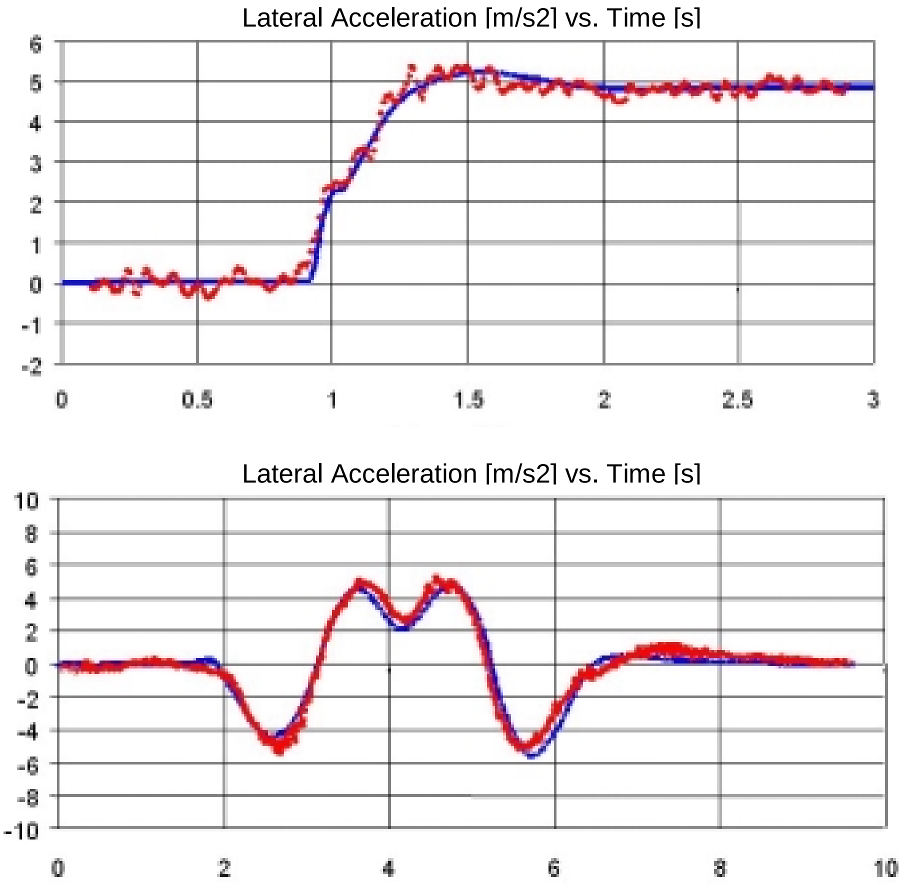


Fig. 2.1 Validation of Full Vehicle Behaviour

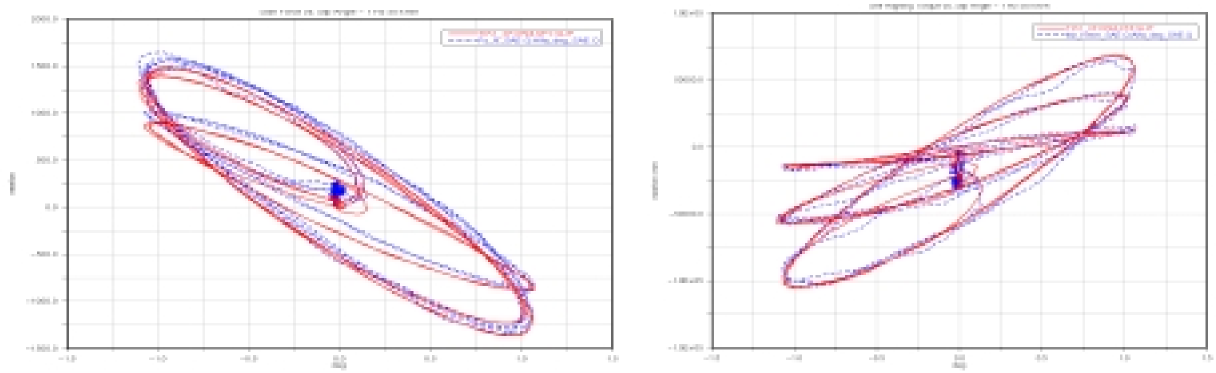


Fig. **2.2** Validation of Tyre Transient Behaviour

The definition of the virtual Design Of Experiments has deeply exploited the opportunity of defining Manoeuvres and Tyre Variations just adjusting the Driver Control Files and Tyre Property Files, without modifying the Vehicle model. In this way, the manoeuvres and the Tyre Variation defined within this activity are immediately suitable for any model in ADAMS/Car environment.

2.1 Definition of Manoeuvres

All the manoeuvres have been implemented with Driver/Lite defining the suitable .dcf Driver Control Files. The following ones have been defined, in order to cover a wide range of working conditions including both Open-Loop manoeuvres (concept closer to “expert” driving or tests on special tracks) and Closed Loop manoeuvres (concept closer to the way of driving of “common” drivers):

a) Open-Loop

- Steering Wheel Step: this manoeuvre concerns both the Transient behaviour (very quick Steering Step) and the Steady-State one.

- Sinusoidal Input: this manoeuvre allows to get a first feeling of the influence of the frequency of Steering Wheel Sinusoidal Input on the Vehicle response

- Frequency Response – Sinusoidal Sweep: this manoeuvre allows a complete investigation of Vehicle response in frequency domain

b) Closed-Loop

- ISO Double Lane Change: transient manoeuvre, where the Driving Style is strongly concerned in the actual time-history of the Steering Wheel Angle.

- Constant Radius Steering Pad: steady-state manoeuvre, where the Driving Style is not actually concerned.

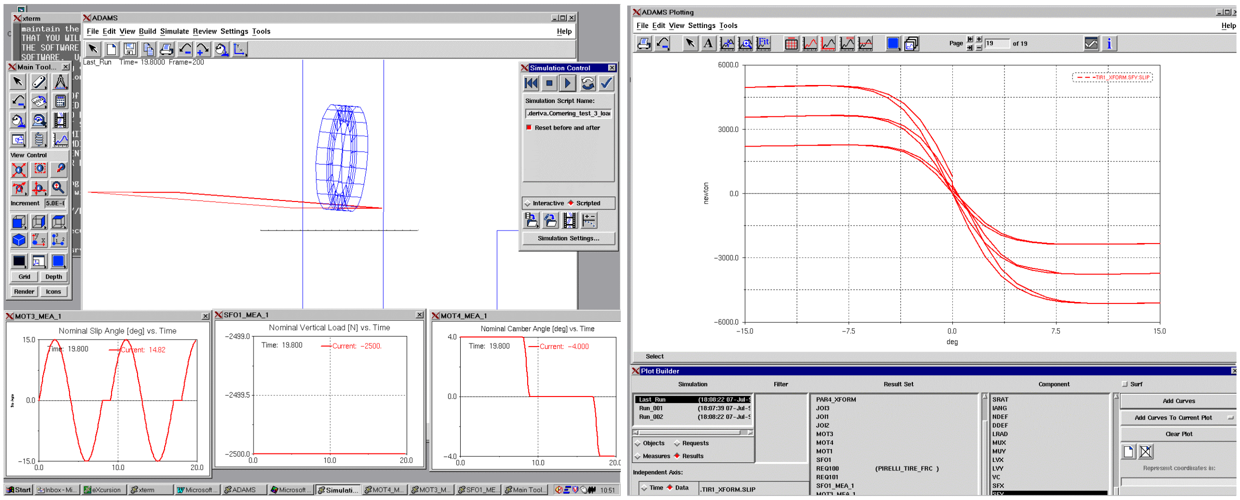
In order to rank the Driving Style with only one parameter, the best way has revealed adjusting the Lateral Preview Time parameter of Driver/Lite, without accessing to “Human” controls of ADAMS/Driver.
Lateral Preview Time (LPT) represents the time the driver knows in advance the path: with higher values, the approach to the task might be more “nervous”: on the other side, higher values of LPT makes the trajectory smoother, but with risk of hitting the cones delimiting the trajectory.

2.2 Definition of Virtual tyre variations with scaling factors

All the tyre variations have been gained adjusting the scaling factors with respect to the reference tyre, always represented with Magic Formula 5.0. The investigation has focused on five parameters, with ranges defined in order to actually enable to detect significant differences in the vehicle behaviour.

Scaling Factor	Scaling factor in Tyre Property File	Physical Meaning	Investigated Range
λKy	LKY	Cornering Stiffness	± 15 %
$\lambda\sigma\alpha$	LSGAL	Relaxation Length for Lateral Force	± 100%
$\lambda\mu y$	LMUY	Peak Friction Coeff.	± 50 %
$\lambda\gamma y$	LGAY	Camber Force Stiffness	± 50 %
λt	LTR	Pneumatic Trail	± 50 %

The effect of these adjustments of the Scaling Factors has been always checked with the Pirelli Virtual Test Rig:



maintain the THAT YOU WILL THE SOFTWARE SOFTWARE.

Last_Run Time= 19.8000 Frame=200

Simulation Script Name: .deriva.Cornering_test_3_loa

Reset before and after

Time: 19.800 Current: 14.82

Time: 19.800 Current: -2500.

