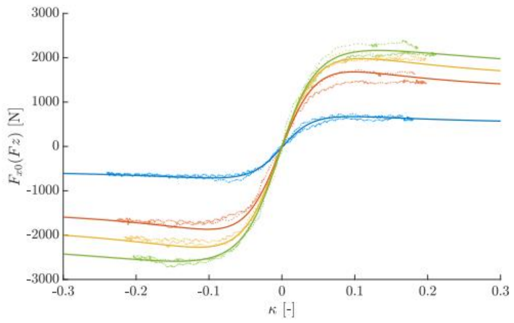
UNIVERSITÀ DI TRENTO

DoV Project Team 6

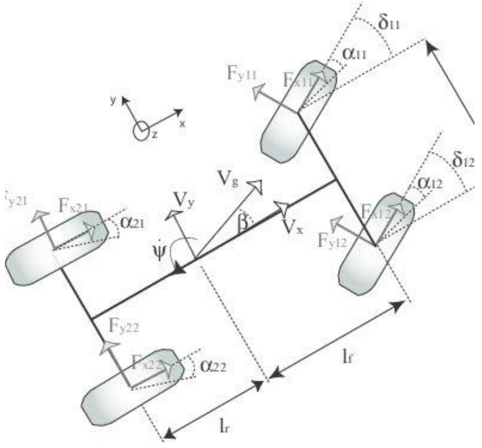
Consalvi Natale, Pettene Mattia, Zumerle Matteo

DoV Project team 6

- Tire fitting analysis



- Double track model analysis



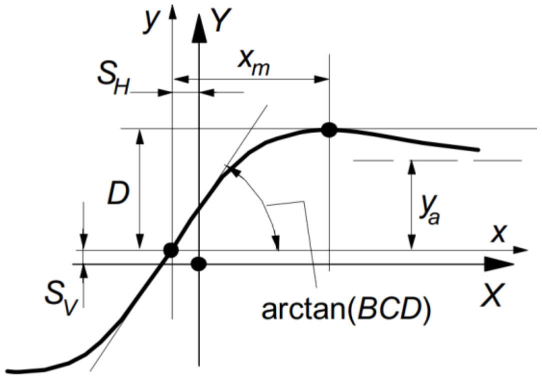
Consalvi, Pettene, Zumerle

Tire fitting analysis

Team 6

Pacejka Magic formula

$$y(x) = D\sin(C\arctan(Bx - E(Bx - \arctan(Bx))))$$
$$Y(X) = y(x) + S_V$$
$$x = X + S_H$$



- Similarity method: curves remain similar

- B stiffness factor
- C shape factor
- D peak value
- E curvature
- SH and SV horizontal and vertical shifts

UNIVERSITÀ DI TRENTO

MF96 full equations

Pure Longitudinal force coefficients

$$S_{Hx} = p_{Hx1} + p_{Hx2} \cdot df_z$$
$$\kappa_x = \kappa + S_{Hx}$$
$$C_x = p_{Cx1}$$
$$\mu_x = (p_{Dx1} + p_{Dx2} \cdot df_z)(1 - p_{Dx3}\gamma^2)$$
$$D_x = \mu_x F_z$$
$$K_{xk} = F_z(p_{Kx1} + p_{Kx2} \cdot df_z) \cdot e^{-(p_{Kx3} \cdot df_z)}$$
$$E_x = (p_{Ex1} + p_{Ex2} \cdot df_z + p_{Ex3} \cdot df_z^2)(1 - p_{Ex4}\,\mathrm{sign}(\kappa_x))$$
$$B_x = K_{xk}/(C_x D_x)$$
$$S_{Vx} = F_z(p_{Vx1} + p_{Vx2} \cdot df_z)$$

Pure Lateral force coefficients

$$S_{Hy} = p_{Hy1} + p_{Hy2} \cdot df_z + p_{Hy3}\gamma$$
$$\alpha_y = \alpha + S_{Hy}$$
$$C_y = p_{Cy1}$$
$$\mu_y = (p_{Dy1} + p_{Dy2} \cdot df_z)(1 - p_{Dy3}\gamma^2)$$
$$D_y = \mu_y F_z$$
$$K_{ya} = F_{z0} \cdot p_{Ky1} \sin\left(2\arctan\left(\frac{F_z}{F_{z0}}\frac{1}{p_{Ky2}}\right)\right)(1 - p_{Ky3}|\gamma|)$$
$$= F_{z0} \cdot p_{Ky1} \sin\left(2\arctan\left(\frac{1 + df_z}{p_{Ky2}}\right)\right)(1 - p_{Ky3}|\gamma|)$$
$$E_y = (p_{Ey1} + p_{Ey2} \cdot df_z)(1 - (p_{Ey3} - p_{Ey4}\gamma)\,\mathrm{sign}(\alpha_y))$$
$$B_y = K_{ya}/(C_y D_y)$$
$$S_{Vy} = F_z\left(p_{Vy1} + p_{Vy2} df_z + (p_{Vy3} + p_{Vy4} df_z)\gamma\right)$$

Longitudinal force

$$F_{y0} = D_y \sin\left(C_y \arctan\left(B_y\alpha_y - E_y(B_y\alpha_y - \arctan(B_y\alpha_y))\right)\right) + S_{Vy}$$

Lateral force

$$F_{x0} = D_x \sin\left(C_x \arctan\left(B_x\kappa_x - E_x(B_x\kappa_x - \arctan(B_x\kappa_x))\right)\right) + S_{Vx}$$

MF96 full equations

Combined Longitudinal force coefficients

$$S_{Hxa} = r_{Hx1}$$
$$B_{xa} = r_{Bx1}\cos(\arctan(\kappa \cdot r_{Bx2}))$$
$$C_{xa} = r_{Cx1}$$
$$D_{xa} = 1/\cos(C_{xa}\arctan(B_{xa}S_{Hxa}))$$
$$G_{xa} = D_{xa}\cos(C_{xa}\arctan(B_{xa}(\alpha + S_{Hxa})))$$

Combined Lateral force coefficients

$$D_{Vyk} = \mu_y F_z(r_{Vy1} + r_{Vy2}df_z + r_{Vy3}\gamma)\cos(\arctan(r_{Vy4}\alpha))$$
$$S_{Vyk} = D_{Vyk}\sin(r_{Vy5}\arctan(r_{Vy6}\kappa))$$
$$S_{Hyk} = r_{Hy1}$$
$$B_{yk} = r_{By1}\cos\left(\arctan(r_{By2}(\alpha - r_{By3}))\right)$$
$$C_{yk} = r_{Cy1}$$
$$D_{yk} = 1/\cos(C_{yk}\arctan(B_{yk}S_{Hyk}))$$
$$G_{yk} = D_{yk}\cos(C_{yk}\arctan(B_{yk}(\kappa + S_{Hyk})))$$

Longitudinal force

$$F_x = G_{xa}F_{x0}$$

Lateral force

$$F_y = G_{yk}F_{y0} + S_{Vyk}$$

Aligning moment

$$S_{Ht} = q_{Hz1} + q_{Hz2} df_z + (q_{Hz3} + q_{Hz4} \cdot df_z)\gamma$$

$$\alpha_t = \alpha + S_{Ht}$$

$$B_t = (q_{Bz1} + q_{Bz2} df_z + q_{Bz3}(df_z)^2)(1 + q_{Bz4}\gamma + q_{Bz5}|\gamma|)$$

$$C_t = q_{Cz1}$$

$$D_t = F_z(q_{Dz1} + q_{Dz2} f_z)(1 + q_{Dz3}\gamma + q_{Dz4}\gamma^2)(R_o/F_{z0})$$

$$E_t = (q_{Ez1} + q_{Ez2} df_z + q_{Ez3} \cdot (df_z)^2)(1 + (q_{Ez4} + q_{Ez5}\gamma)\arctan(B_t C_t \alpha_t))$$

$$S_{Hf} = S_{Hy} + S_{Vy}/K_{ya}$$

$$\alpha_r = \alpha + S_{Hf}$$

$$B_r = q_{Bz9} + q_{Bz10} B_y C_y$$

$$D_r = F_z\left(q_{Dz6} + q_{Dz7} df_z + (q_{Dz8} + q_{Dz9} df_z)\gamma\right)R_o$$

$$M_{zr} = D_r \cos(\arctan(B_r \alpha_r))\cos(\alpha)$$

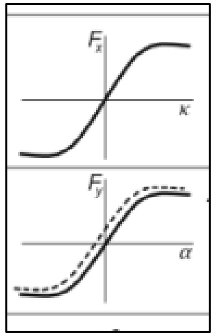
$$t = D_t \cos\left(C_t \arctan\left(B_t\alpha_t - E_t(B_t\alpha_t - \arctan(B_t\alpha_t))\right)\right)\cos(\alpha)$$

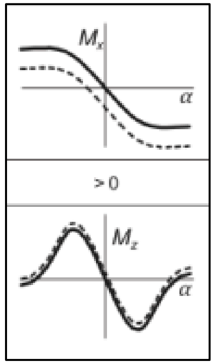
$$M_{z0} = -tF_y + M_{zr}$$

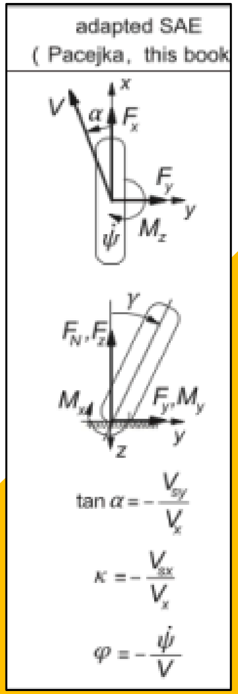
- Reference condition:
  - Zero camber angle (γ = 0 [rad])
  - Free rolling condition (κ = 0 [-]) or zero slip angle (α = 0 [rad])
  - Nominal vertical load applied (FZ0=220 [N])

- Hoosier 6.0 / 18 .0 - 10 LCO

- Adapted SAE sign convention





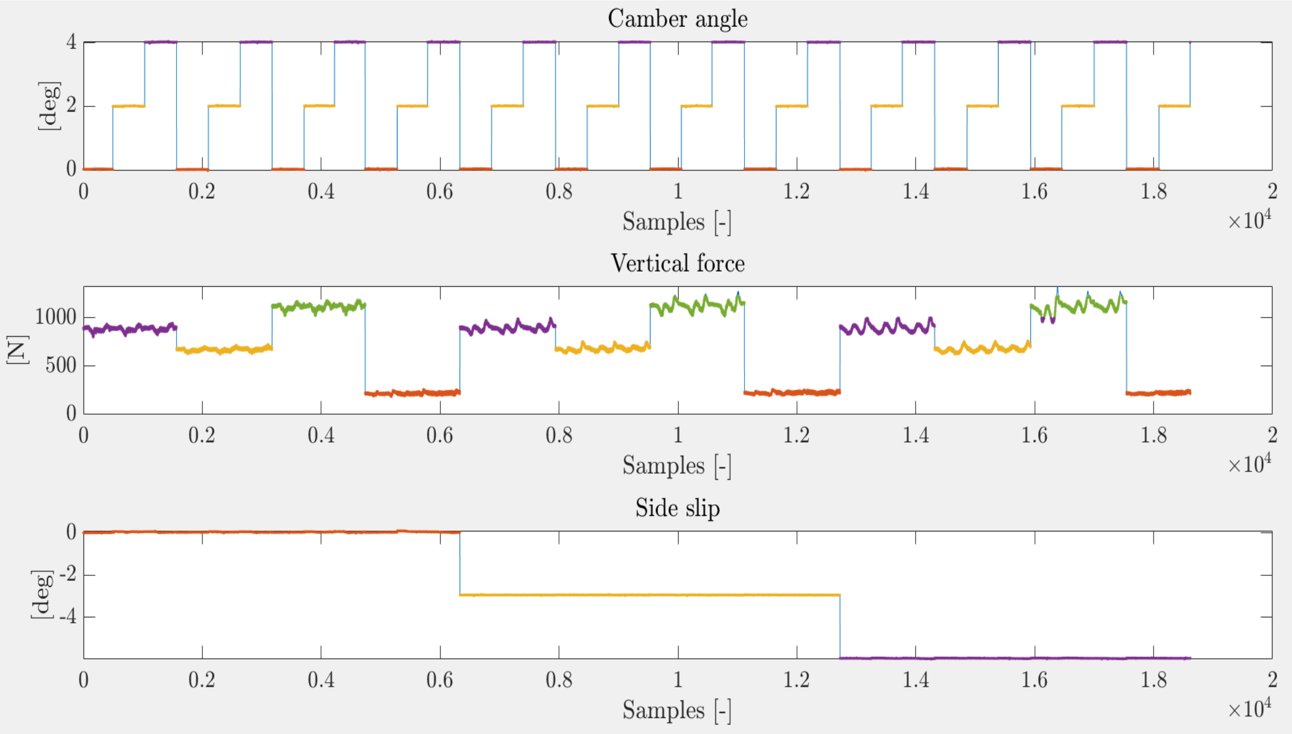


General fitting procedure

- Data cropping
- Set of conditions for each analysis
- Optimization of the residuals
- Variations of guess and boundaries vectors
- Model validation
- Tire coefficient backup

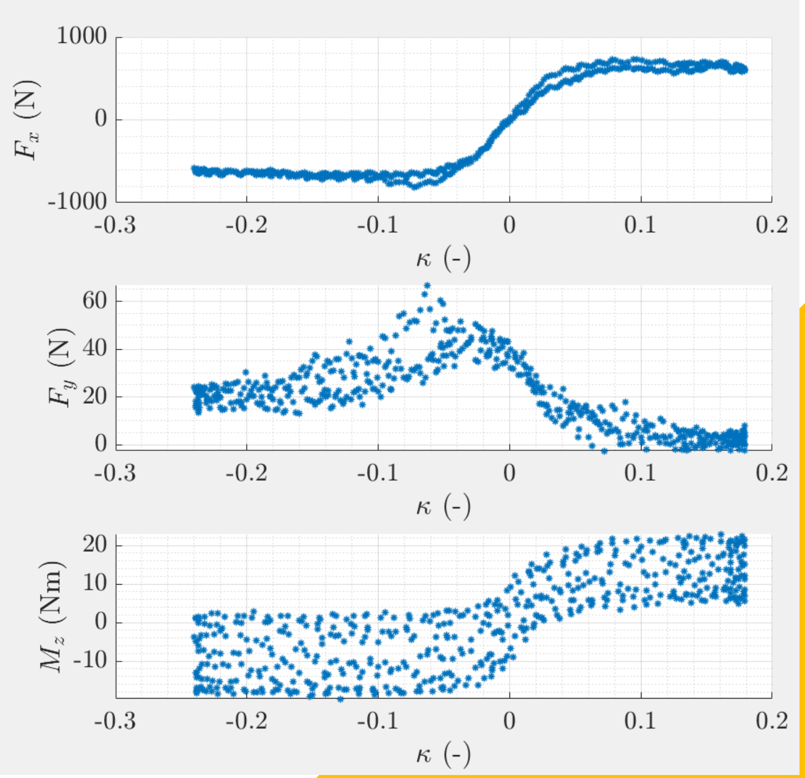
Data cropping

- B1464run30.mat pure longitudinal force and combined behavior
- B1464run23.mat pure lateral and aligning moment.
- Select high pressure for stabilized values



Condition of analysis

- Function intersect_table_data generates a table structure that contains all the values of the dataset that satisfy some conditions.
- [TData, ~] = intersect_table_data(SA_0, GAMMA_0, FZ_220);



Consalvi, Pettene, Zumerle

Guess vector and parameter boundaries

```
% Guess values for parameters to be optimised
%    [pCx1 pDx1 pEx1 pEx4  pHx1  pKx1  pVx1]
P0_FX0_pure = [  1,   2,   1,  0,   0,   1,   0];

% Limits for parameters to be optimised
%    [pCx1 pDx1 pEx1 pEx4  pHx1  pKx1  pVx1
lb_FX0_pure = [1,   0.1,   0,   0,  -10,    0,   -10];
ub_FX0_pure = [2,    4,   1,   1,   10,   100,  10];
```

Optimization of the residuals (validation 1/2)

```
% Minimization of the residual
[P_opt_FY0_pure,fval_FY0_pure,exitflag_FY0_pure] = fmincon(@(P)resid_pure_Fy(P,FY_vec, ...
    ALPHA_vec,0,mean(TData0_pl.FZ), tyre_coeffs_pl),...
    P0_FY0_pure,[],[],[],[],lb_FY0_pure,ub_FY0_pure);


R_squared_FY0_pure = 1 - fval_FY0_pure;
```

Tire coefficient backup (validation 2/2)

F_{X0}	F_{Y0}	M_{Z0}
$B_x = 14.77$	$B_y = 11.31$	$B_r = -4.434$
$C_x = 1.538$	$C_y = 1.135$	$B_t = 1.4916$
$D_x = 2.167e3$	$D_y = 2.567e3$	$C_t = 4.999$
$E_x = 0.2788$	$E_y = 0.9474$	$D_r = 48.14$
$S_{Vx} = -213.4$	$S_{Vy} = 47.99$	$D_t = 0.041$
$S_{Hx} = 0.0043$	$S_{Hy} = 0.0038$	$E_t = -0.1087$
$\mu_x = 1.9347$	$\mu_x = 2.3724$	$\alpha_r = 0.0052$
		$\alpha_t = -0.0426$

```
%% -Save tyre data structure to mat file
save('tyre_coeffs_team6.mat','tyre_coeffs_pl');
```

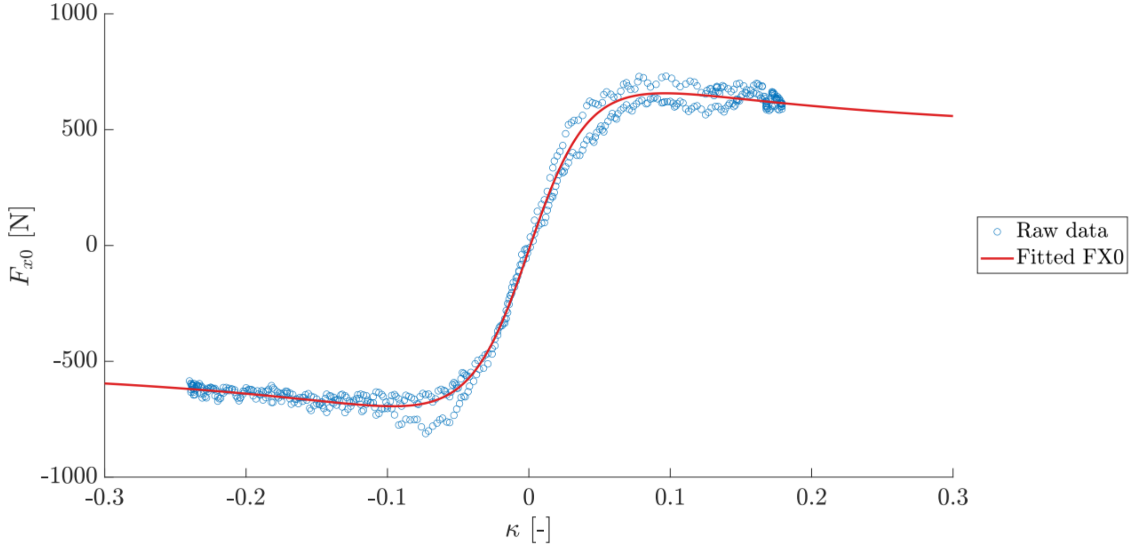
- All parameter to be checked have been successfully verified