Time: 19.800 Current: -4.000

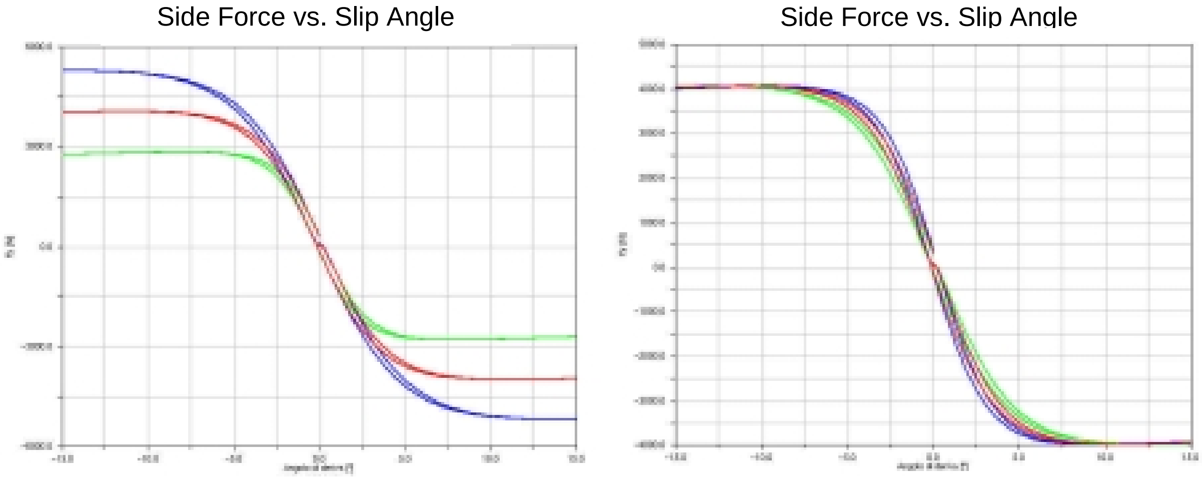
Last_Run (18:08:22 07-Jul-
Run_001 (18:07:39 07-Jul-
Run_002 (18:08:22 07-Jul-

PAR4_XFORM
JOI3
JOI1
JOI2
MOT3
MOT4
MOT1
SFO1
REQ100 (PIRELLI_TIRE_FRC)
REQ101
SFO1_MEA_1
MOT3_MEA_1

SRAT
IANG
NDEF
DDEF
LRAD
MUX
MUY
LVX
LVY
VC
SFX
SFY

Independent Axis: Time Data .TIR1_XFORM.SLIP

Figure 2.2.1: Virtual Cornering Test for the visual check of Tyre Behaviour


Side Force vs. Slip Angle

Side Force vs. Slip Angle

Figure 2.2.2: Effect of Scaling respectively Side Friction and Cornering Stiffness on Tyre Behaviour (Side Force vs. Slip Angle)

3 Sensitivity Analysis to detect the vehicle sensitivity to tyre characteristics

3.1 Open Loop manoeuvres

a) Steering Wheel Step

Steering Wheel Step manoeuvre allows to investigate both Steady-State and Transient aspects of Vehicle Response, as it consists of a very quick ramp and a few seconds of constant Steering Angle. The following investigation will be based in this way (Fig. 3.1.1) on the Steady State value of Lateral Acceleration (Ay) and the time delay between 50% of the Steering Wheel Angle and 50% of Steady State Ay.

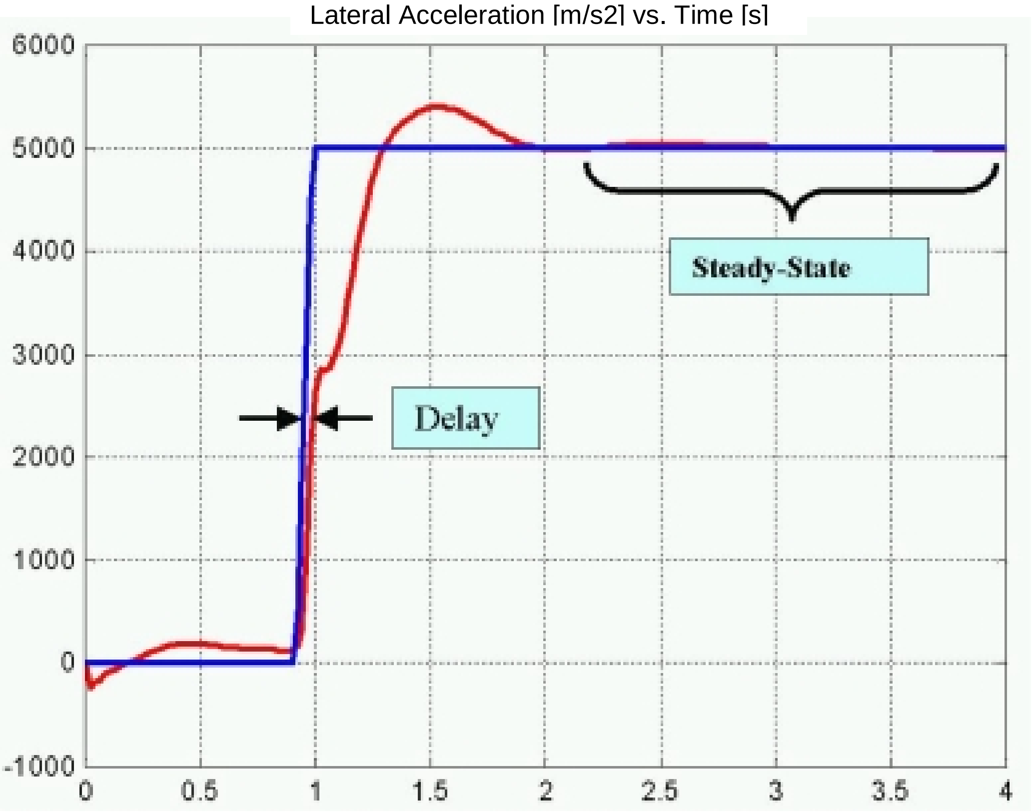


Fig.3.1.1 Main outputs of Steering Wheel Step

Fig. 3.1.2.and 3.1.3 represent the percentage influence of the Tyre Characteristics on the main vehicle outputs referring to the tyre variations reported in Tab. 3.1.1 (for a Steering Wheel Step of 40° at 100 km/h).

	Percentage Variations				
	Ky	**s0**	**µy**	**γy**	**t**
++	15	100	50	50	50
+	10	50	30	30	30
	0	0	0	0	0
-	-10	-50	-30	-30	-30
--	-15	-100	-50	-50	-50

Tab 3.1.1. Summary of Tyre variations investigated

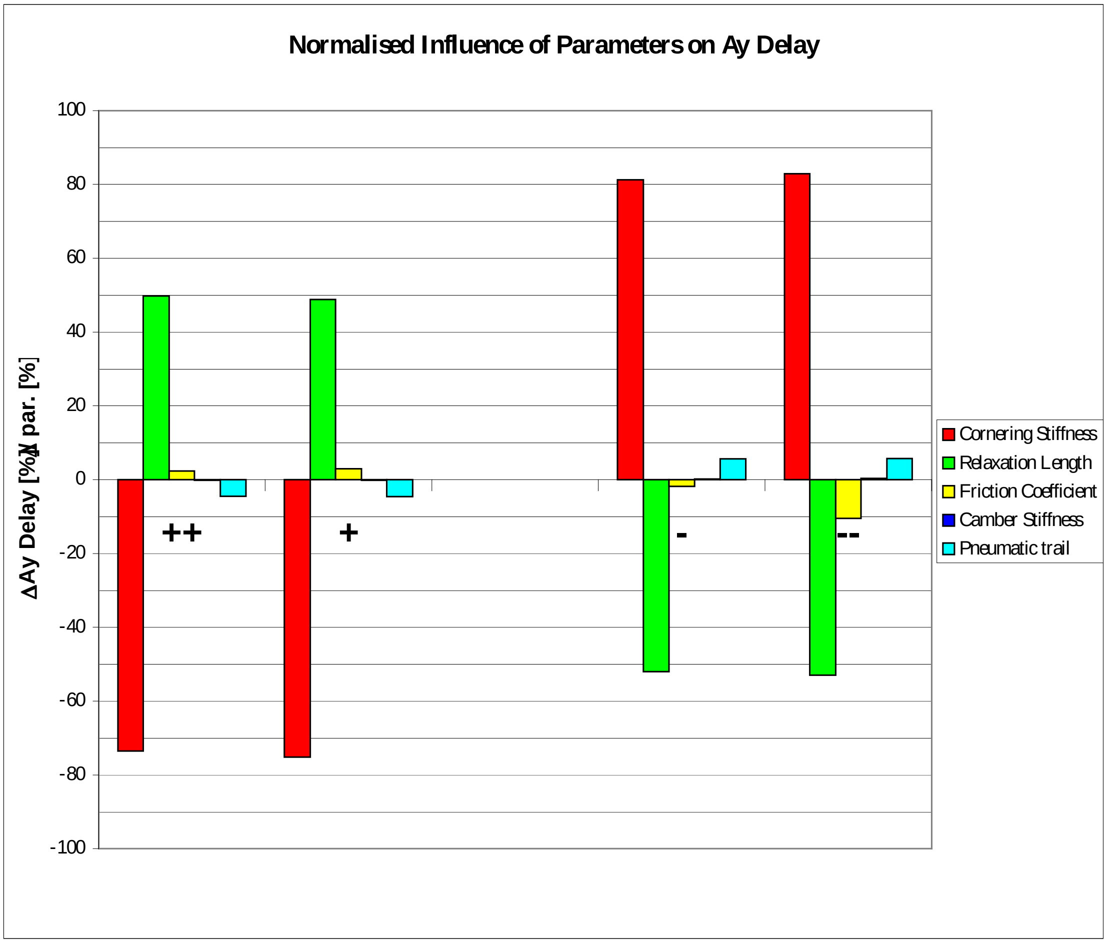


Fig. 3.1.2 Normalised Influence of Tyre Parameters on Ay delay.

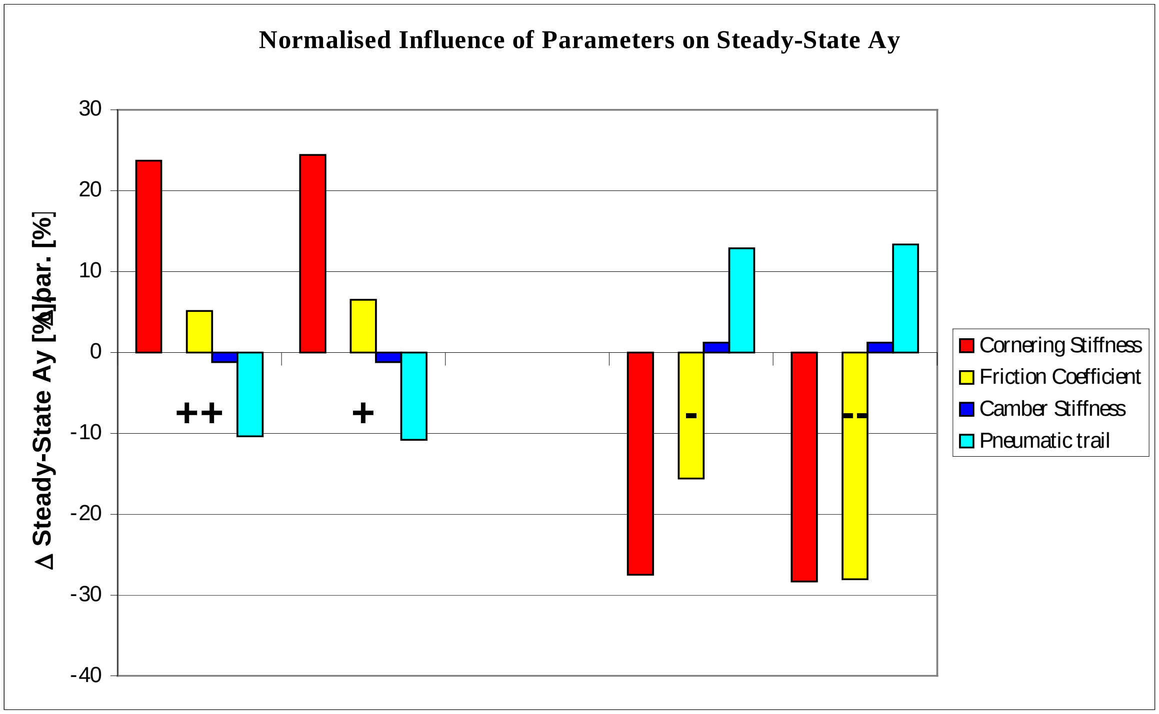


Fig.3.1.3 Normalised Influence of Tyre Parameters on Ay Steady-State

b) Sinusoidal Input

This manoeuvre allows to get a first feeling of the influence of the frequency of Steering Wheel Sinusoidal Input on the Vehicle response and the vehicle sensitivity to tyre characteristics (e.g. Fig. 3.1.4 and Fig. 3.1.5).

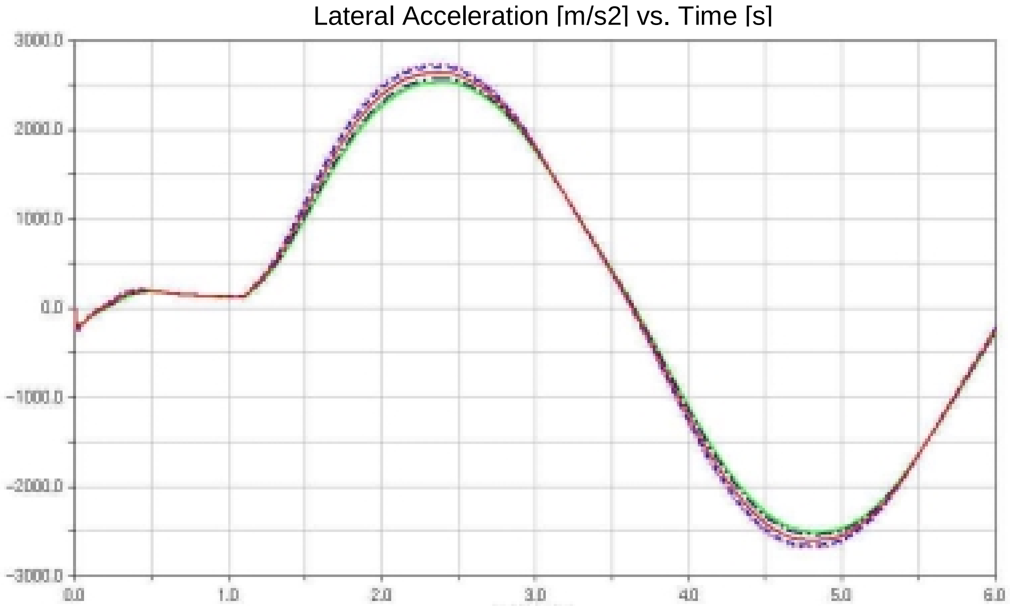


Fig. 3.1.4 Lateral Acceleration with 0.2 Hz Sinusoidal Input varying Cornering Stiffness (Red Line: Standard Tyre, Violet Ky +15%, Blue Ky +10%, Black Ky –10%, Green Ky –15%

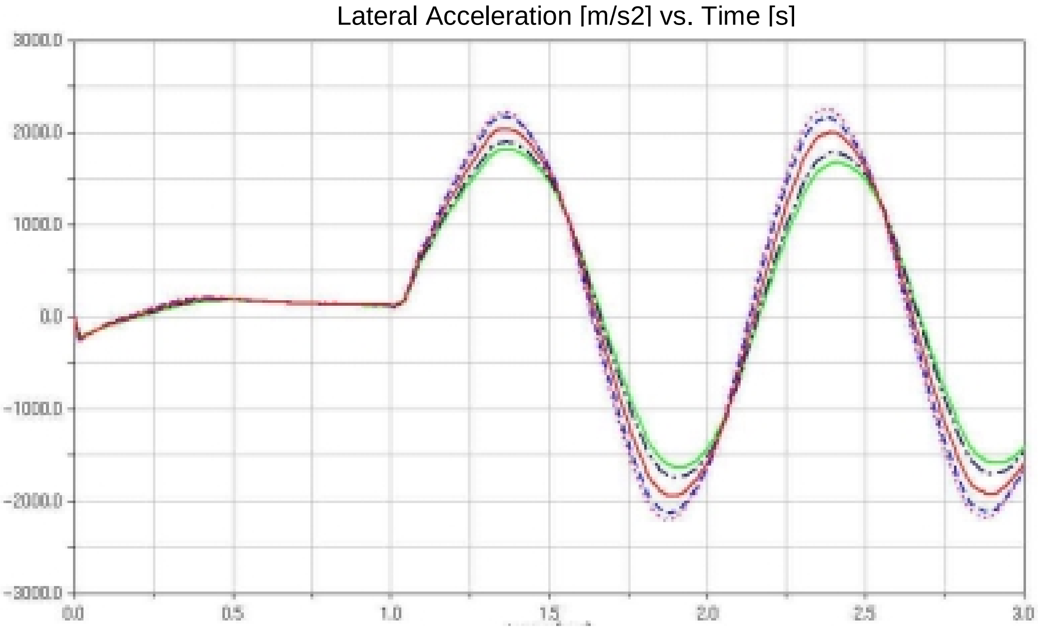


Fig. 3.1.5 Lateral Acceleration with 1 Hz Sinusoidal Input varying Cornering Stiffness (Red Line: Standard Tyre, Violet Ky +15%, Blue Ky +10%, Black Ky –10%, Green Ky –15%

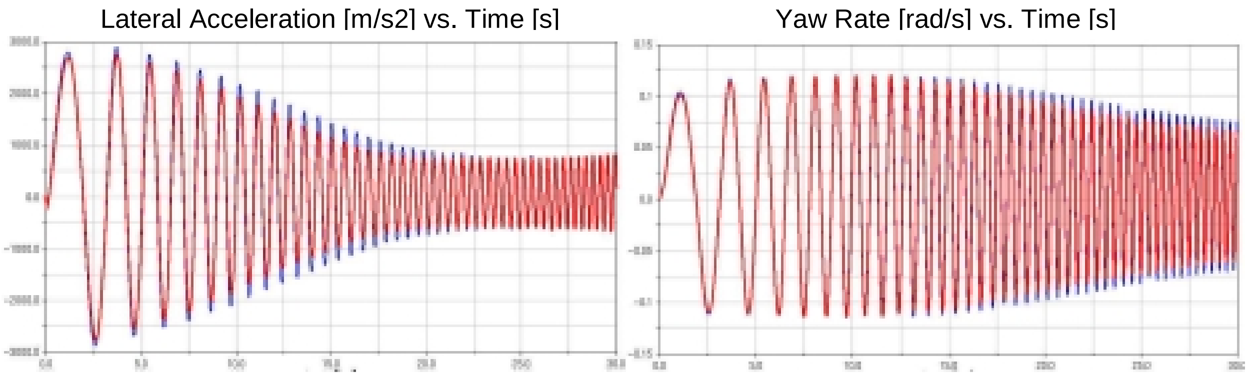
b) Frequency Response – Sinusoidal Sweep

A Sinusoidal Sweep is the best solution to get a complete investigation of Vehicle response and sensitivity in frequency domain. Fig. 3.1.6, for instance, shows a Steering Wheel Angle time history covering a frequency range up to 3 Hz with an amplitude of 20°.