F_{X0}	F_{Y0}	M_{Z0}	F_X	F_Y
$C_x > 0$	$C_y > 0$	$C_t > 0$	$G_{xa} > 0$	$G_{yk} > 0$
$D_x > 0$	$\mu_y > 0$	$B_t > 0$	$B_{xa} > 0$	$B_{yk} > 0$
$E_x \leq 1$	$E_y \leq 1$	$E_t \leq 1$		

Consalvi, Pettene, Zumerle

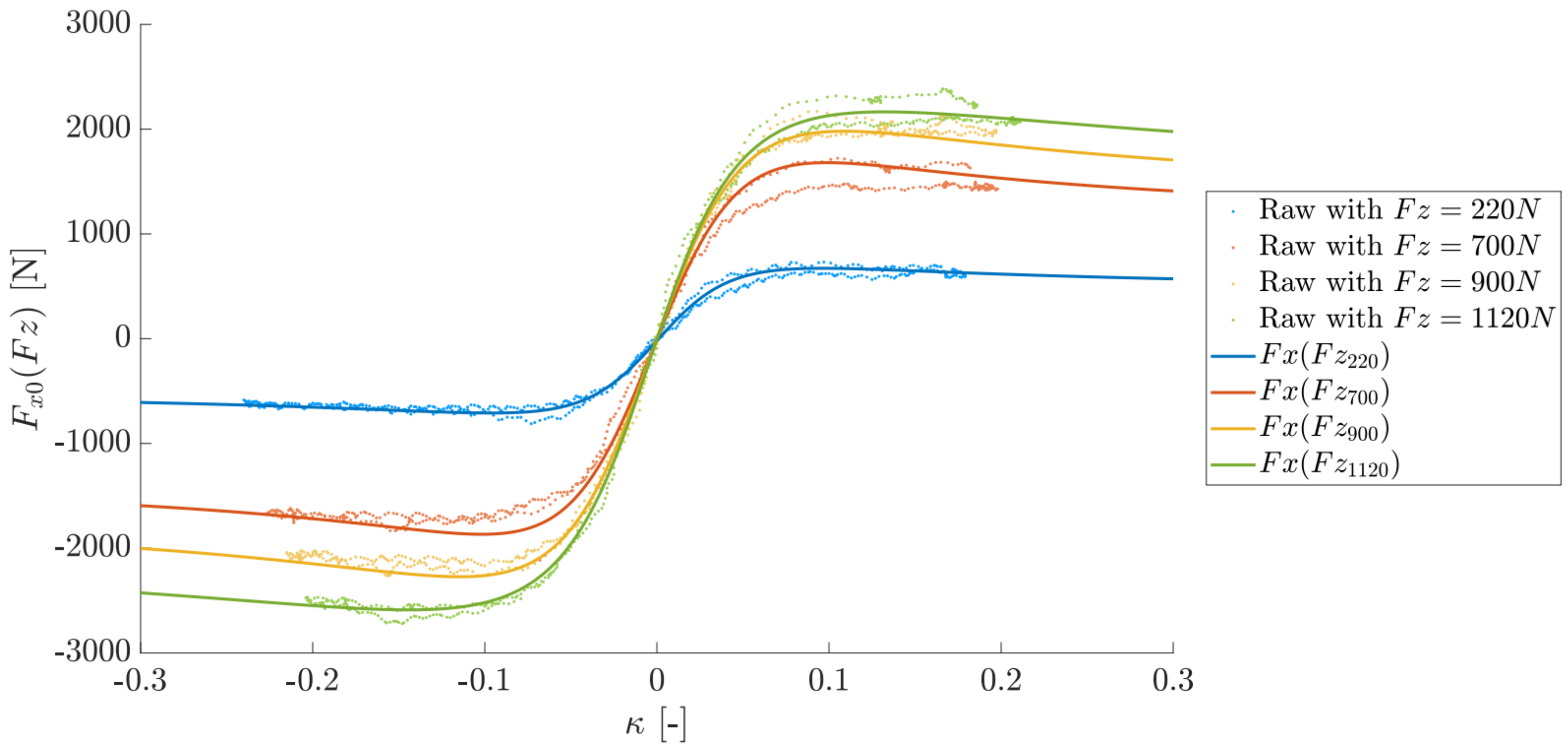
Results: pure longitudinal force

	pCx1	pDx1	pEx1	pEx4	pHx1	pKx1	pVx1
Guess	1	2	1	0	0	1	0
L bound	1	0.1	0	0	-10	0	-10
U bound	2	4	1	1	10	~	10
Optm par	1.539	3.147	1.133e-2	8.063e-2	-2.092e-5	8.241e1	-8.577e-2
R^2				**0.9955**			

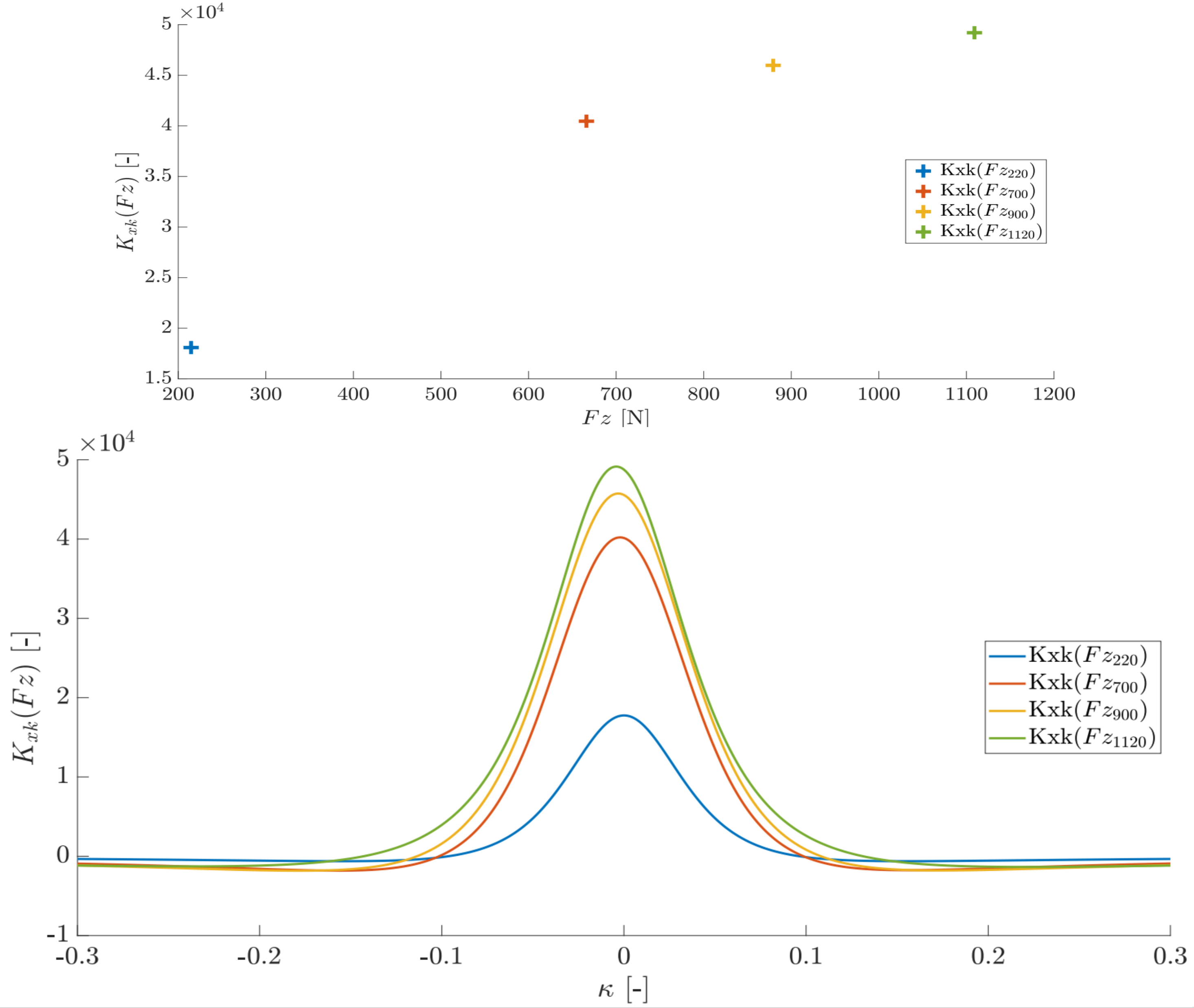


Vertical load variation

	pDx2	pEx2	pEx3	pHx2	pKx2	pKx3	pVx2
Guess	0	0	0	0	0	0	0
L bound	~	~	~	~	~	~	~
U bound	~	~	~	~	~	~	~
Optm par	-2.496e-1	-3.619e-1	1.059e-1	1.050e-3	-1.859e-3	1.536e-1	-2.559e-2
R^2				**0.9971**			



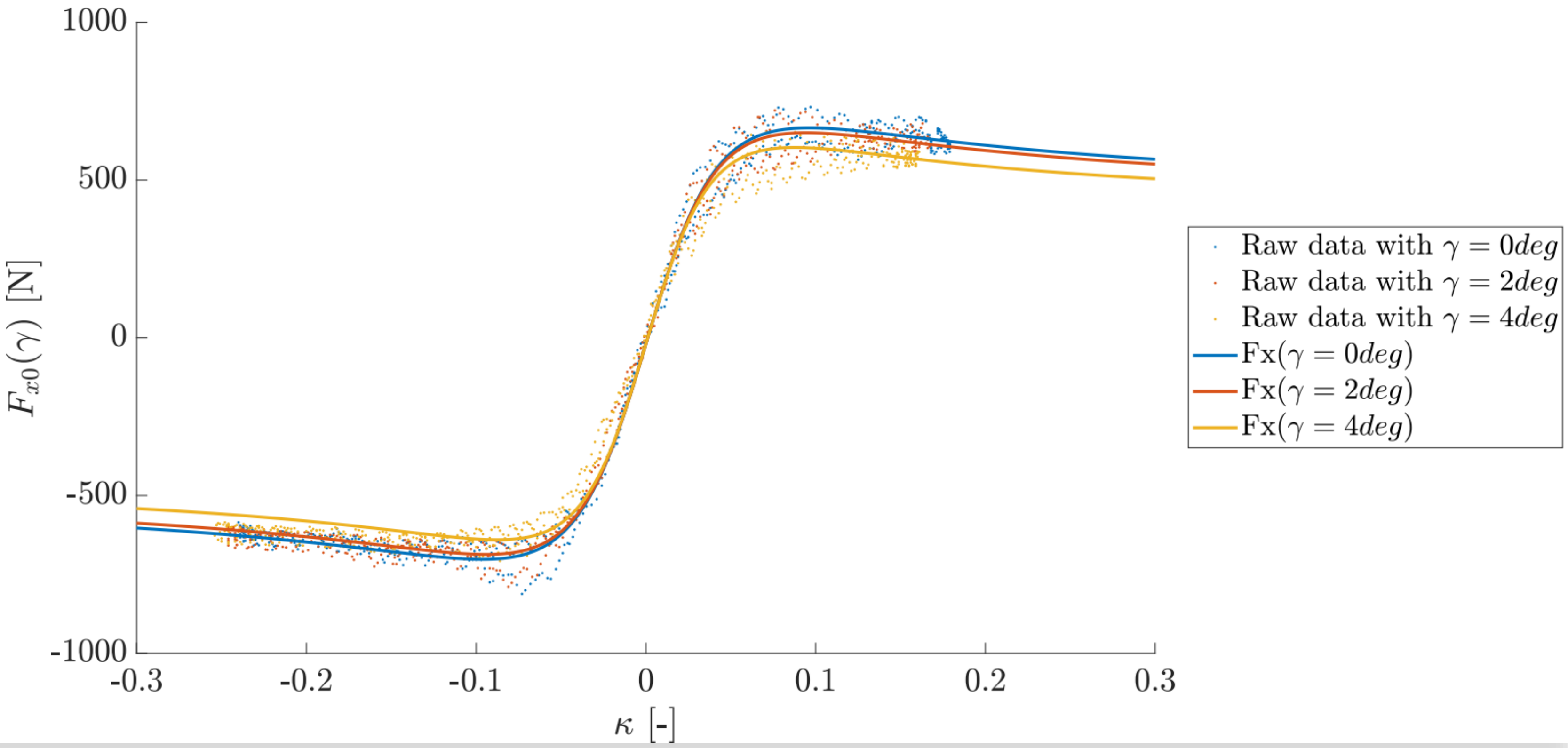
Consalvi, Pettene, Zumerle



UNIVERSITÀ DI TRENTO

Longitudinal cornering stiffness

	pDx3
Guess	0
L bound	$\sim$
U bound	$\sim$
Optm par	1.844e1
$\mathbf{R^2}$	**0.9938**

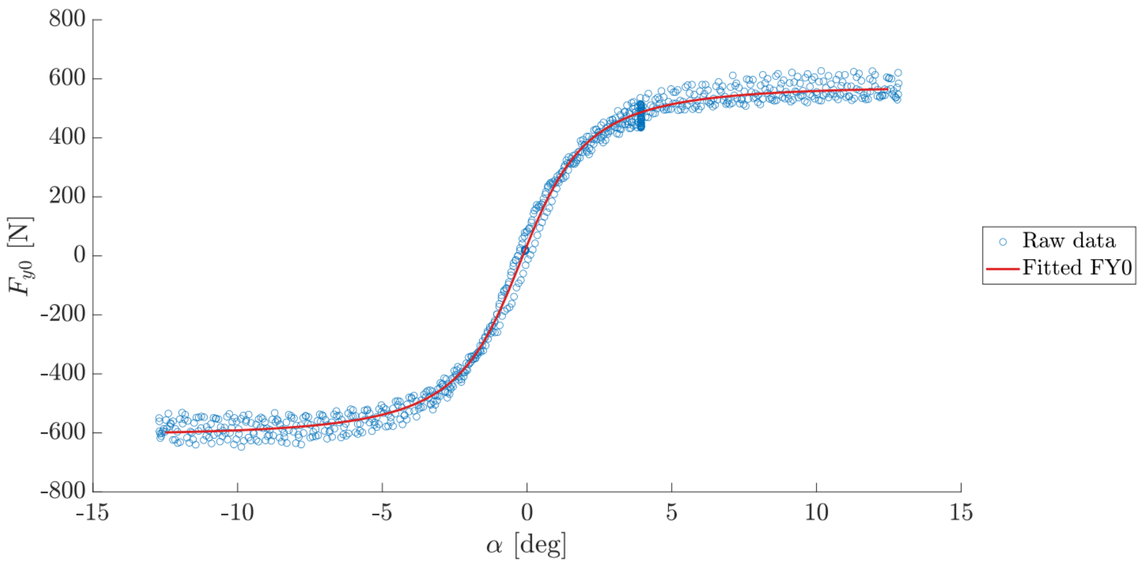


UNIVERSITÀ DI TRENTO

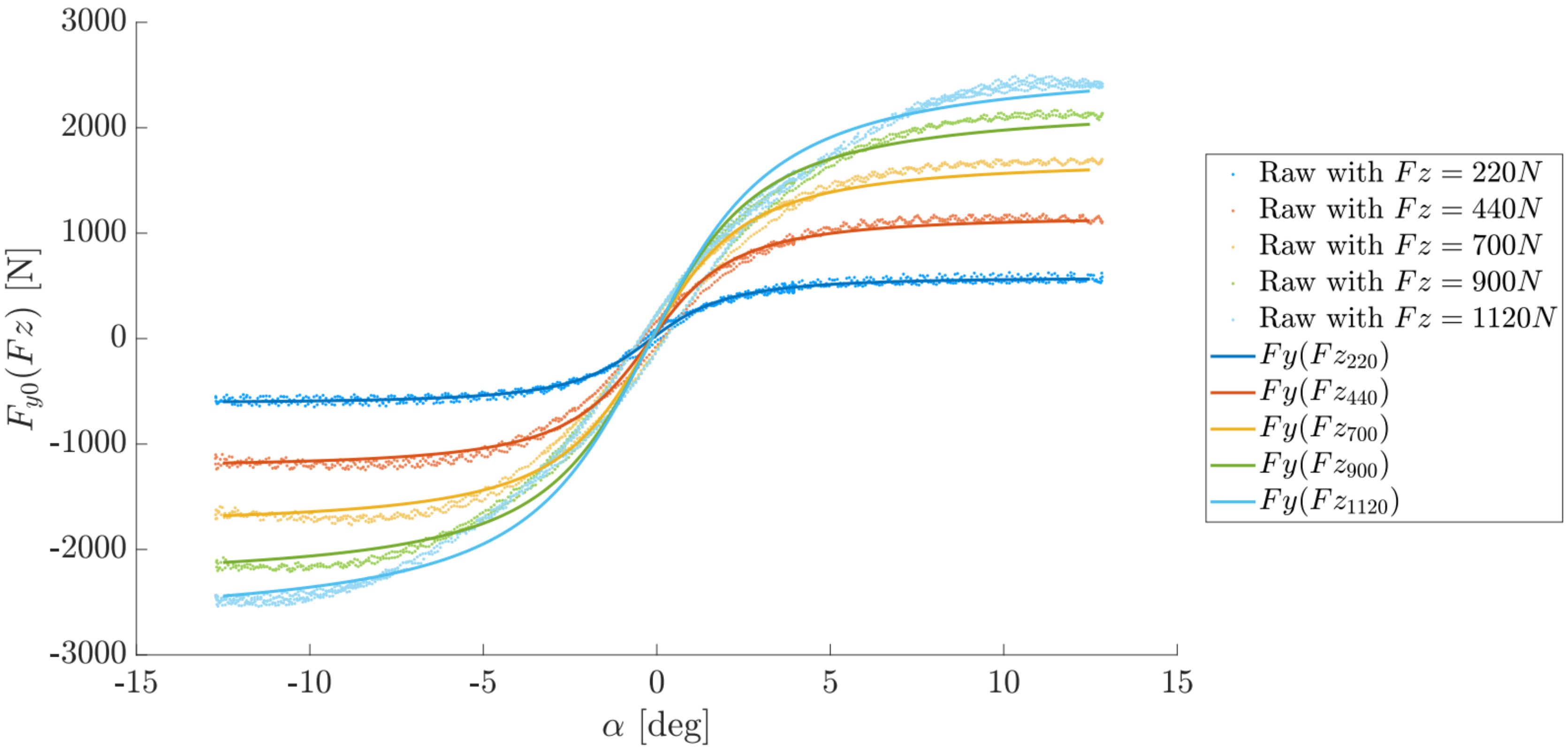
Camber angle variation

Results: pure lateral force

	pCy1	pDy1	pEy1	pHy1	pKy1	pKy2	pVy1
Guess	1.3	2.7	-1	0.0038	170	5.05	-0.0792
L bound	1.1	2.5	~	~	0	4.9	~
U bound	~	~	1	~	175	5.1	~
Optm par	1.135	2.717	0.4583	3.803e-2	1.675e2	4.981	-7.923e-2
R^2				**0.9963**			