Steering Wheel Angle [deg] vs. Time [s]

Fig. 3.1.6 Steering Wheel Angle Time History for a 20° Amplitude 0-3 Hz Frequency Sweep (duration 30 s)

Fig. 3.1.7 clearly shows how the sensitivity to Tyre Cornering Stiffness is strongly increased at intermediate frequencies.

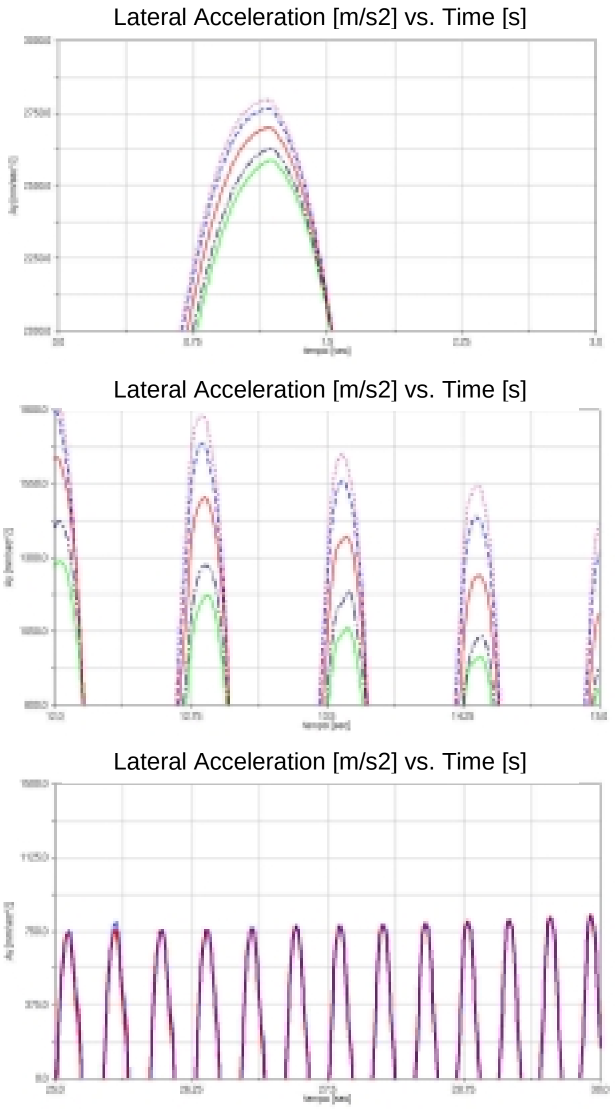

Lateral Acceleration [m/s2] vs. Time [s]

Yaw Rate [rad/s] vs. Time [s]

Fig. 3.1.7 Lateral Acceleration and Yaw Rate vs. Time for a Frequency Sweep – Red Line Standard Tyre, Blue Line +15% Ky Tyre

This first effect makes necessary to investigate with more detail the dependance of Vehicle sensitivity to Tyre Characteristics (in particular Cornering Stiffness) on Frequency as a key-point for understanding several aspects of Vehicle behaviour.

Fig. 3.1.8 Shows with more detail how the vehicle sensitivity to Tyre Cornering Stifness is stronger within 1.2-1.5 Hz and is nearly neglectable beyond 2 Hz.



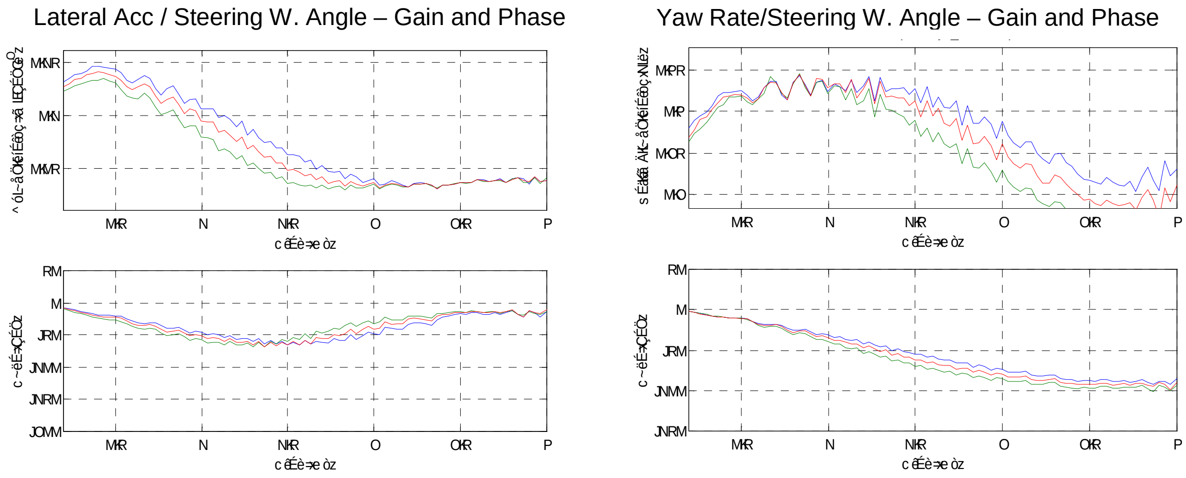
Lateral Acceleration [m/s2] vs. Time [s]

Lateral Acceleration [m/s2] vs. Time [s]

Lateral Acceleration [m/s2] vs. Time [s]

Fig. 3.1.8 Ay response for five tyres (Scaling Ky) in three Frequency Ranges (0-0.3 Hz, 1.2-1.5 Hz and 2.5-3 Hz)

The best analytic representation of Frequency response is of course the Gain/Phase of Lateral Acceleration and Yaw Rate as a function of Frequency. Fig. 3.1.9 and Fig. 3.1.10 shows respectly the effects of Cornering Stiffness and Relaxation Length variation:



Lateral Acc / Steering W. Angle – Gain and Phase

Yaw Rate/Steering W. Angle – Gain and Phase

Fig. 3.1.9 Lat. Acceleration and Yaw Rate Gain/Phase
(Red Line: Standard Tyre, Blue Ky +15%, Green Ky –15%), 100 km/h 20°

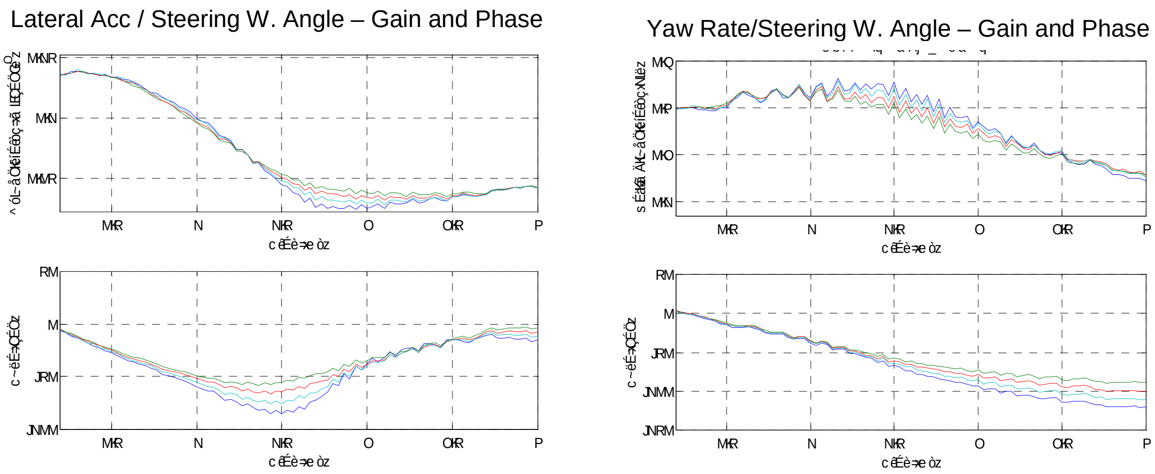


Fig. 3.1.10 Lat. Acceleration and Yaw Rate Gain/Phase
(Red Line: Standard Tyre, Blue S0 +100%, Light Blue S0 +50%, Green S0 –50%), 100 km/h 20°

The test speed has of course an influence on the aspect of the outputs, as shown in Fig. 3.1.11:

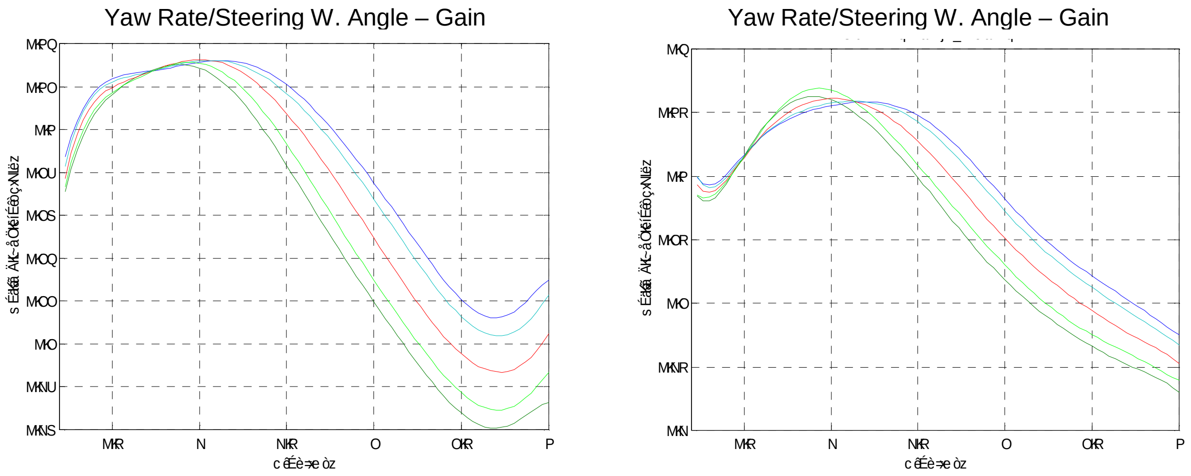


Fig. 3.1.11 Yaw Rate Response at 100 km/h (Left) and 120 km/h (Right) and 20° Steering Wheel Angle (Red Line: Standard Tyre, Light Blue Ky +10%, Blue +15%, Light Green Ky –10%, Green Ky –15%)

All these considerations can be quickly summarised in the Bar Charts of Fig 3.1.12 and 3.1.13, clearly showing the higher sensitivity of the vehicle response to tyre characteristics in an intermediate frequency range.

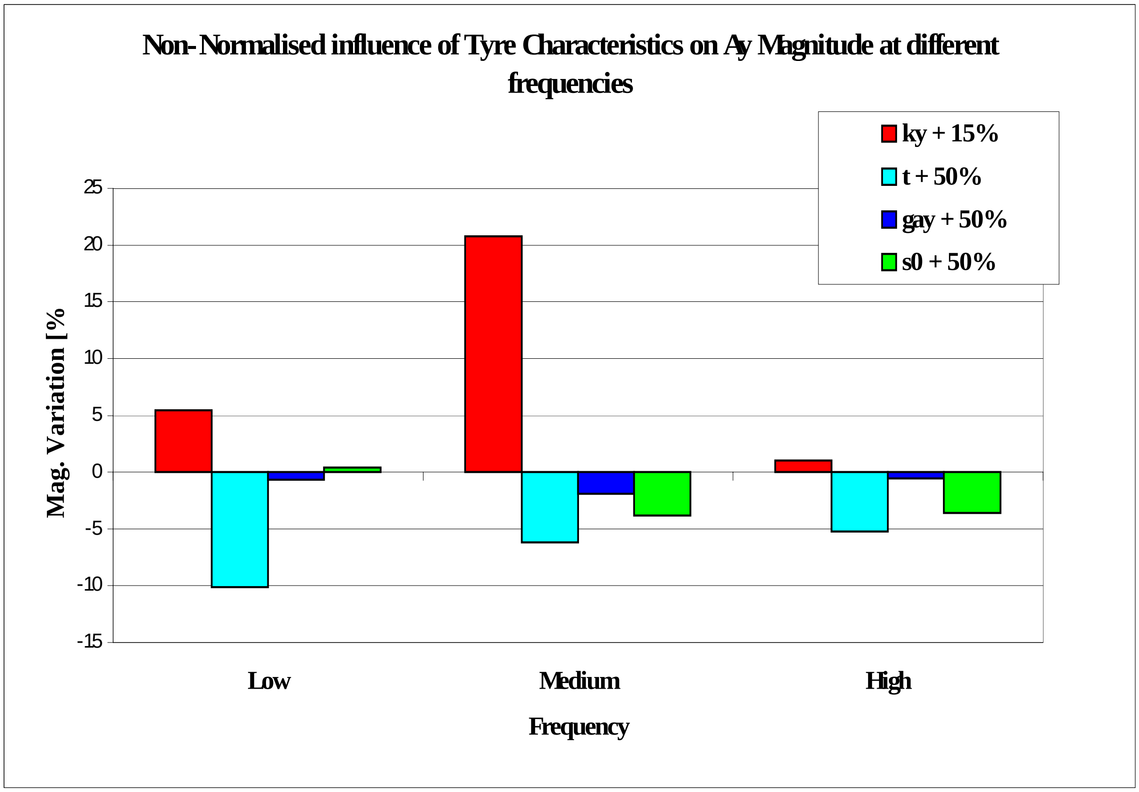


Fig. 3.1.12 Percentage Variations of Side Acceleration Magnitude in three frequency ranges (100 km/h, 20° Amplitude)

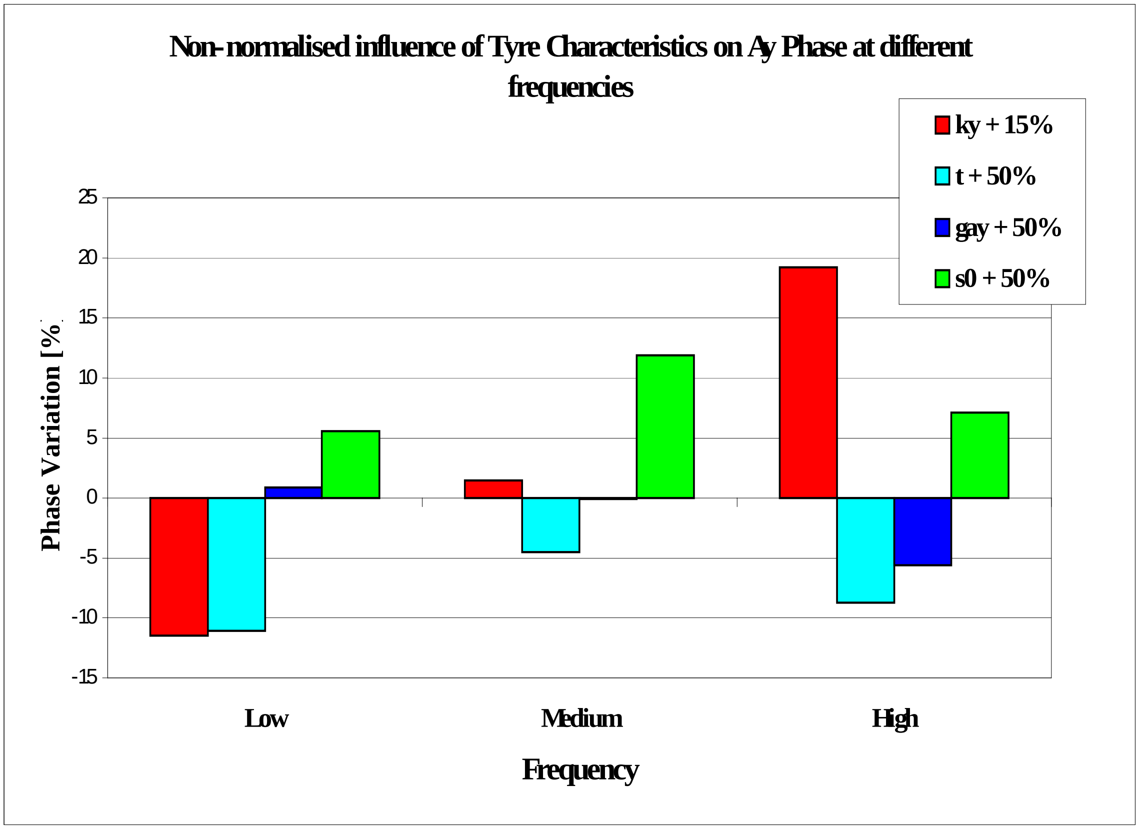


Fig. 3.1.13 Percentage Variations of Side Acceleration Phase in three frequency ranges (100 km/h, 20° Amplitude)

3.2 Closed Loop manoeuvres with Driver/Lite

Closed-Loop manoeuvres require of course a representation of the Driver with the opportunity of defining different Driving Style. In this way it is possible to investigate the influence of Driving Style on the sensitivity to tyre characteristics.
For this activity, Driver/Lite (included in ADAMS/Car 10.0) was exploited. Driver/Lite defines the driving style with one parameter called Lateral Preview Time (LPT), representing the time the Driver knows in advance the desired trajectory. In this way, low values of LPT make possible to represent "nervous" driver reactions and high values of LPT very "smoothing" driving styles. This allows also to get a satisfactory ranking of different driving styles adding only one parameter to the Design of Experiments. The working principle of Driver/Lite is showed in Fig. 3.2.1:

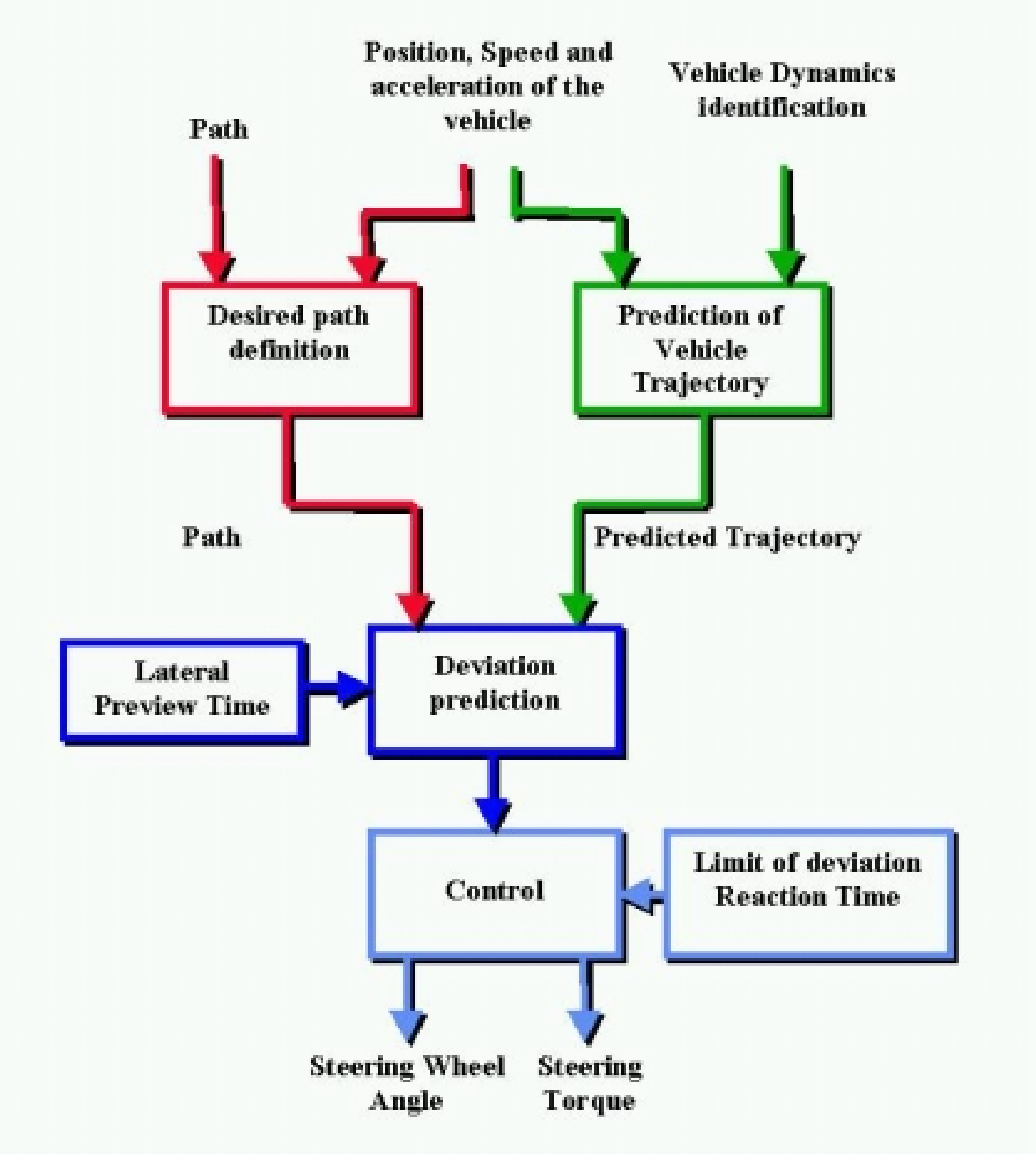


Fig.3.2.1 Driver/Lite working principle

a) ISO Double Lane Change

The influence of LPT can be clearly seen in a standard manoeuvre of ISO Double Lane Change. In order to concentrate only on the influence of Driving Style on the sensitivity to Tyre Characteristics, all the manoeuvres are taken into account even if they might lead to hitting some of the cones.

Fig.3.2.2 and Fig.3.2.3 report the Steering Wheel Angle vs. Time and the Vehicle Trajectory for different values of the Lateral Preview Time.

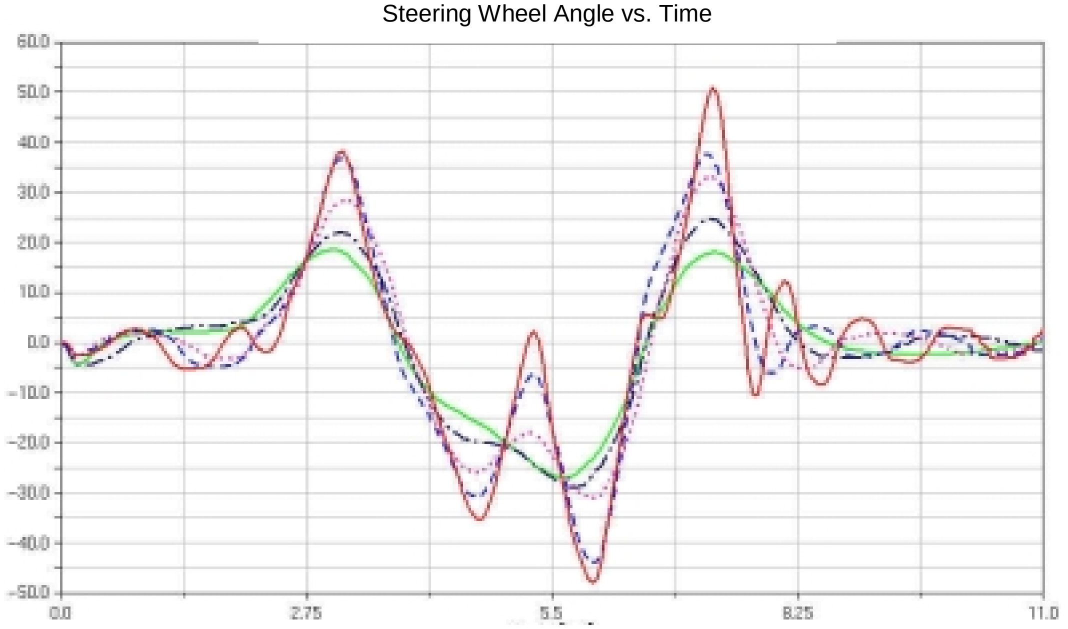

Steering Wheel Angle vs. Time

Fig. 3.2.2 Steering Wheel Angle vs. Time in a 70 km/h ISO Double Lane Change with Various Lateral Preview Times: Red Line LPT 0.1 s, Blue Line LPT 0.2 s, Violet Line LPT 0.4 s, Black Line LPT 0.6 s, Green Line LPT 0.8 s

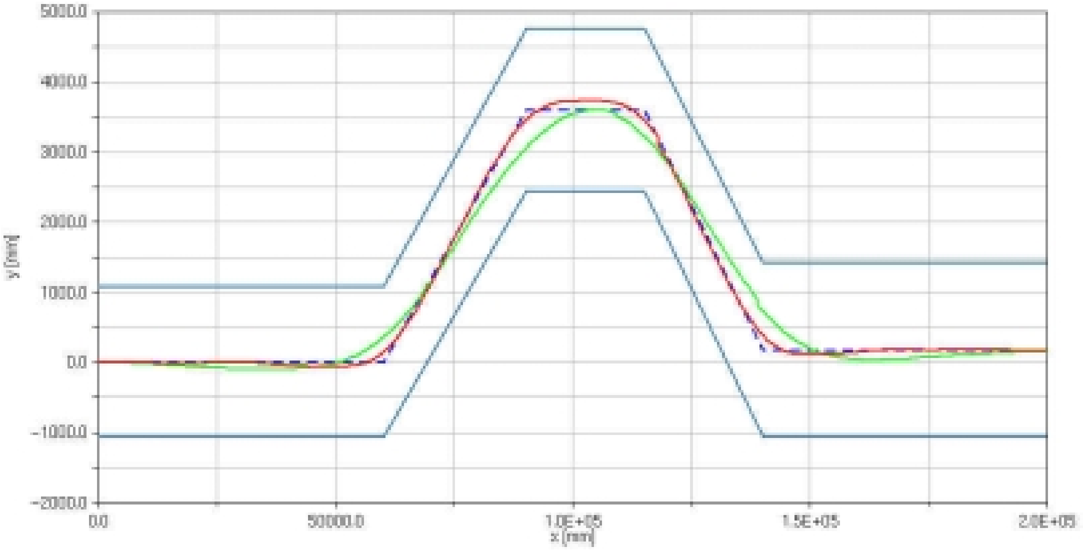


Fig.3.2.3 Vehicle Trajectory in a 70 km/h ISO Double Lane Change with 0.8 s LPT (Green Line) and 0.1 s LPT (Red Line)

The influence of LPT on Vehicle sensitivity to Tyre Characteristics can be clearly seen from Fig.3.2.4 and Fig.3.2.5: decreasing the value of LPT in fact strongly increases the sensitivity to Tyre Cornering Stiffness as the manoeuvre concerns higher frequencies.