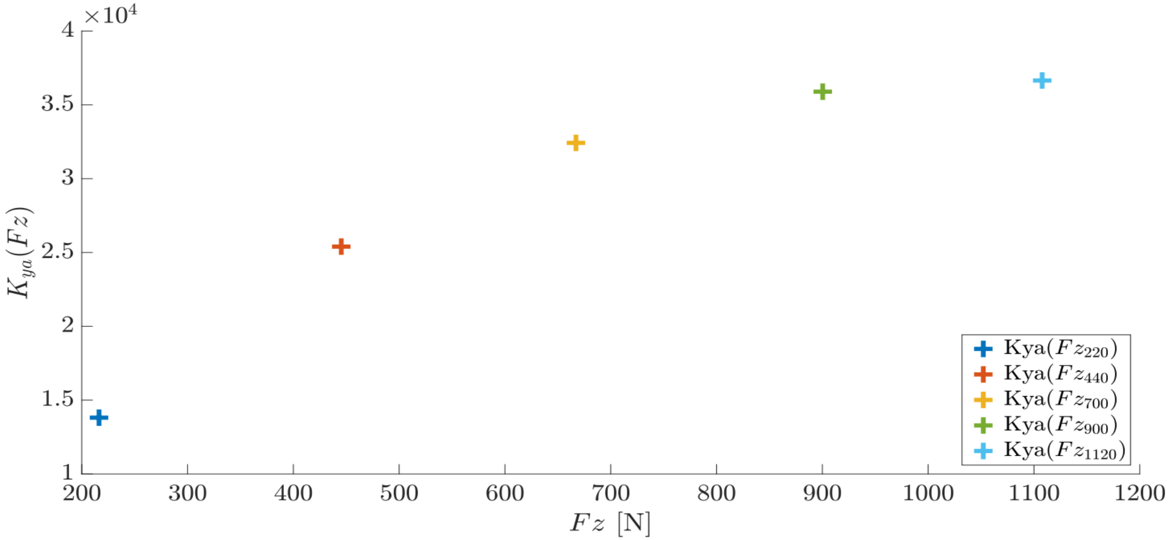


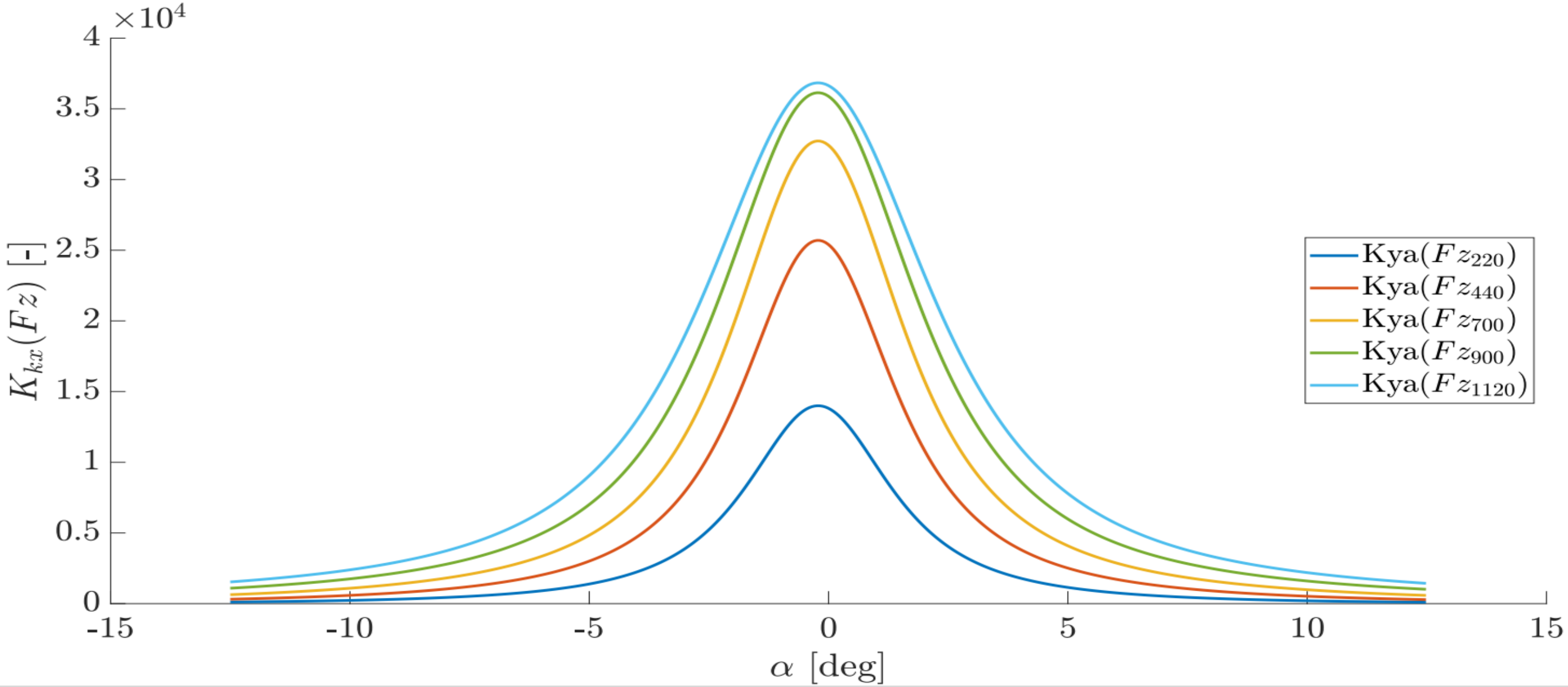
	pDy2	pEy2	pHy2	pVy2
Guess	-0.05	-1	0	0
L bound	-0.2	~	~	~
U bound	0	~	~	~
Optm par	-8.464e-2	7.214e-2	1.004e-5	7.942e-3
R^2	0.9912			



UNIVERSITÀ DI TRENTO

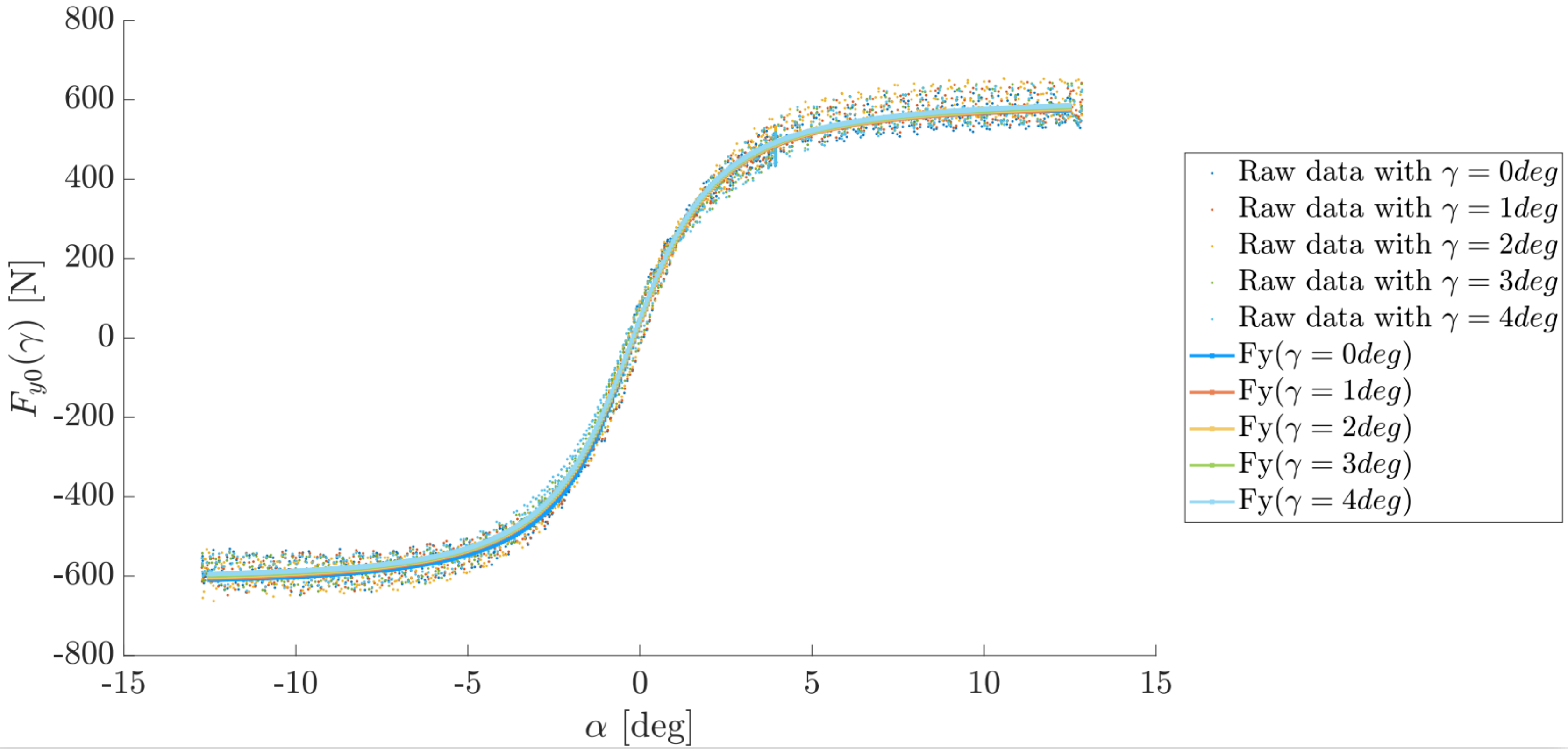
Vertical load variation





Lateral cornering stiffness

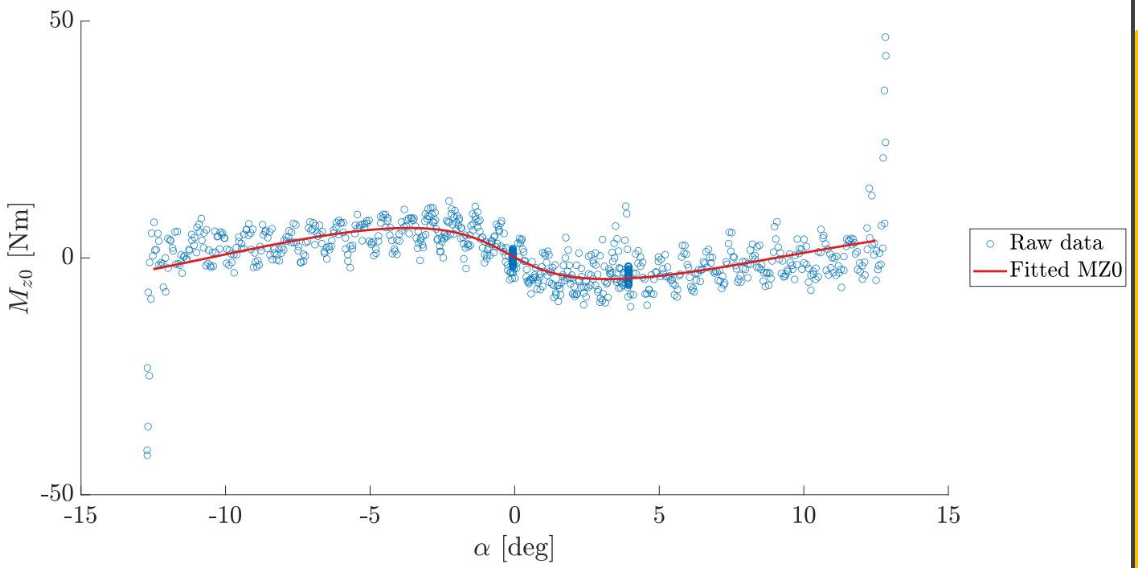
	pDy3	pEy3	pEy4	pHy3	pKy3	pVy3	pVy4
Guess	-2	0	-2	0	0	0.15	0
L bound	~	~	-3	~	~	~	~
U bound	~	~	~	~	~	~	~
Optm par	-1.089e-1	-9.200e-3	-2.945	-1.402e-4	7.433e-2	1.027	0
$\mathbf{R^2}$	**0.9960**						



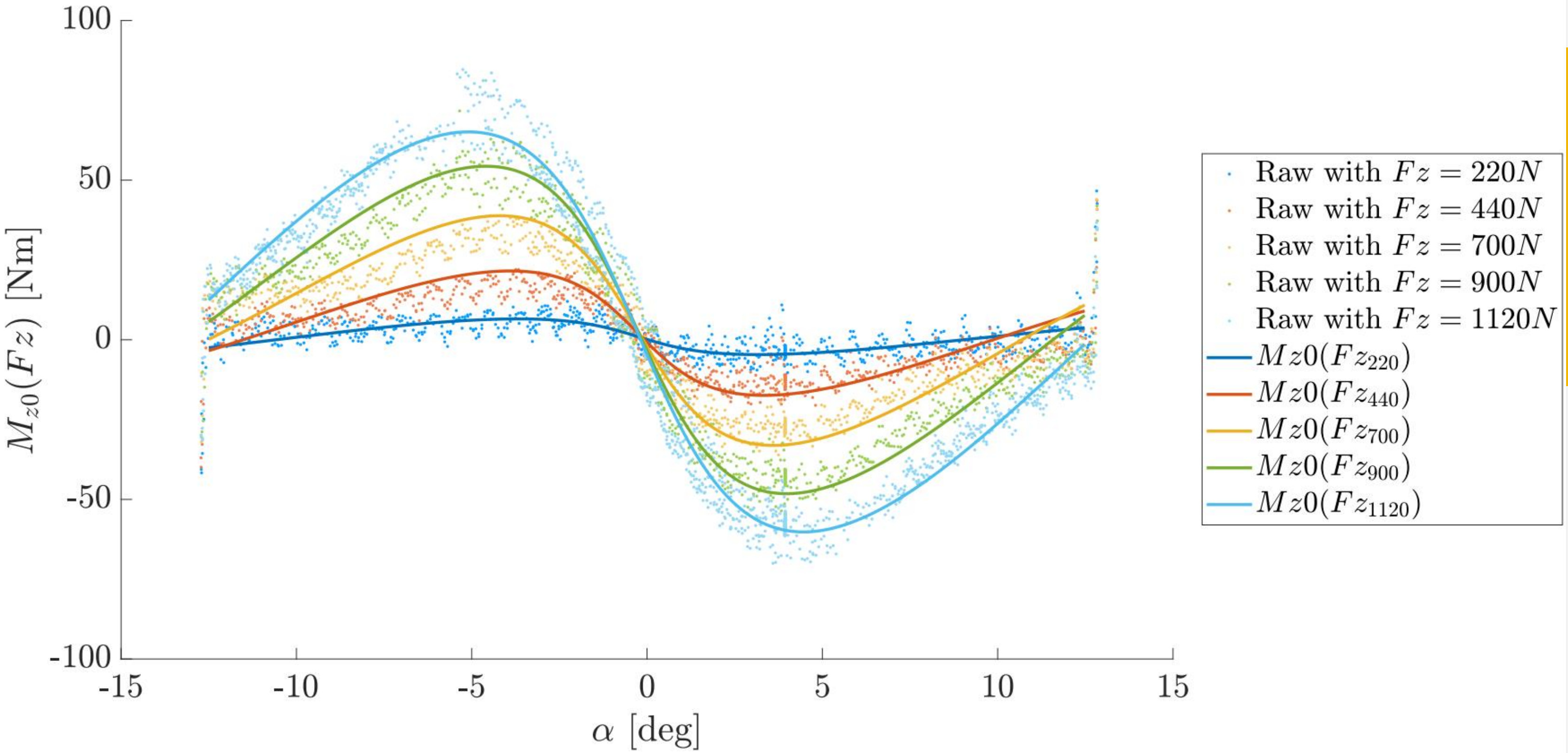
Camber angle variation

Results: pure aligning moment

	qBz1	qBz9	qBz10	qCz1	qDz1	qDz6	qEz1	qEz4	qHz1
Guess	6	0	0.7	1	0	0	-1	-0.5	0
L bound	-10	-1	-5	-5	-10	-10	-0.8	-0.8	-1
U bound	10	1	5	5	10	10	0.8	0.8	1
Optm par	1.848	2.686e-3	-3.459e-1	4.999	5.898e-2	1.205e-2	-7.998e-1	-3.561e-1	1.008e-2
R^2	**0.3711**								