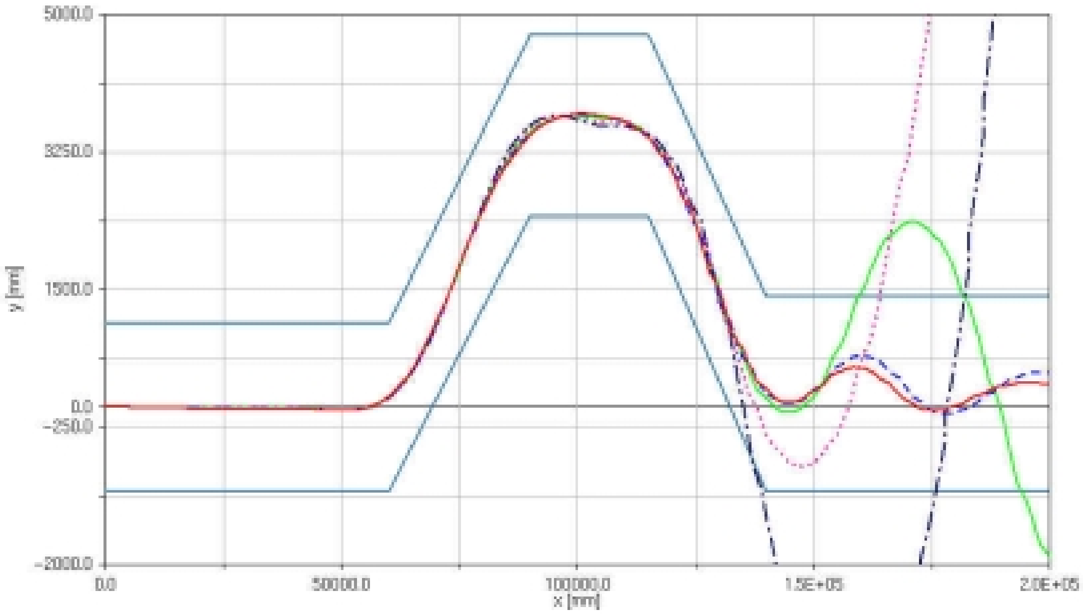


Fig.3.2.4 Influence of Cornering Stiffness on Vehicle Trajectory , 90 km/h ISO Double Lane Change, LPT 0.2 s, Standard Tyre (Green Line), Ky –10/15% (Violet and Black), Ky + 10/15% (Blue and Red)

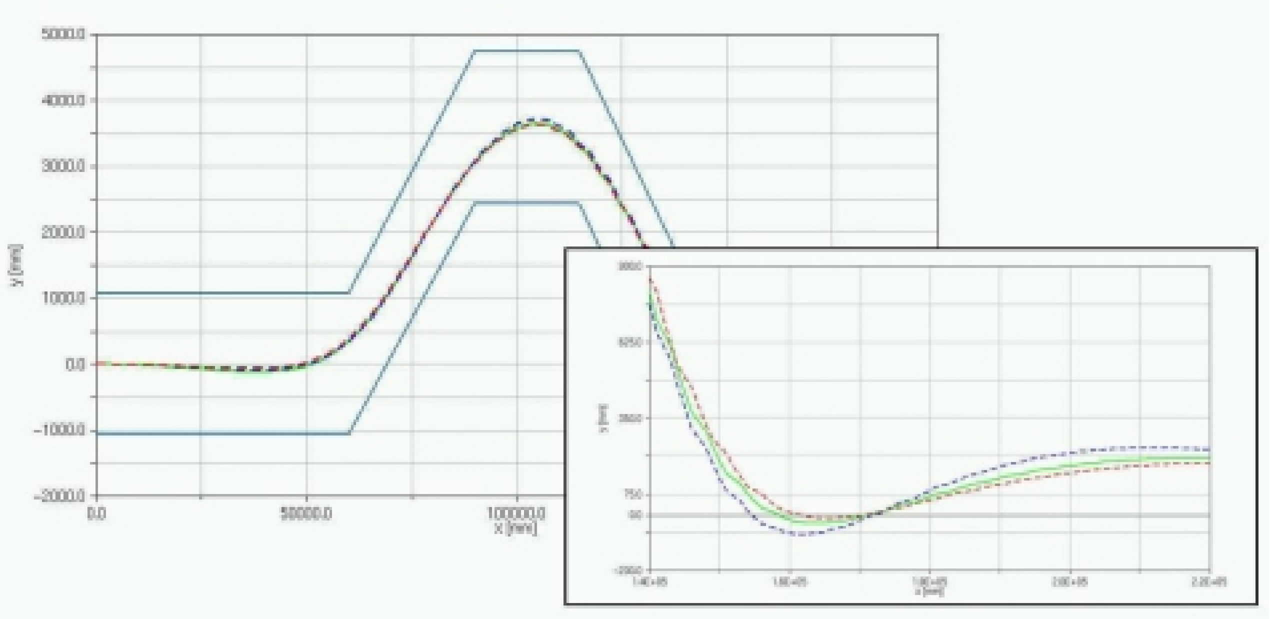


Fig.3.2.5 Influence of Cornering Stiffness on Vehicle Trajectory , 90 km/h ISO Double Lane Change, LPT 0.8 s: Green Line Standard Tyre, Red Line Ky +15%, Blue Line Ky –15%

The sensitivity to all main Tyre Characteristics is summarised in the Fig. 3.2.6 and 3.2.7, reporting the Round Mean Square of Steering Wheel Angle Time History and clearly showing the higher sensitivity due to lower values of LPT.

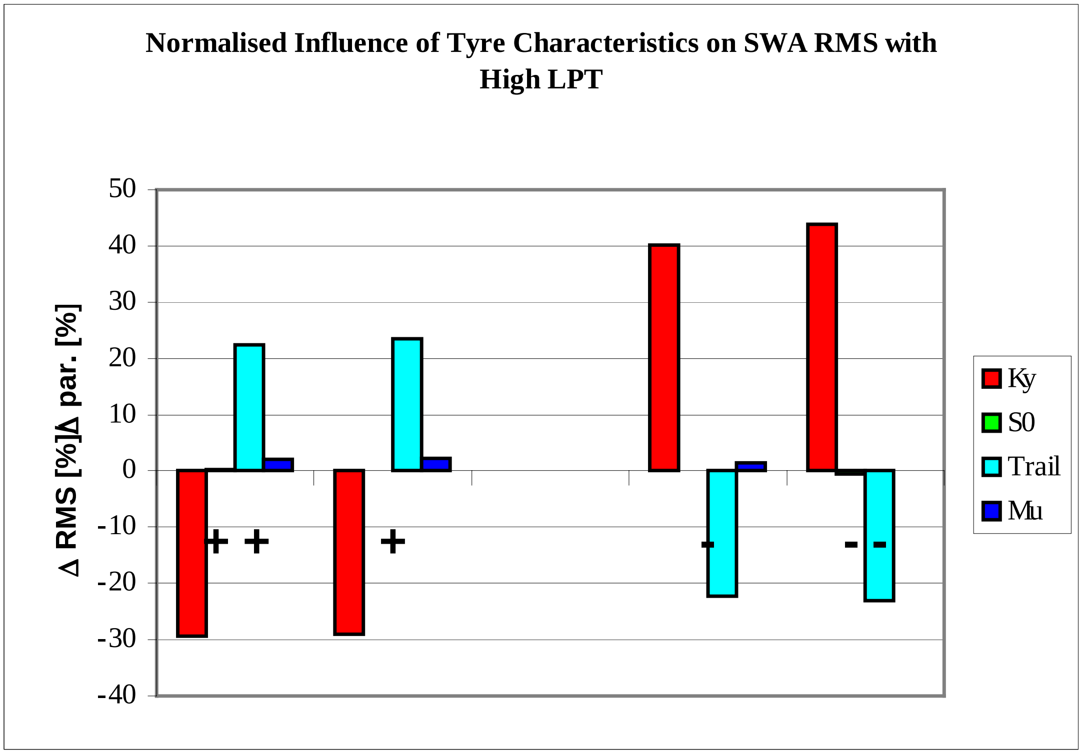


Fig.3.2.6 Percentage variations of Steering Wheel Angle Round Mean Square with respect to Tyre Characteristics Variations for high values of LPT