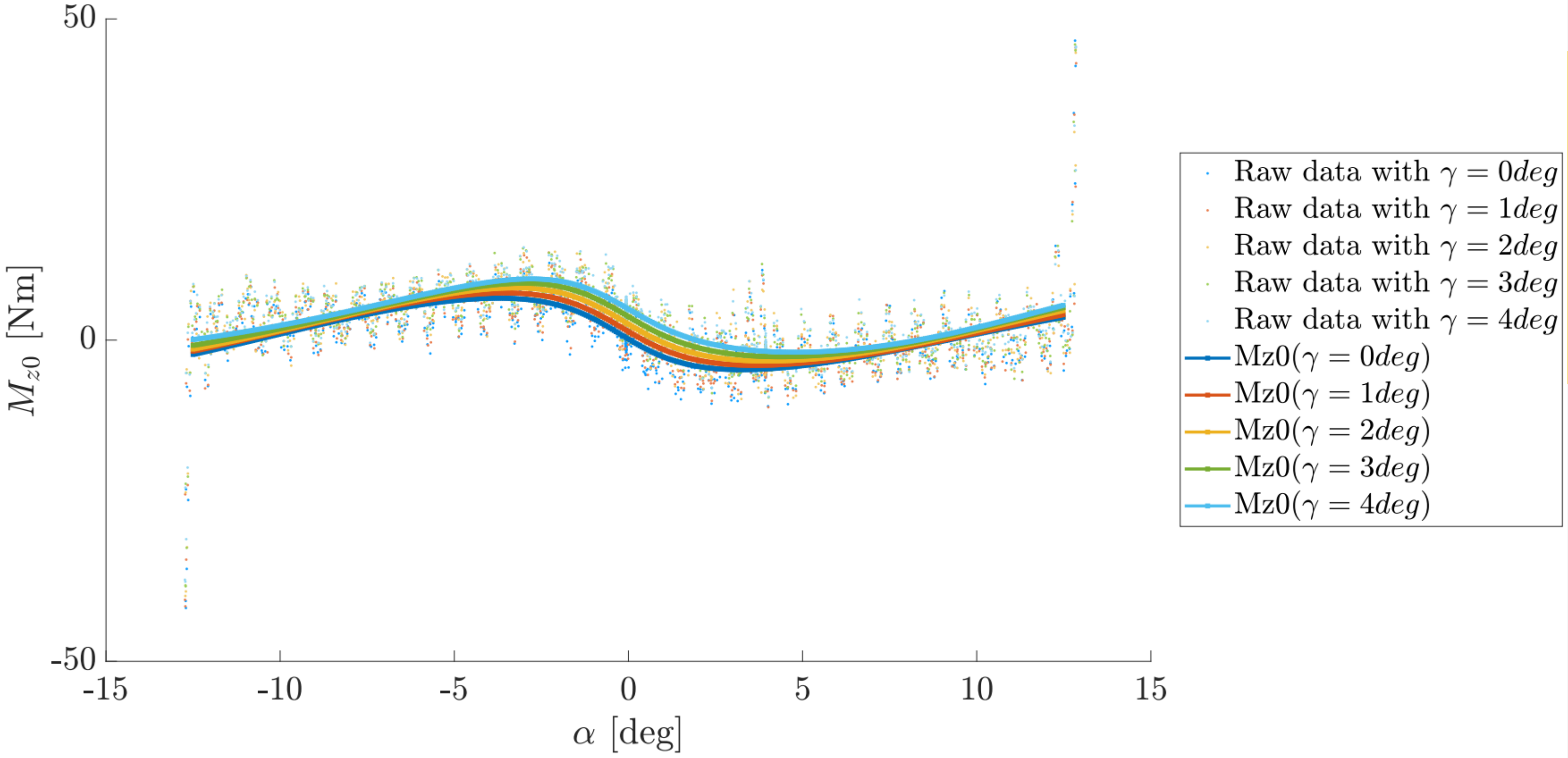
	qBz2	qBz3	qDz2	qDz7	qEz2	qEz3	qHz2
Guess	0	0	0	0	0	0	0
L bound	-4	-4	-5	-5	-2	-1	-5
U bound	4	4	5	5	2	1	5
Optm par	-3.673e-2	-1.591e-2	-6.105e-3	-3.992e-3	1.999	-4.196e-1	-1.3408e-4
R^2				**0.9574**			



UNIVERSITÀ DI TRENTO

Vertical load variation

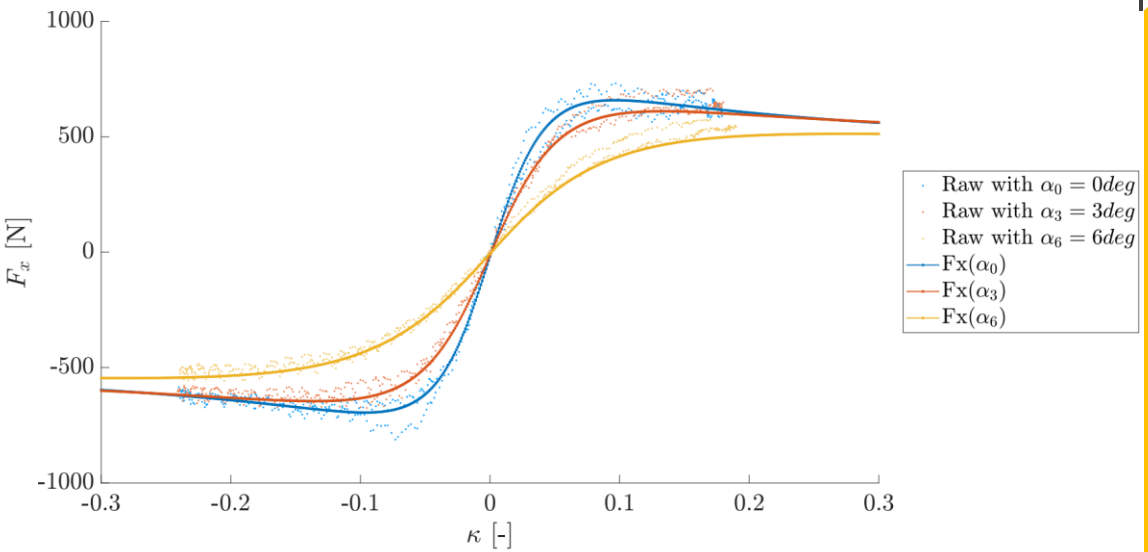
	qBz4	qBz5	qDz3	qDz4	qEz5	qDz8	qDz9	qHz3	qHz4
Guess	0	0	0	-1	0	0.6	0.2	0	0
L bound	~	~	-3	~	~	~	~	~	~
U bound	~	~	-3	~	~	~	~	~	~
Optm par	9.671e-1	-4.208e-2	1.707	-1.620e1	5.258e1	1.369	2e-1	-5.978e-1	0
R^2					**0.4633**				



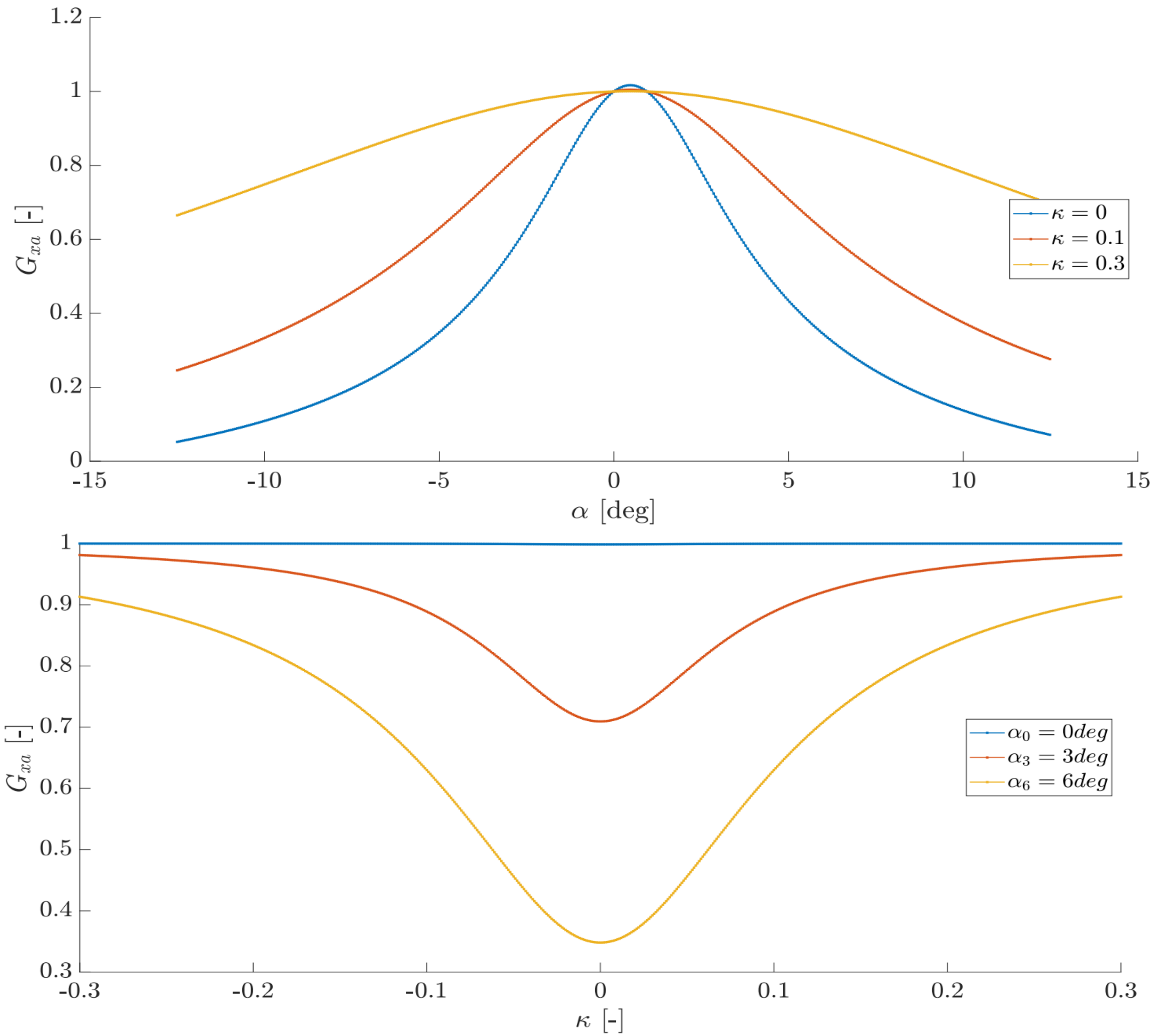
Camber angle variation

Results: combined longitudinal force

	rBx1	rBx2	rCx1	rHx1
Guess	17	-11	1	0
L bound	0	-16.5	-0.5	-0.015
U bound	20	20	10	0.015
Optm par	1.997e1	-1.578e1	1.228	-8.222e-3
R^2	**0.9947**			



Consalvi, Pettene, Zumerle



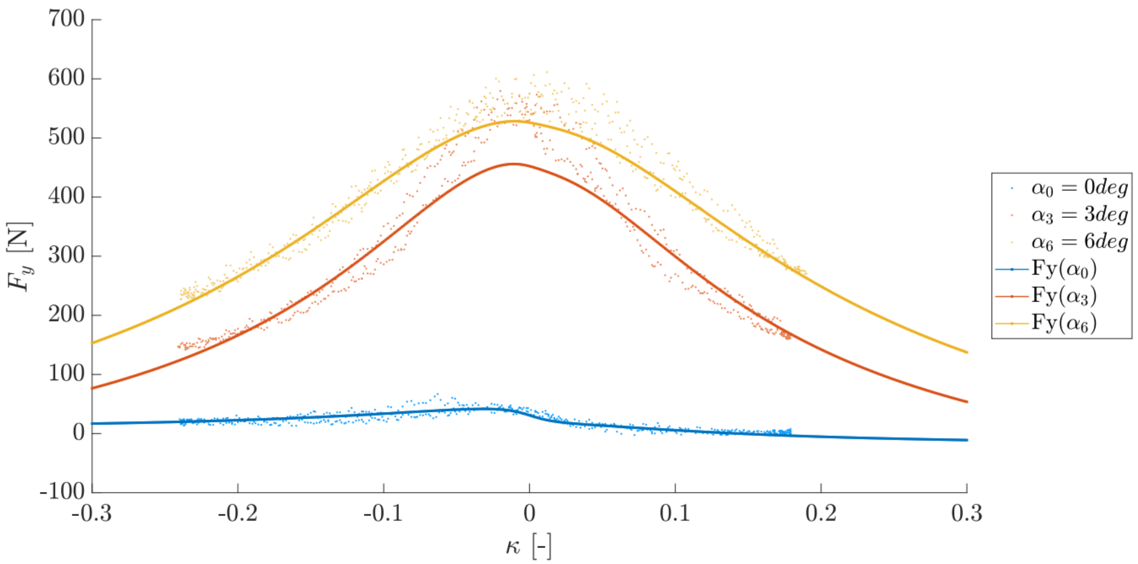
UNIVERSITÀ DI TRENTO

Weighting functions of the longitudinal force FX

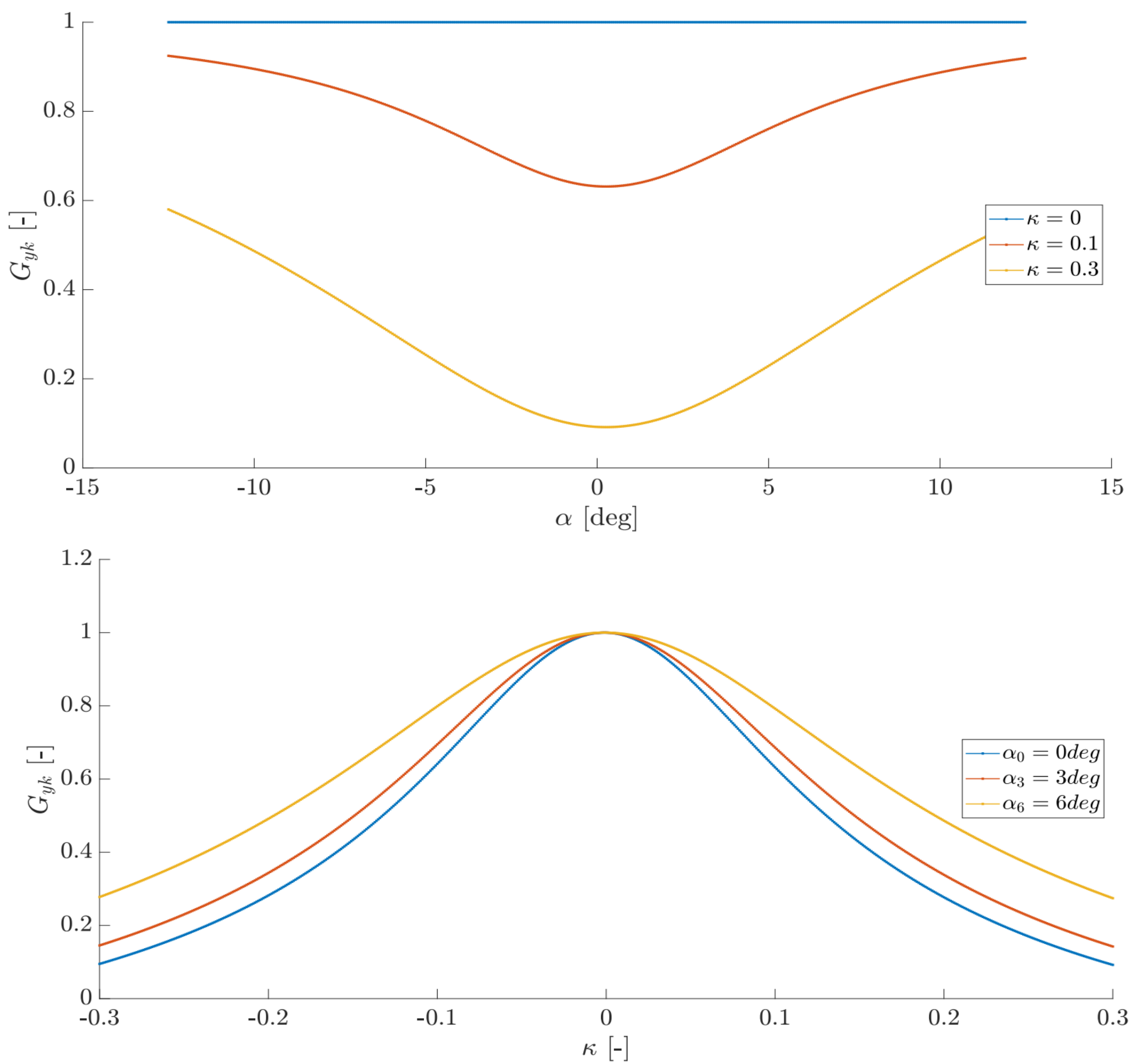
Consalvi, Pettene, Zumerle

Results: combined lateral force

	rBy1	rBy2	rBy3	rCy1	rHy1	rVy1	rVy4	rVy5	rVy6
Guess	7	2.5	0.1	1	0.02	0	30	1.9	10
L bound	~	~	-3	~	~	~	~	~	~
U bound	~	~	-3	~	~	~	~	~	~
Optm par	8.782	1.117e1	4.555e-3	1.223	9.987e-4	-2.381e-2	1.677e1	1.082	5.084e1
$\mathbf{R^2}$					**0.9921**				



Consalvi, Pettene, Zumerle

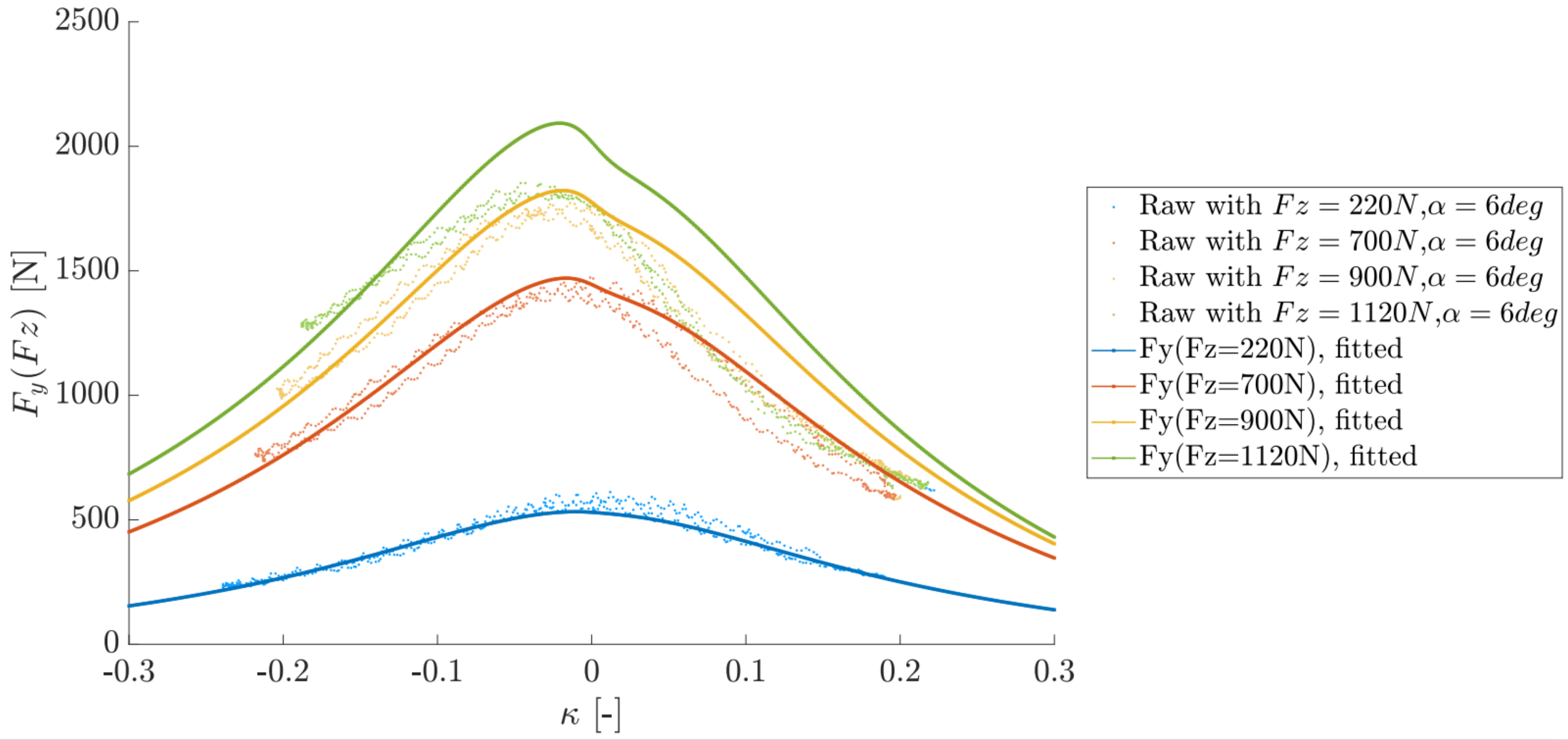


UNIVERSITÀ DI TRENTO

Weighting functions of the lateral force FY

Consalvi, Pettene, Zumerle

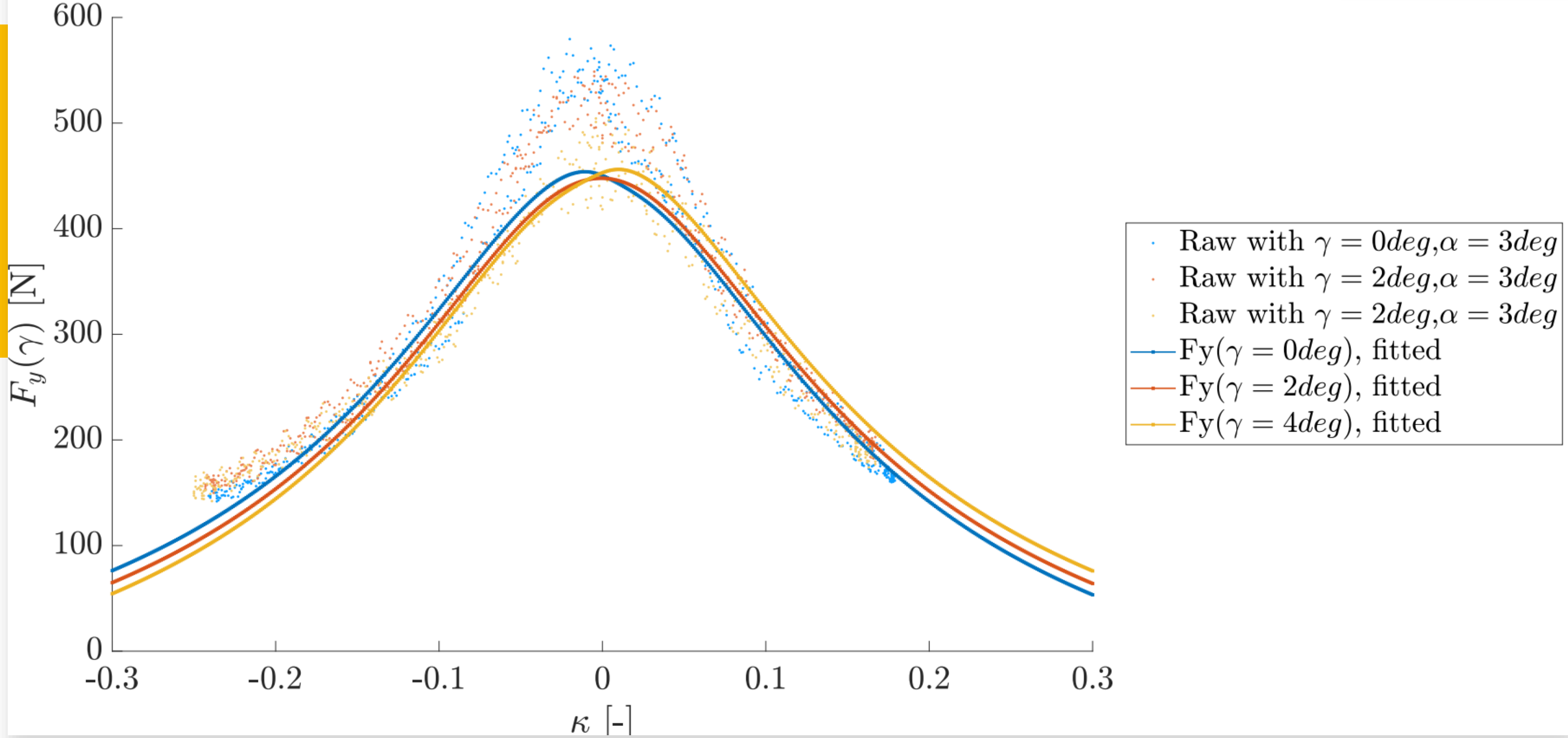
	rVy2
Guess	-0.01
L bound	~
U bound	~
Optm par	-1.736e-2
R^2	**0.9709**



UNIVERSITÀ DI TRENTO

Vertical load variation

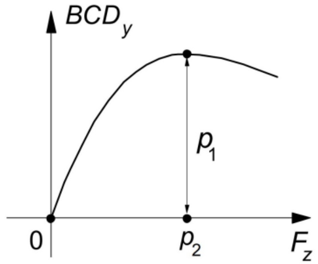
	rVy3
Guess	1
L bound	0.7
U bound	~
Optm par	7e-1
R^2	0.9848



Camber angle variation

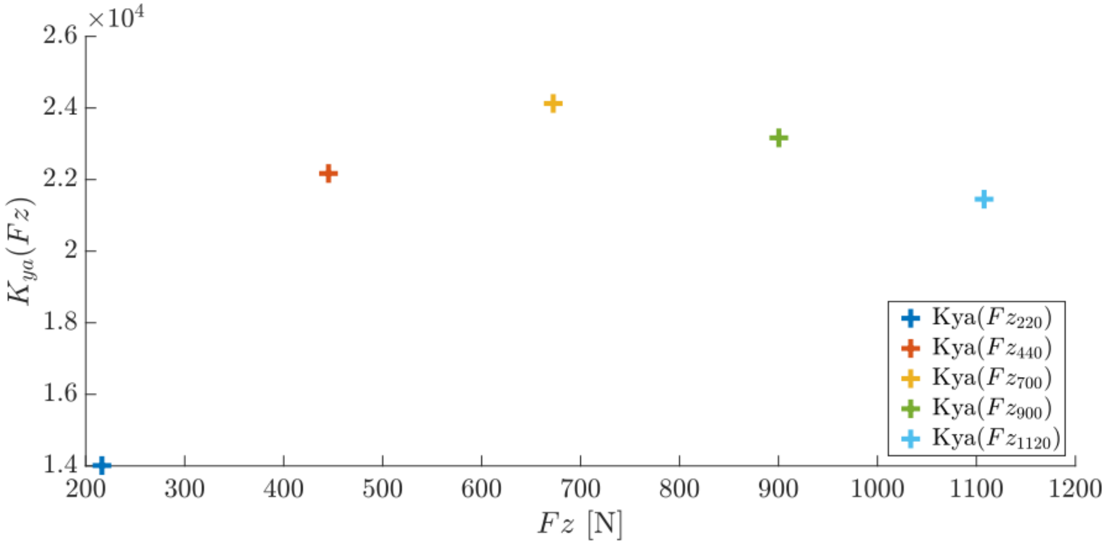
Consalvi, Pettene, Zumerle

Cornering stiffness focus 1/3

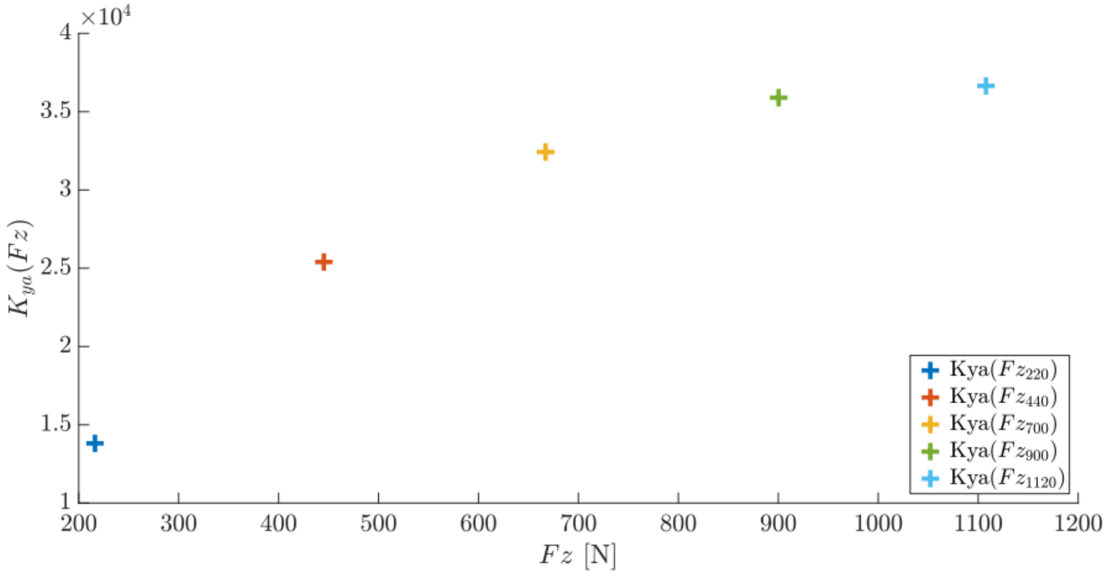


Influence of Pacejka coefficients:

pKy1 on P1, pKy2 on P2

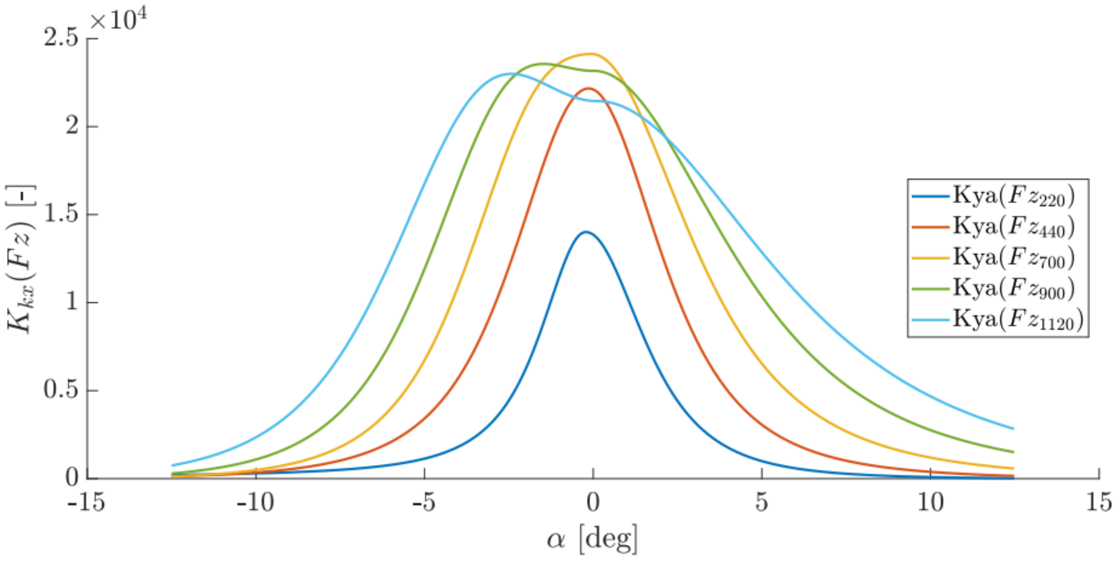


(a) K_{ya} obtained by old fitting parameters.

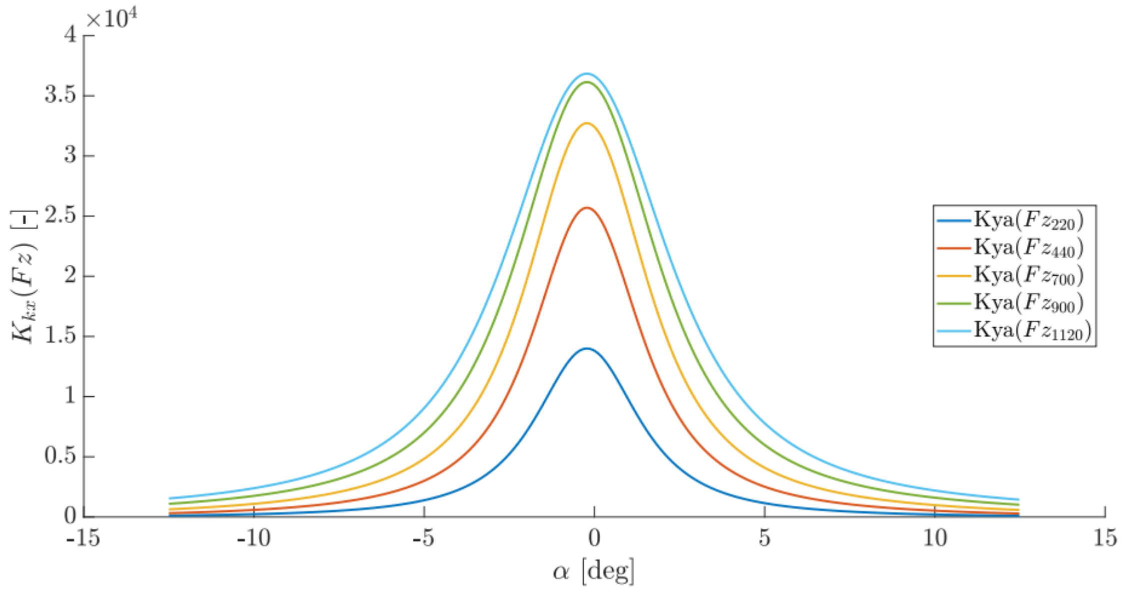


(b) K_{ya} obtained by new fitting parameters.

Cornering stiffness focus 2/3



(a) K_{ya} obtained by old fitting parameters.

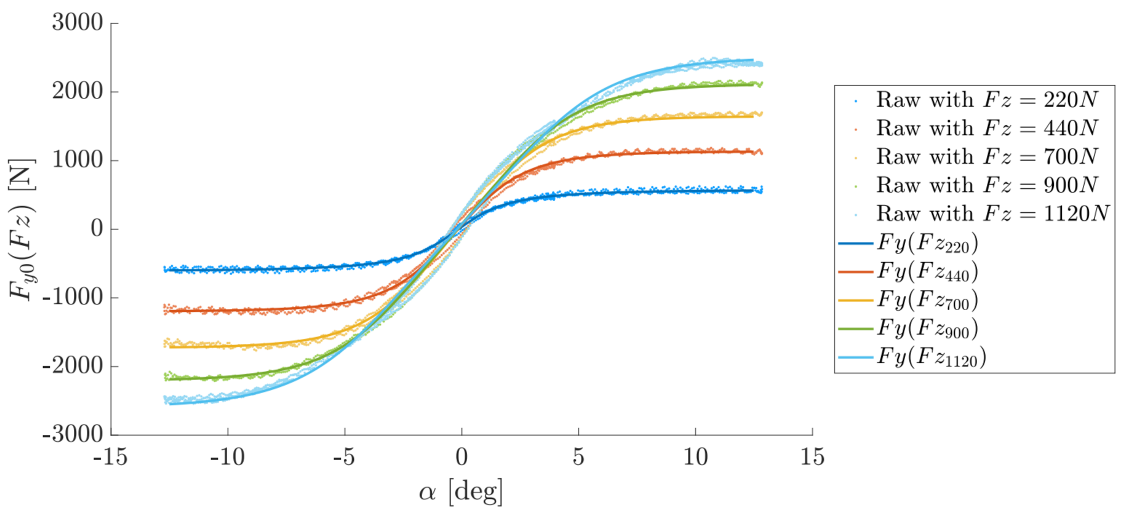


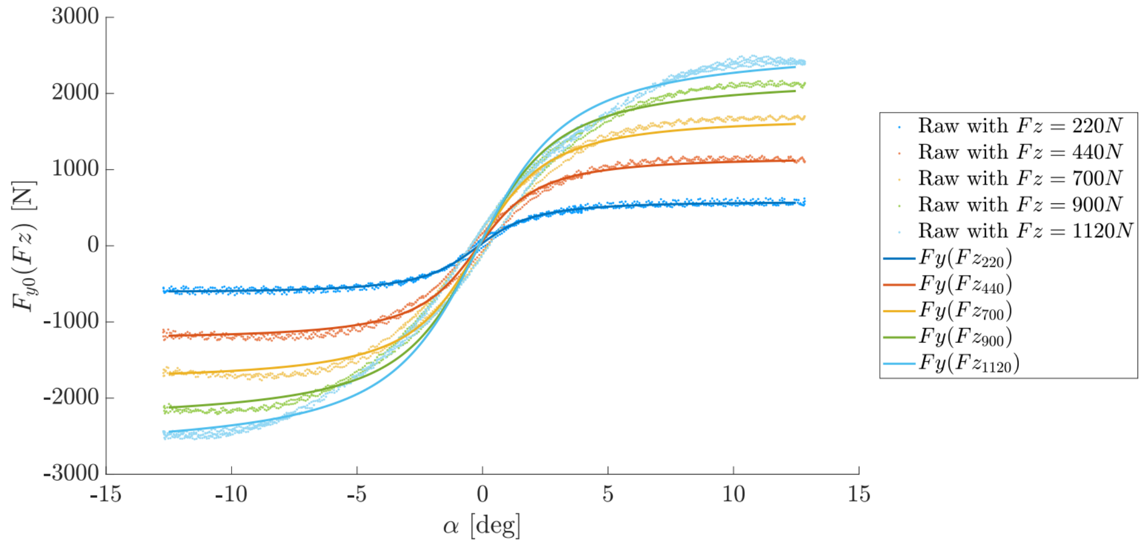
(b) K_{ya} obtained by new fitting parameters.