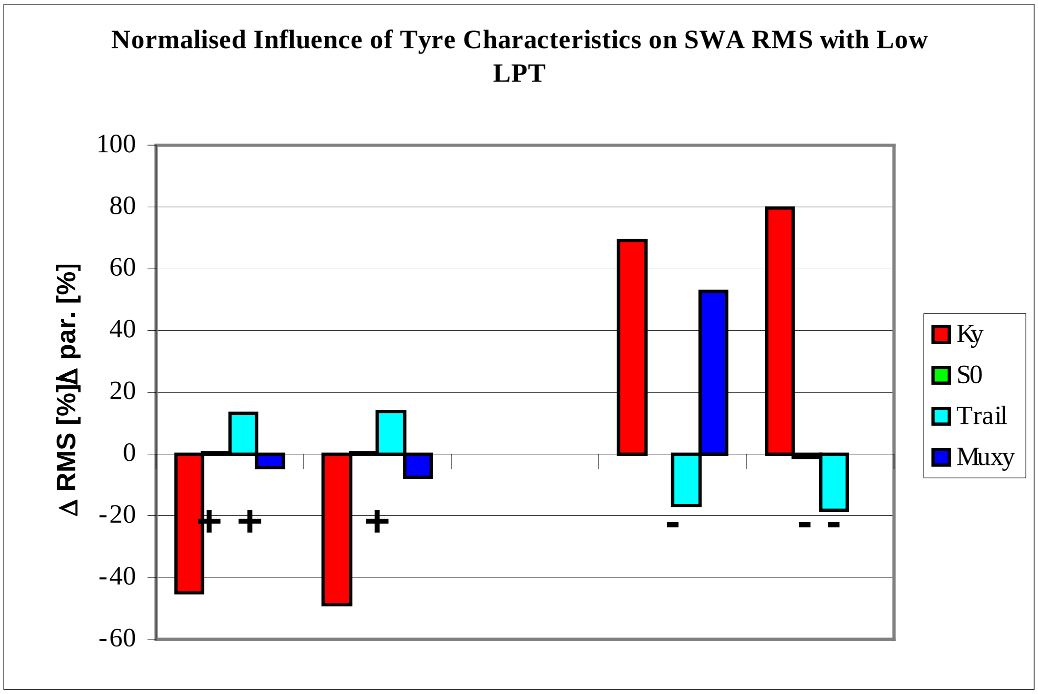


Fig.3.2.7 Percentage variations of Steering Wheel Angle Round Mean Square with respect to Tyre Characteristics Variations for low values of LPT

b) Constant Radius Steering Pad

As Steering Pad is a very slow quasi-static manoeuvre, the LPT has actually a neglectable influence on the execution of the manoeuvre.

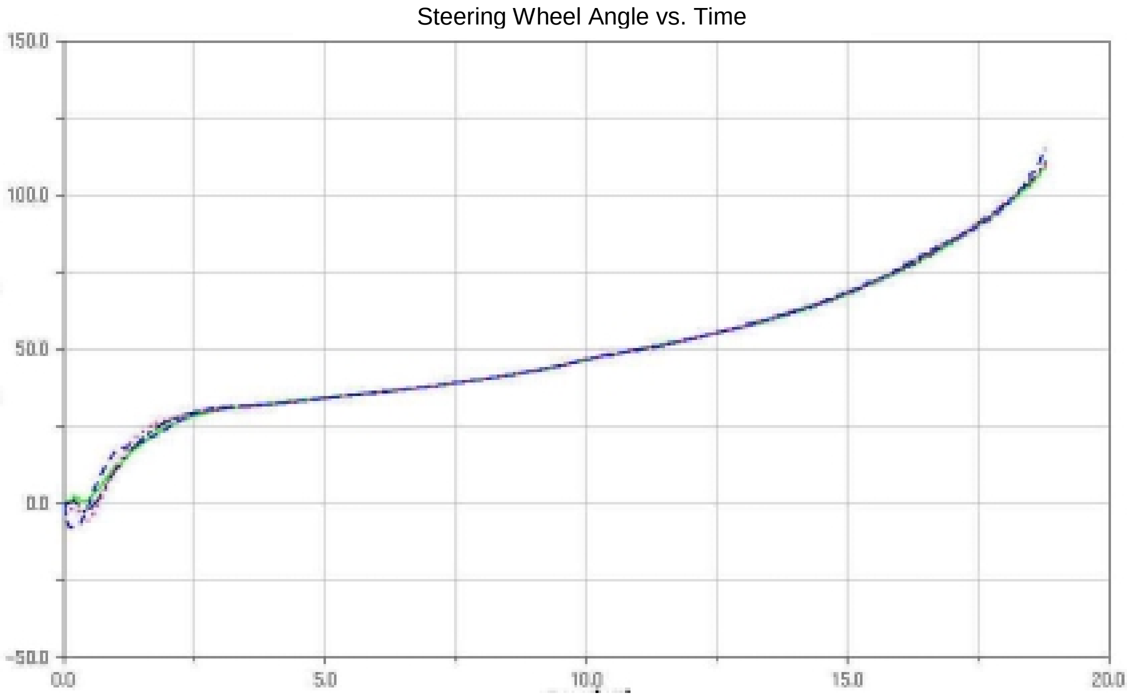


Fig.3.2.8 Steering Wheel Angle Time History for LPT=0.2 s (Blue), LPT=0.4 s (Violet), LPT=0.6 s (Black), LPT=0.8 s (Green)

The vehicle sensitivity to Tyre Characteristics in this steady-state manoeuvre is actually already included in the considerations of the previous manoeuvres and is not reported for sake of simplicity. Only Fig.3.2.9 reports the effects of Cornering Stiffness variations.

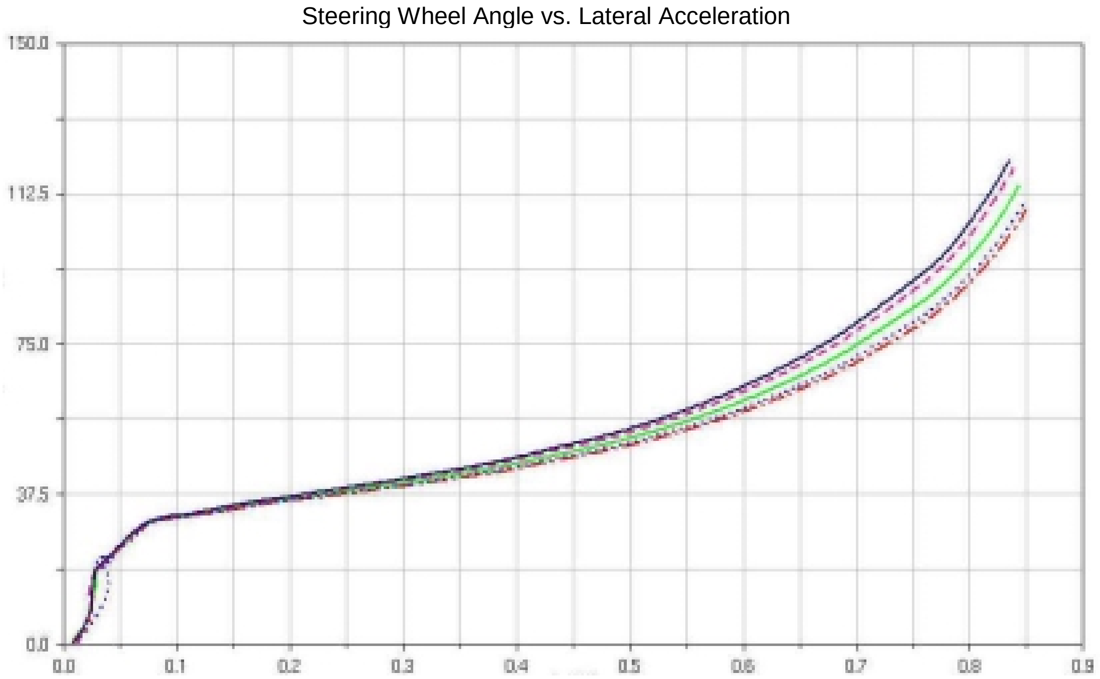


Fig.3.2.9 Steering Wheel Angle vs. Lateral Acceleration with different tyres (Green Line: Standard, Blue ky + 10%, Red ky + 15%, Violet ky - 10%, Black ky - 15%

4 Conclusions

The results herewith presented clearly show how the well-known influence of the driving style on the Vehicle sensitivity to tyre characteristics in Closed-Loop manoeuvres can be explained with the basis of the conclusions of the Open-Loop analysis.

Open-Loop manoeuvres show that the Vehicle system is in fact most strongly sensitive to Tyre

Characteristic in a certain range of frequency (approximately from 0.5 to 1.8 Hz). A driving style (e.g in a manoeuvre as ISO Double Lane Change) tending to include "corrections" within this range of frequency increases in this way the whole sensitivity to Tyre. On the other side, a very "smooth" approach to the manoeuvre (even with the risk to hit the cones) with only low-frequency corrections results in a weaker sensitivity to the tyre characteristics.

5 Further developments

Two further developments of this activity can be immediately detected:

- Definition of other Closed-Loop manoeuvres, requiring higher-frequency corrections by the driver and increasing in this way the capability of detecting the differences among the tyres.

- Exploitation of ADAMS/Driver, featuring also "Human" control of driving style, enabling further investigations about the sensitivity to Driver Style.

- Introduction of the opportunity of changing the tyre characteristics within the simulation in order to reproduce changes of road conditions, dangerous situations, etc.

Moreover, the Manoeuvre Definition in .dcf – Driver Control File format enables excellent opportunities of exchanging among Co-Design partners manoeuvre definitions suitable for any model in ADAMS/Car environment.

6 Acknowledgements

Acknowledgements are due to Mr Claudio Bonci and Mr Davide Chiaramonte for their valuable contributions to the presented activities.

7 References

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