Consalvi, Pettene, Zumerle

Variable load pure lateral focus

- Worsening of the behaviour, detaching from measurement points





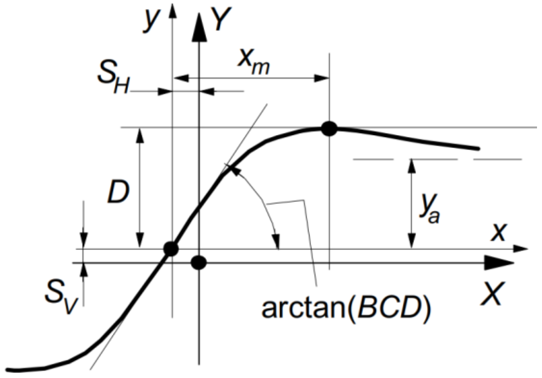
Final coefficients

F_{X0}	F_{Y0}	M_{Z0}
$B_x = 14.77$	$B_y = 11.31$	$B_r = -4.434$
$C_x = 1.538$	$C_y = 1.135$	$B_t = 1.4916$
$D_x = 2.167e3$	$D_y = 2.567e3$	$C_t = 4.999$
$E_x = 0.2788$	$E_y = 0.9474$	$D_r = 48.14$
$S_{Vx} = -213.4$	$S_{Vy} = 47.99$	$D_t = 0.041$
$S_{Hx} = 0.0043$	$S_{Hy} = 0.0038$	$E_t = -0.1087$
$\mu_x = 1.9347$	$\mu_x = 2.3724$	$\alpha_r = 0.0052$
		$\alpha_t = -0.0426$

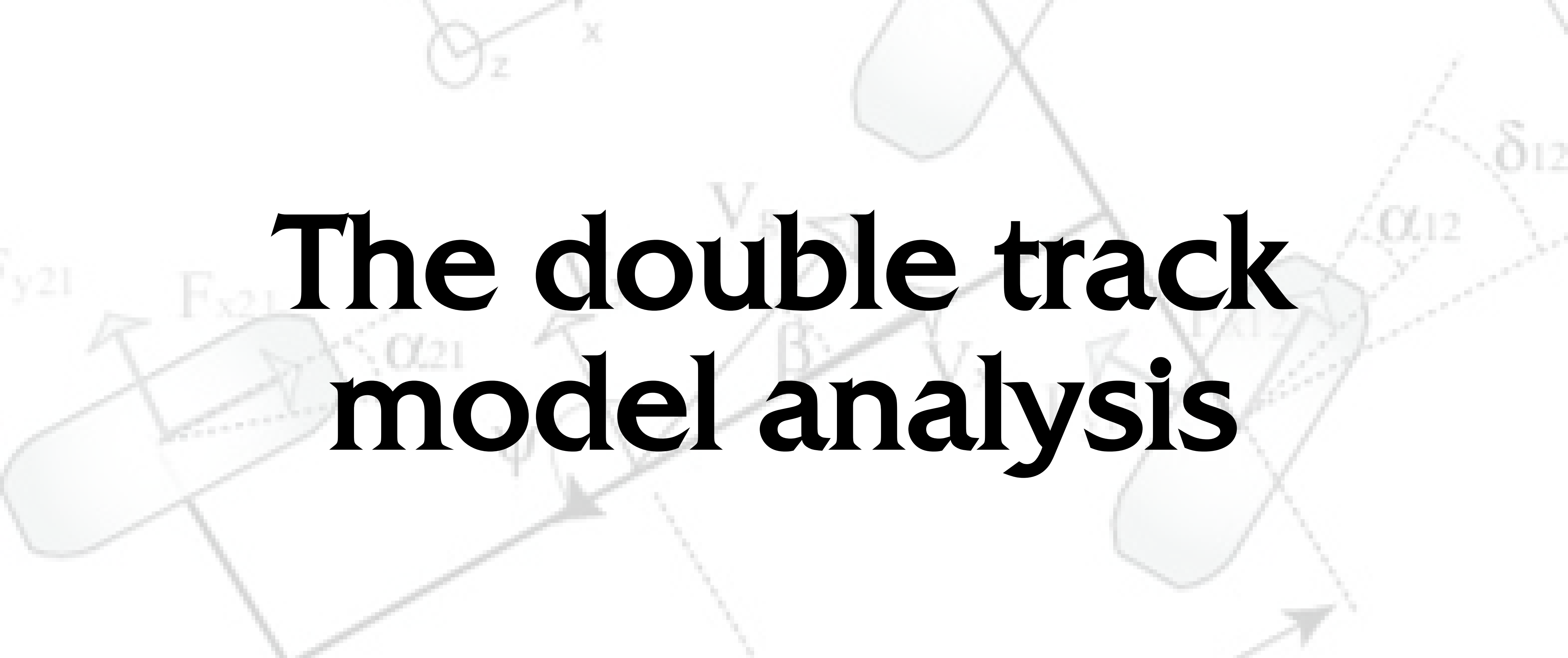
F_{X0}	F_{Y0}	M_{Z0}	F_X	F_Y
$C_x > 0$	$C_y > 0$	$C_t > 0$	$G_{xa} > 0$	$G_{yk} > 0$
$D_x > 0$	$\mu_y > 0$	$B_t > 0$	$B_{xa} > 0$	$B_{yk} > 0$
$E_x \leq 1$	$E_y \leq 1$	$E_t \leq 1$		

Coefficient	Respective parameter	Value	Affects
C	pCx1, pCy1, …	>=1	Cornering stiffness -> shape factor
D (=μ*Fzo)	pDx1, pDy1, … pDx2, pDy2, …	>0	Variable load -> peak value
E	pEx1, pEx2, … pEy1, pEy2, …	<=1	Curvature factor -> more peaky curve
Cornering stiffness	pKx1, pKx2,.. pKy1, pKy2,..	~	Slope at the origin and peak position

Coefficients meanings: examples



Consalvi, Pettene, Zumerle



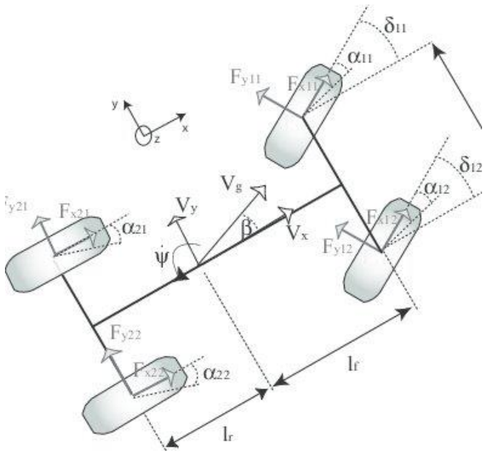
The double track model analysis

Team 6

Double track model

- Overall model to explain the vehicle behaviour

- Assumptions
  - Flat road
  - Negligible effect on suspension on point of contact
  - Vertical steering axis (and no compliance)
  - Only roll motion (no heave, no pitch)
  - No differential effect (open)



Double track model requirements

UNIVERSITÀ DI TRENTO

- Tyre characteristics
- Suspensions characteristics
- Inertias
- Steering system behaviour
- Driveline
- Driver inputs

Double track analysis goals

- Modify the data according to the provided Vehicle_data.m and add the already founded tire fitting data
- Set up tests and collect corresponding data
  - Speed ramp test
  - Steer ramp test
- Compute the main parameters to evaluate the model.
- Evaluate the effects of
  - Suspension stiffness
  - Static toe angle
  - Camber angle

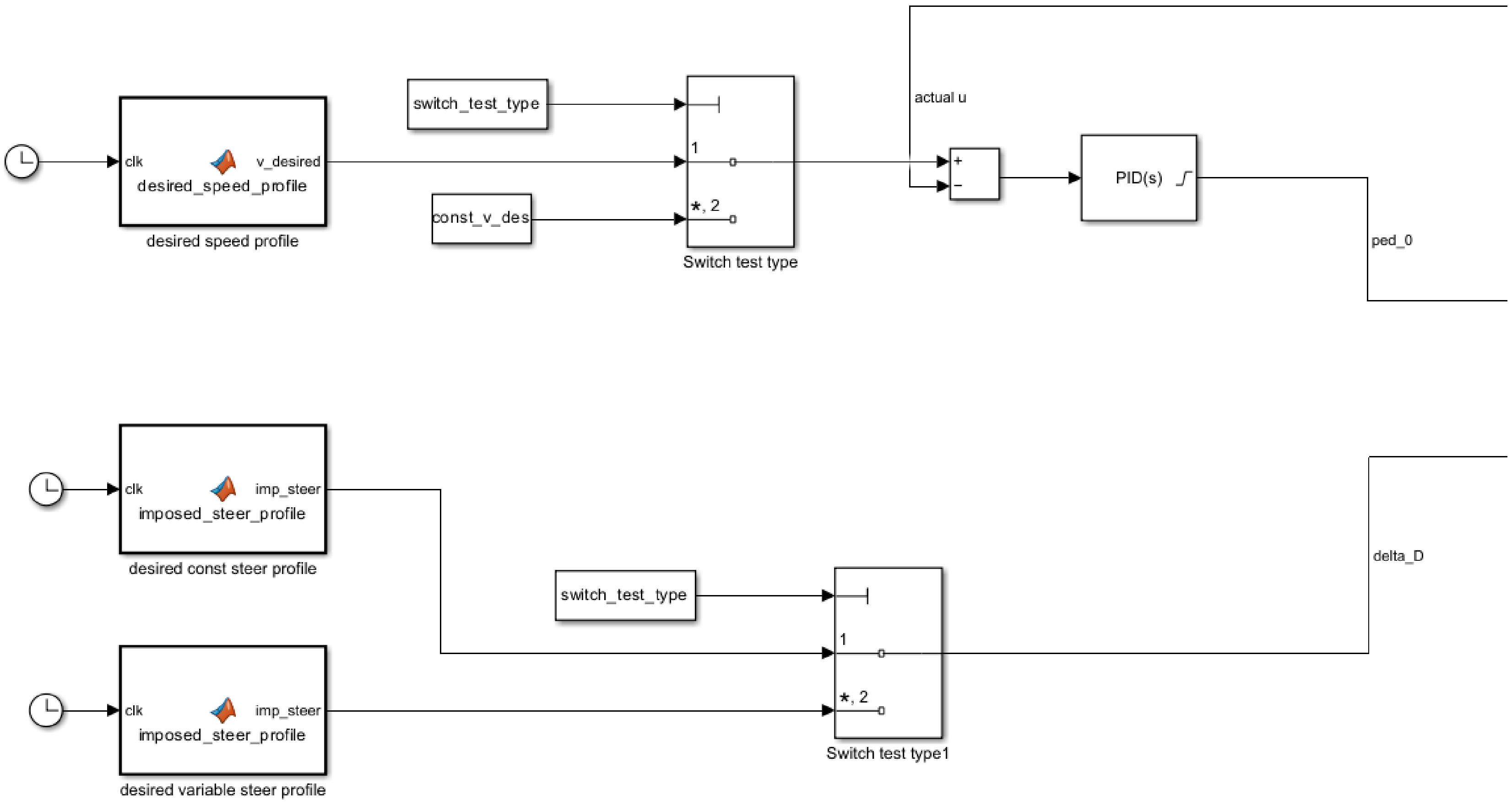
Use of the model

```
%% Define initial conditions for the simulation and type of test
% ----------------------------
% Description:
%
% - if switch_test_type = 1 -> speed ramp test at constant steering angle
% - if switch_test_type = 2 -> steer ramp test at constant forward speed

V0 = 5/3.6; % Initial speed
X0 = loadInitialConditions(V0);
V_final = 95/3.6; % [m/s]
t1_speed = 1;
t1_steering = 0.5;
const_steer_angle = 15; % [deg]

t1_ramp_steer = 15;
deltaH_final = 25; % [deg]
const_v_des = 70/3.6; % [m/s]

switch_test_type = 1; %1 = speed ramp test with const steer, 2 = steer ramp test  with const speed;
```

Evaluation of the results

```
%% Post-Processing
% ----------------------------
dataAnalysis(model_sim,vehicle_data,Ts,switch_test_type);

effect_suspensions(vehicle_data,Ts,Tf);
vehicle_data = getVehicleDataStruct();
effect_toe(vehicle_data,Ts,Tf);
vehicle_data = getVehicleDataStruct();
effect_camber(vehicle_data,Ts,Tf);

vehicleAnimation(model_sim,vehicle_data,Ts);
```

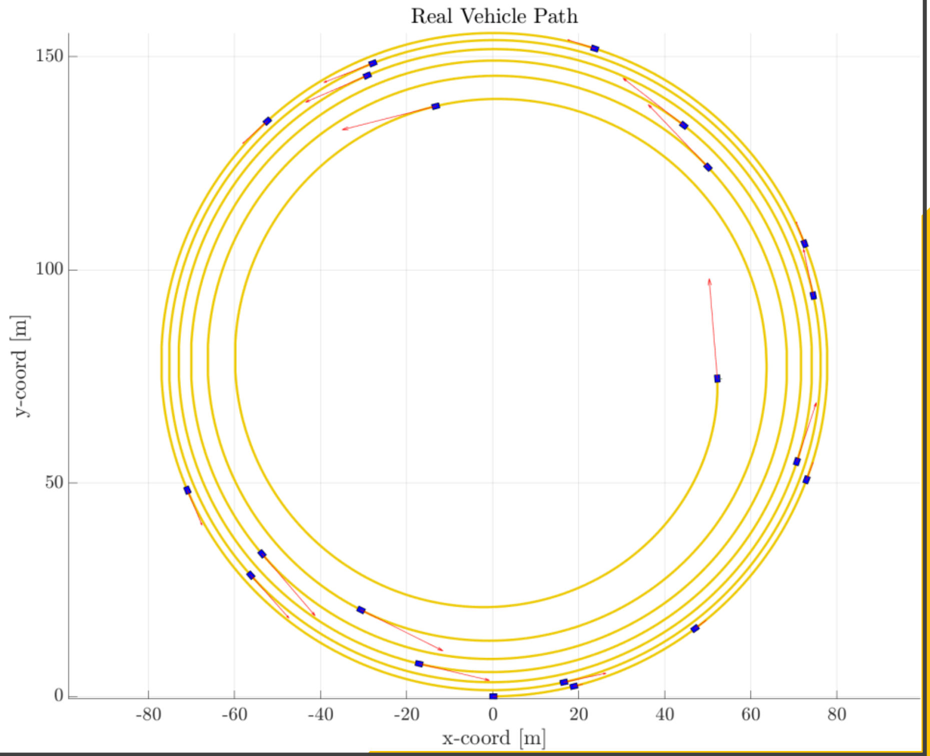
Test: Model implementation



- Switch = 1: speed ramp test
- Switch = 2: steer ramp test

Test 1 : speed ramp test
Parameters and construction

```
function v_desired = desired_speed_profile(clk,t1_speed, V0, V_final, Tf)

    if clk < t1_speed
        v_desired = V0;
    elseif clk >= t1_speed && clk <= Tf
        v_desired = V0 + ((V_final-V0)/(Tf-t1_speed))*(clk - t1_speed);
    else
        error('Errore');
    end

end


if clk < t1_steering
    imp_steer = 0 + ((const_steer_angle-0)/(t1_steering-0))*(clk - 0);
elseif clk >= t1_steering && clk <= Tf
    imp_steer = const_steer_angle;
else
    error('Errore');
end
```

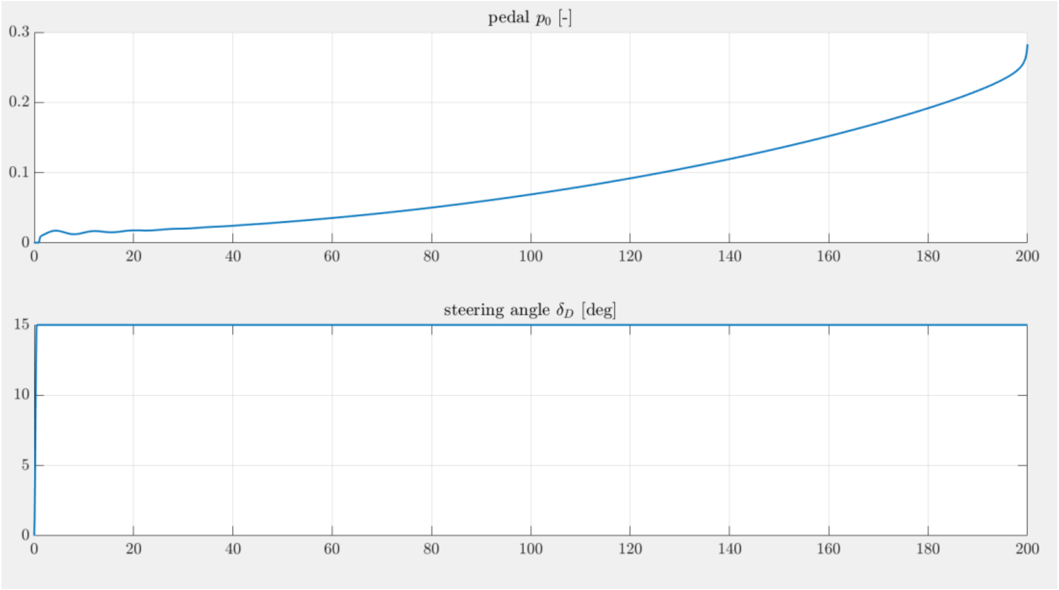


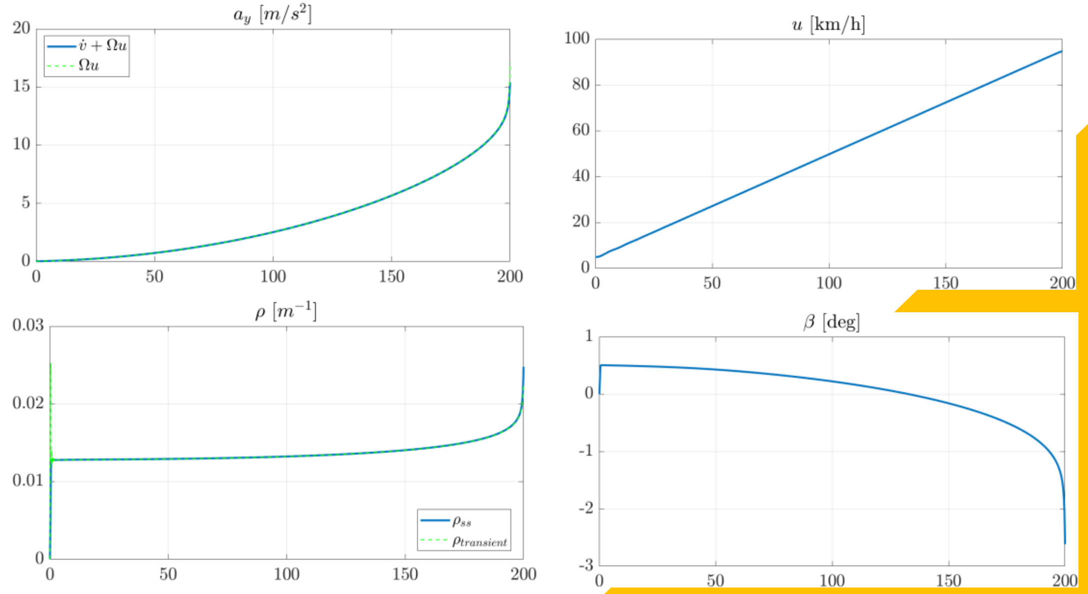
Test 1 : speed ramp test

Imposed values and results

UNIVERSITÀ DI TRENTO

Initial speed	Final speed	Initial steering angle	Constant steering angle	Transition time	Simulation time
5 km/h	95 km/h	0°	15°	1 s	200 s

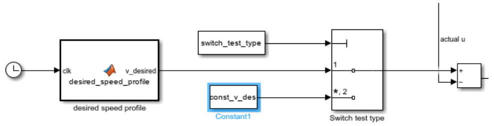


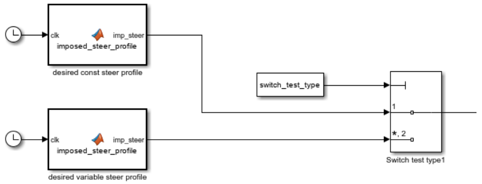


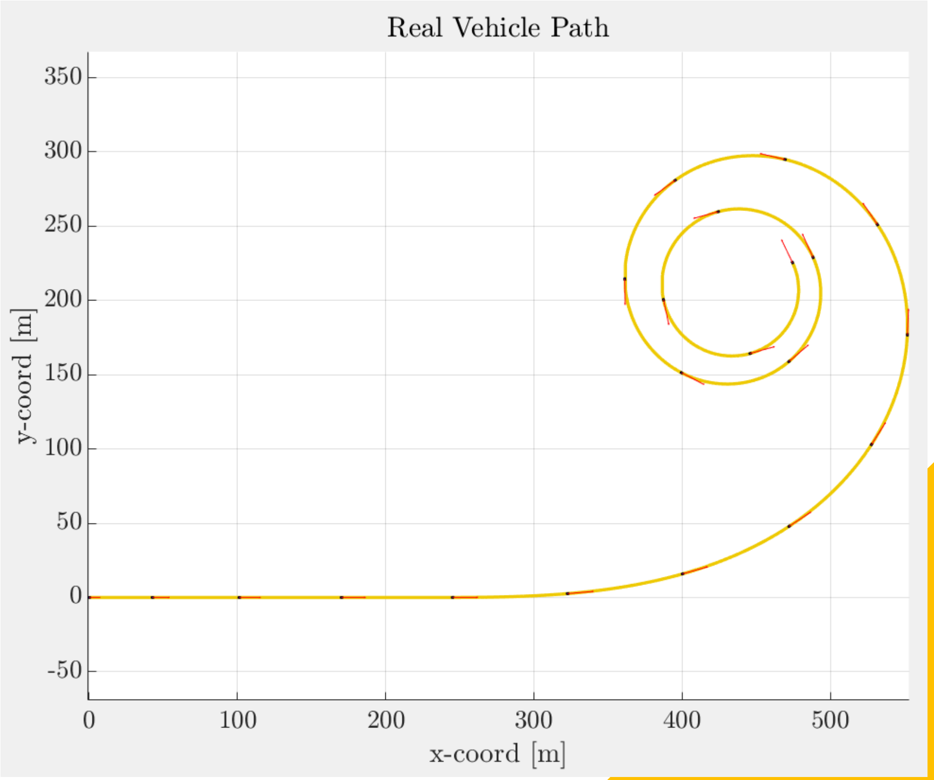
Test 2 : steer ramp test

Parameters and construction

```
function imp_steer = imposed_steer_profile(clk, t1_ramp_steer, Tf, deltaH_final)

    % ------------------------------------------------------------------
    %% Function purpose: compute the imposed steer profile

    % Requested steering angle [deg] at the steering wheel for this time step

    if clk < t1_ramp_steer
        imp_steer = 0;
    elseif clk >= t1_ramp_steer && clk <= Tf
        imp_steer = (deltaH_final/(Tf-t1_ramp_steer))*(clk - t1_ramp_steer);
    else
        error('Errore');
    end
    %10*sin(2*pi*0.18*clk);

end
```



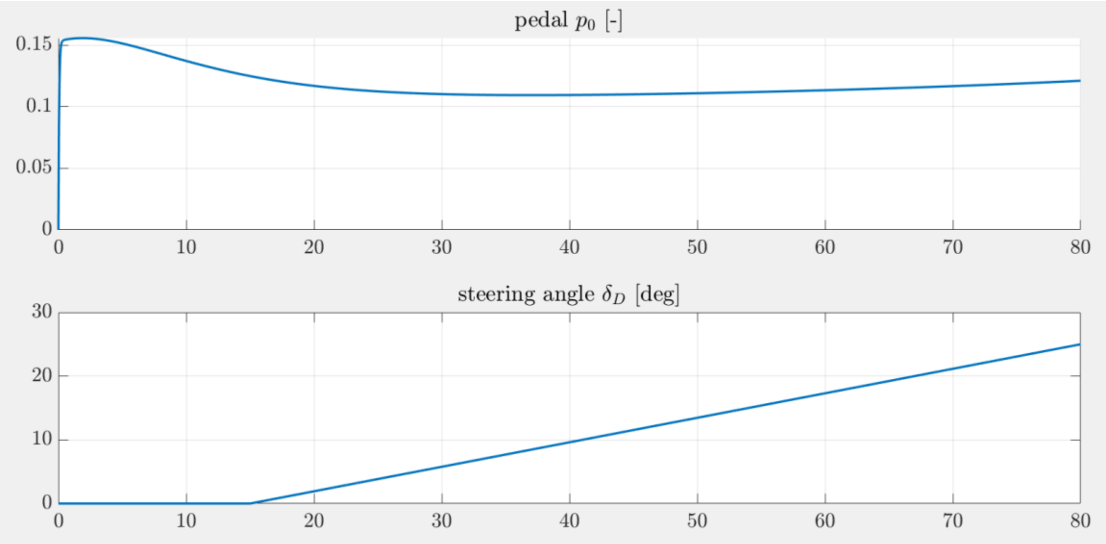


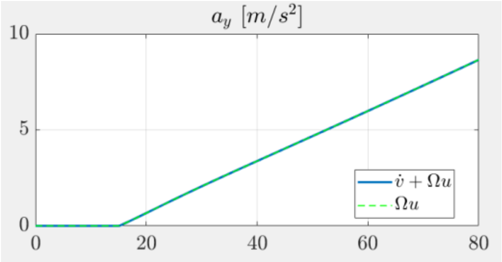


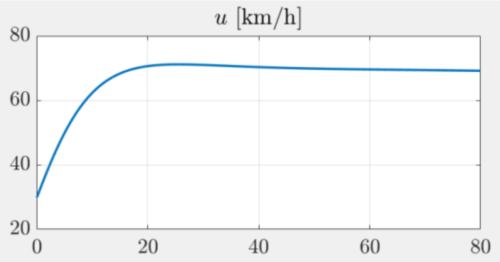
Test 2 : steer ramp test

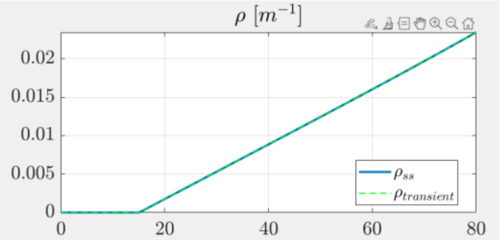
Imposed values and results

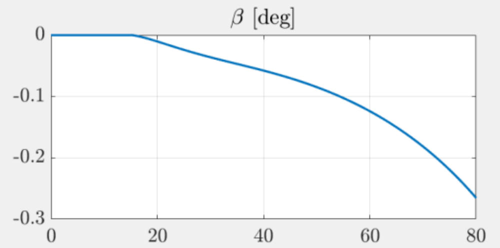
Initial speed	Constant speed	Initial steering angle	Final steering angle	Transition time	Simulation time
30 km/h	70 km/h	0°	25°	15s	80 s











Lateral load transfer

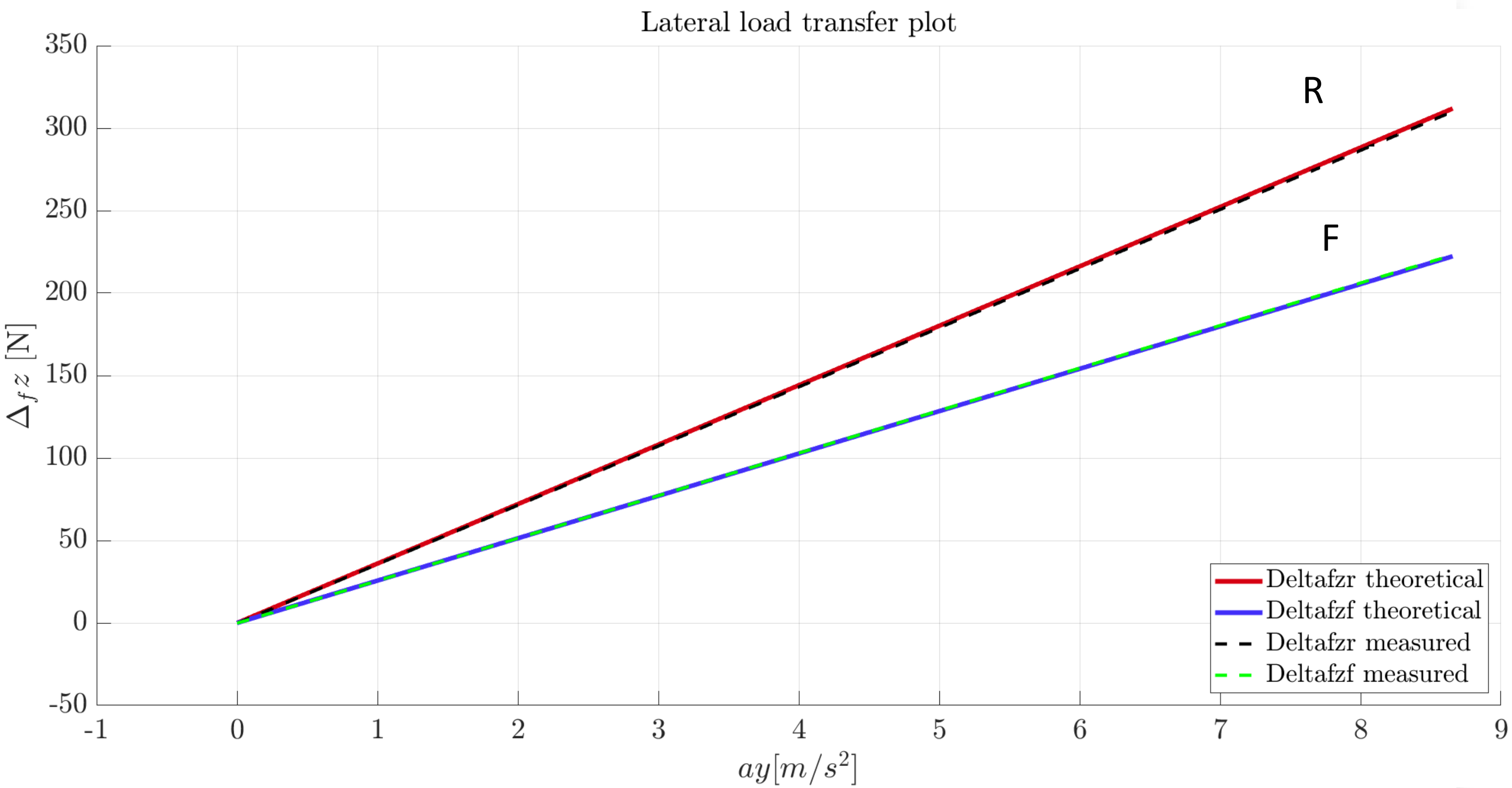
$$\Delta Fz_r = \frac{ma_y}{W_r}\left(\frac{L_f}{L}h_{rr} + (1-\epsilon_\phi)h_s\right)$$

$$\Delta Fz_f = \frac{ma_y}{W_f}\left(\frac{L_r}{L}h_{rf} + \epsilon_\phi h_s\right)$$

$$\epsilon_\phi = \frac{K_{\phi f}}{K_{\phi f} + K_{\phi r}}$$

- Suspension deformation case of study: suspension stiffness much more important than the tyre effect.
- Instantaneous lateral load transfer & elastic lateral load transfer (from spring deformation).

Lateral load transfer plot



$$a_y = \dot{v} + \Omega \cdot u$$

$$a_{y_{lin}} = \Omega \cdot u$$

Normalized axle characteristics

Lateral forces from the model:

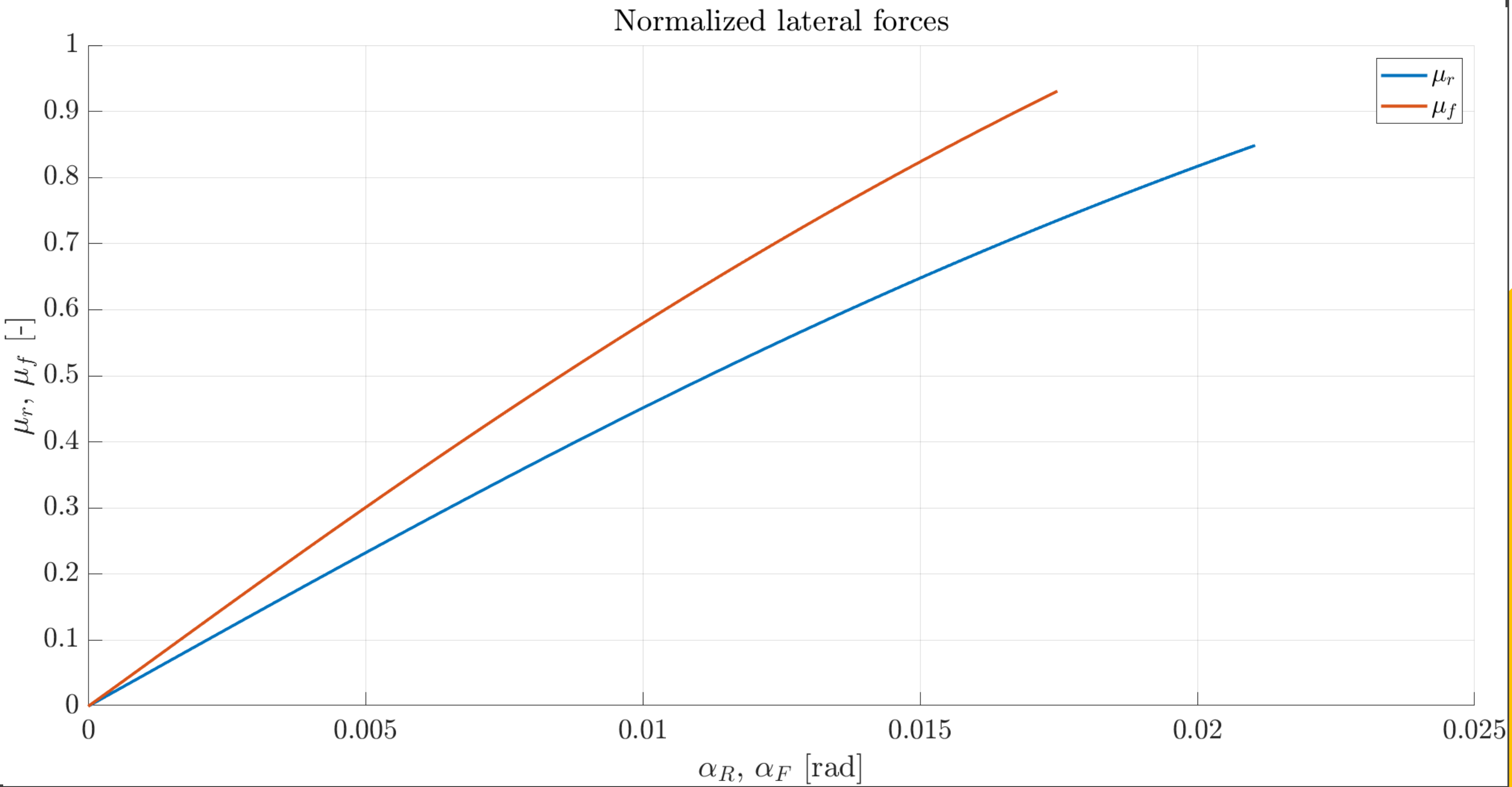
$$Fyr = Fy_{rl} + Fy_{rr}$$

$$Fyf = Fy_{fl} + Fy_{fr} + \sin(\delta_{fl}) \cdot Fx_{fl} + \sin(\delta_{fr}) \cdot Fx_{fr}$$

$$Fzf_0 = m \cdot g \cdot \frac{Lr}{L}$$

$$Fzr_0 = m \cdot g \cdot \frac{Lf}{L}$$

$$\Rightarrow \frac{Fyr}{Fzr_0} = \mu_r \quad \frac{Fyf}{Fzf_0} = \mu_f$$



Normalized axle characteristics

Static lateral forces:

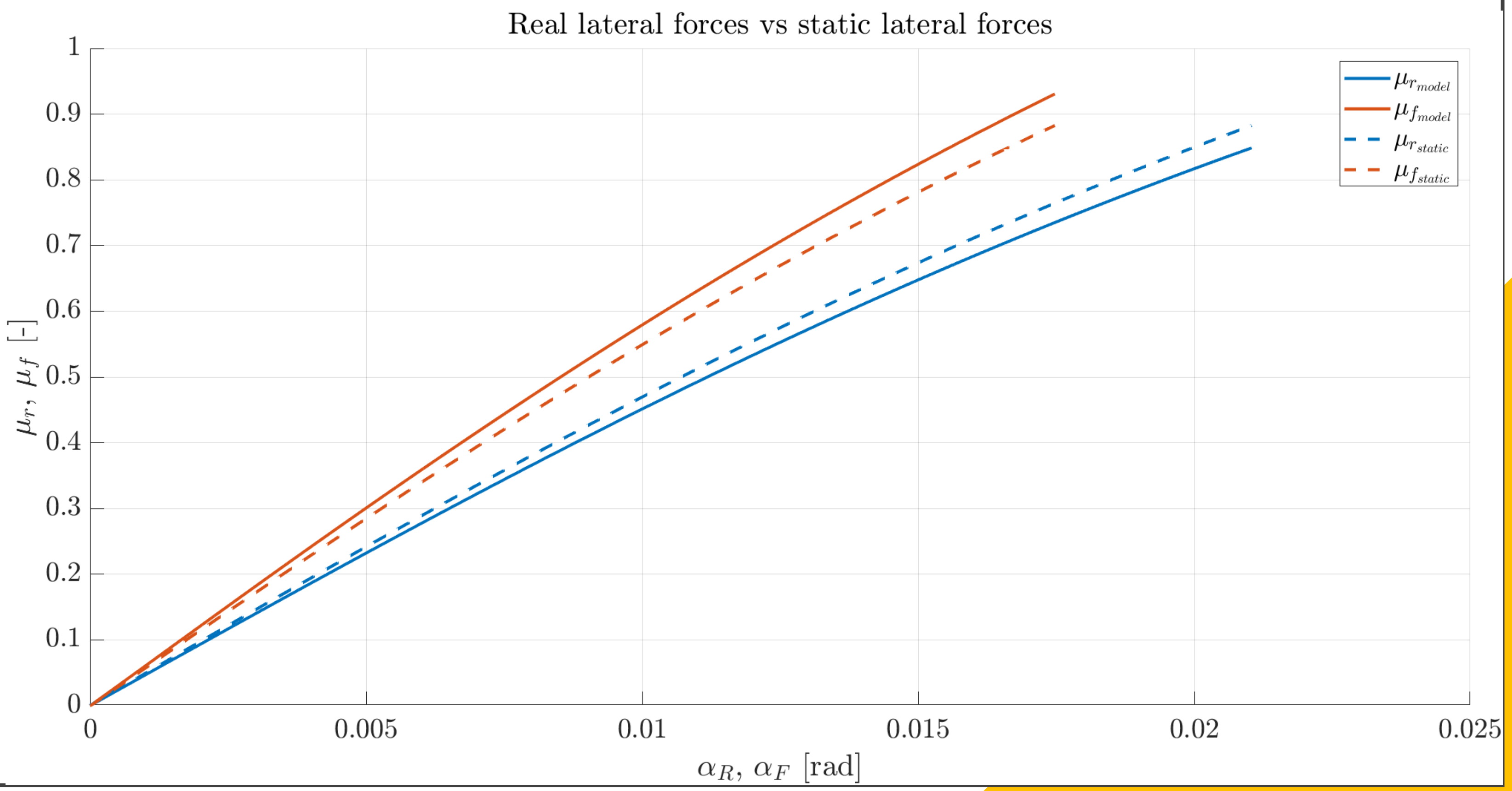
$$Fyr = m \cdot ay \cdot \frac{Lf}{L}$$

$$Fyf = m \cdot ay \cdot \frac{Lr}{L}$$

Lateral force balance:

$$Fyf = ma_y\frac{Lr}{L} + I_{zz}\frac{\dot{\Omega}}{L} - \frac{M_z}{L}$$

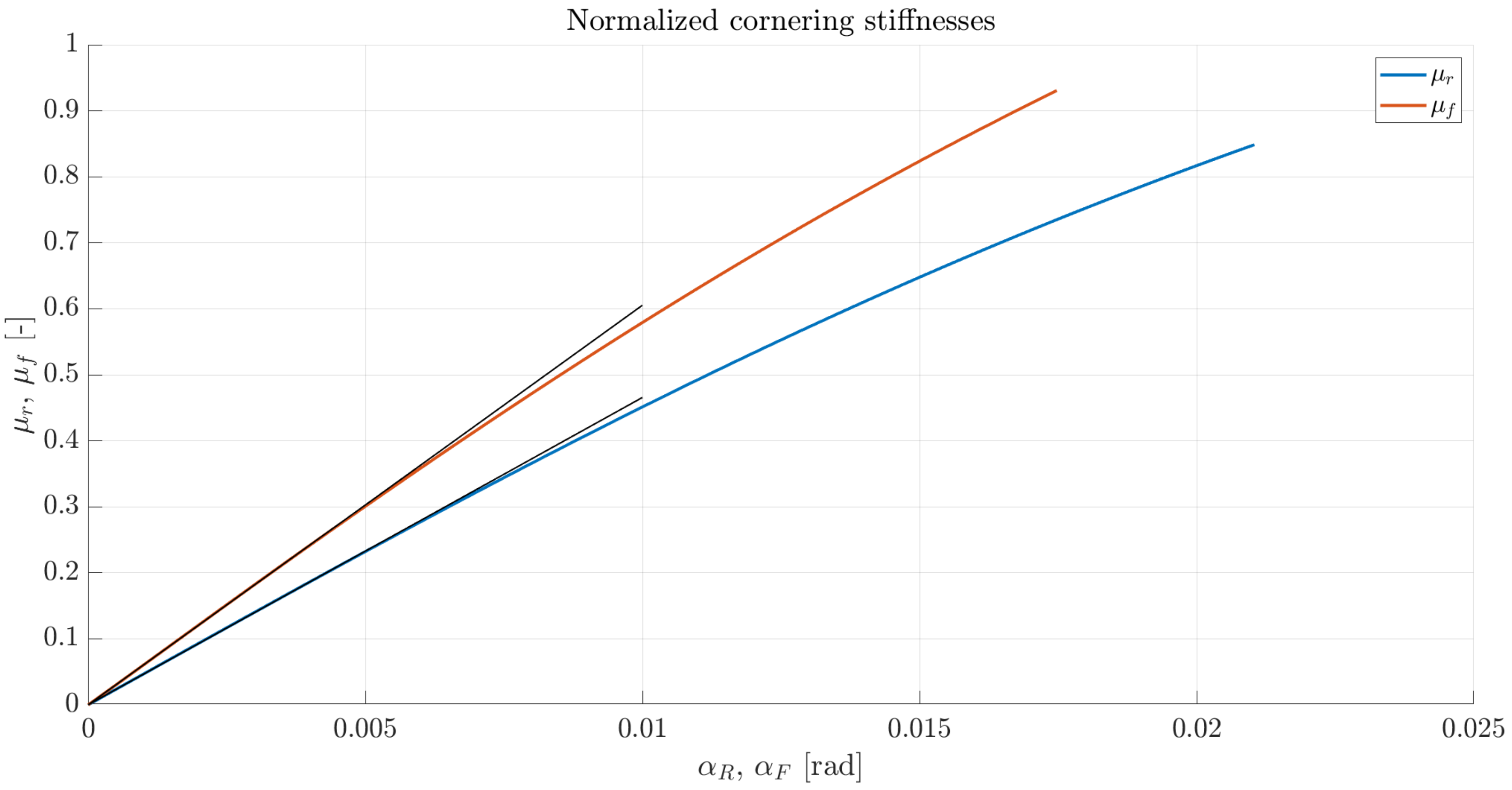
$$Fyr = ma_y\frac{Lf}{L} - I_{zz}\frac{\dot{\Omega}}{L} + \frac{M_z}{L}$$



Consalvi, Pettene, Zumerle

Normalized cornering stiffnesses

UNIVERSITÀ DI TRENTO



$$C_{y_r} = \frac{\partial \mu_r}{\partial \alpha_r}$$

$$C_{y_f} = \frac{\partial \mu_f}{\partial \alpha_f}$$

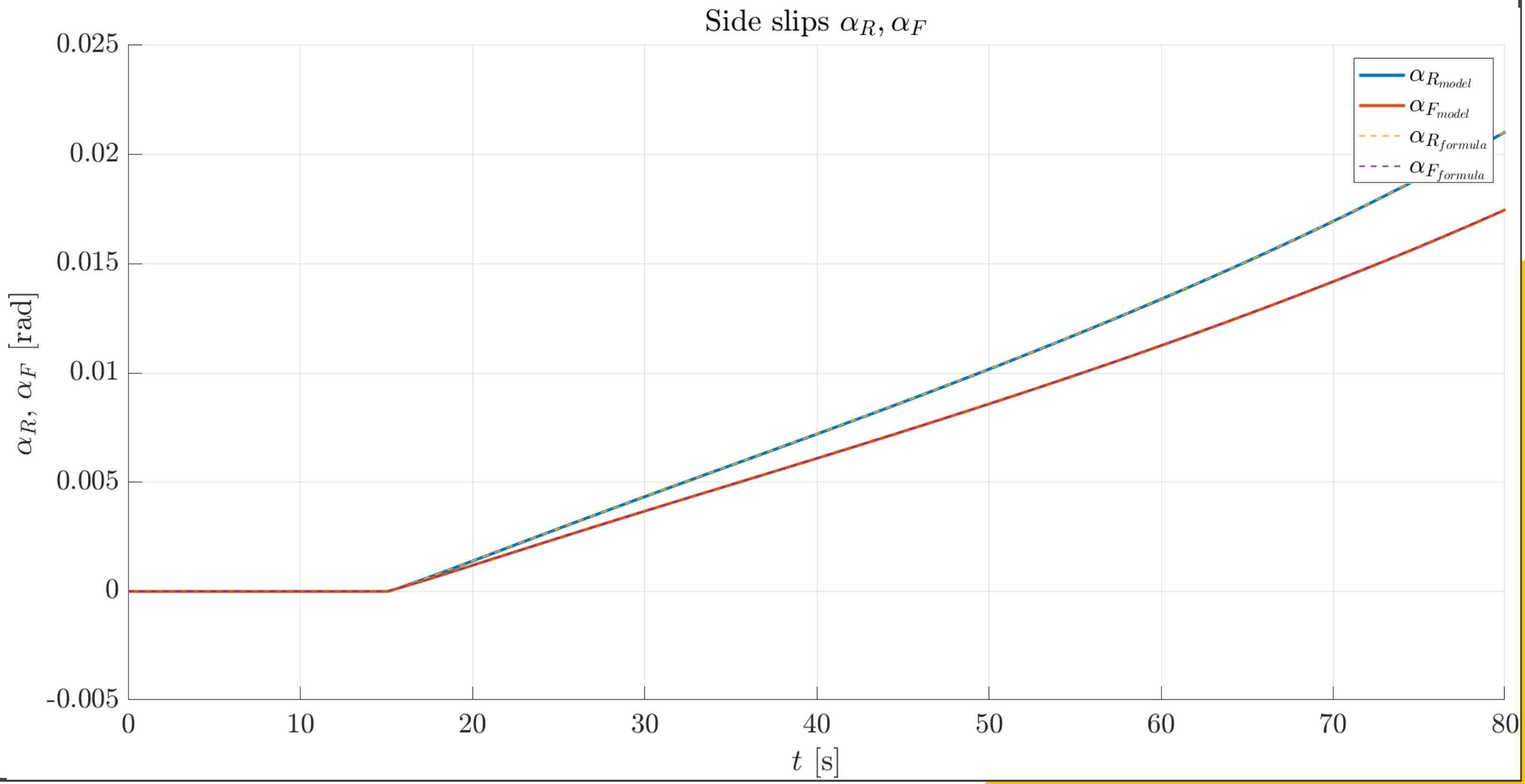
Side slip angles

$$\alpha_r = \frac{\alpha_{rr} + \alpha_{rl}}{2}$$

$$\alpha_f = \frac{\alpha_{fr} + \alpha_{fl}}{2}$$

$$\alpha_r = -\beta + \frac{\Omega}{u} Lr$$

$$\alpha_f = \delta - \beta - \frac{\Omega}{u} Lf$$



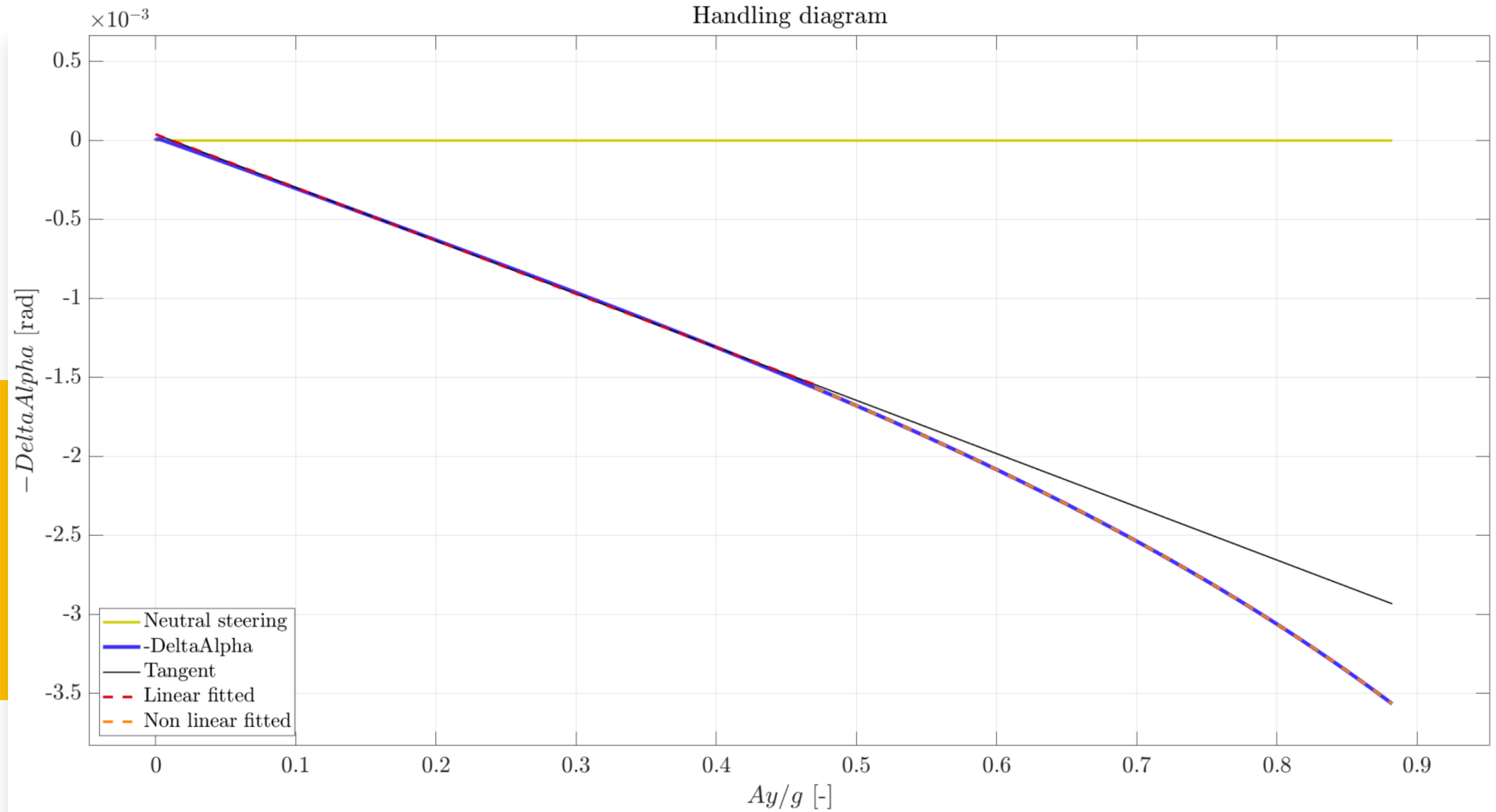
Handling diagram

- Based on the *Steering characteristic* equation:

$$\delta_h \tau_h - \rho_0 L = -\left(\alpha_r\left(\frac{ay}{g}\right) - \alpha_f\left(\frac{ay}{g}\right)\right)$$

- It is the difference between the selected trajectory vs the actual assumed by the vehicle.
- Characterized by linear and non-linear parts.

$$\delta_h \tau_h - \rho_0 L = K_{us} \cdot \left(\frac{a_y}{g}\right) + \hat{K_{us}}\left(\frac{a_y}{g}\right)$$



$$K_{us} = -0.003369$$

$$\hat{K_{us_3}} = 0.005455$$

$$\hat{K_{us_2}} = -0.004829$$

$$\hat{K_{us_4}} = -0.003440$$

UNIVERSITÀ DI TRENTO

Plot of the handling diagram

$$K_{us} = -0.003369$$

Understeering gradients comparison

- To check the two definition change to test 1: need only variation of curvature
- Fitted Kus is founded in normalized acceleration term
- Theoretical Kus is founded without normalizing the acceleration

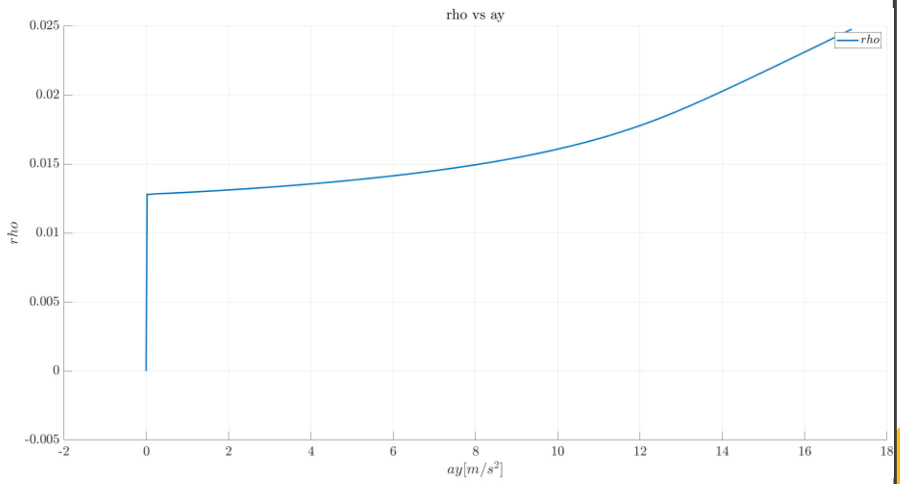
$$\frac{\partial \rho}{\partial a_y} = \frac{1}{Lg}\left(\frac{1}{C_{y_r}} - \frac{1}{C_{y_f}}\right)$$

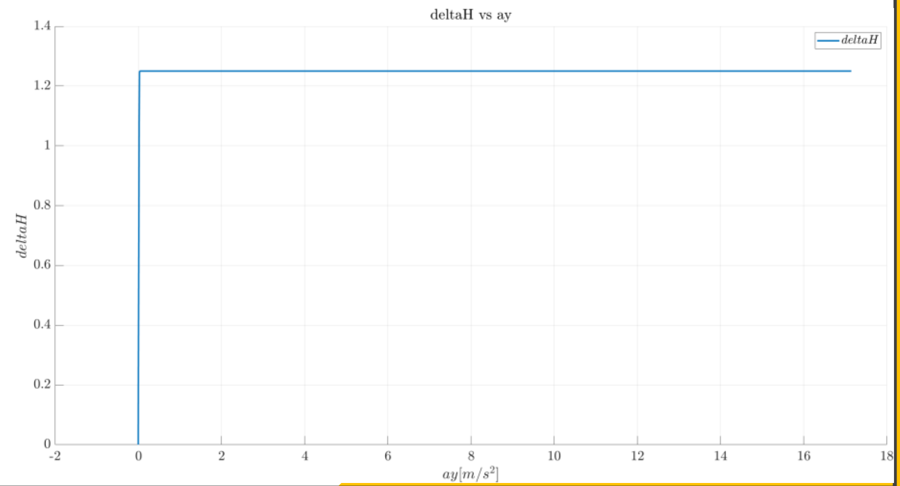
$$\rho L = \tau_H \delta_H + \Delta\alpha$$

$$\frac{\partial \rho}{\partial a_y} = \frac{1}{L}\frac{\partial \Delta\alpha}{\partial a_y}$$

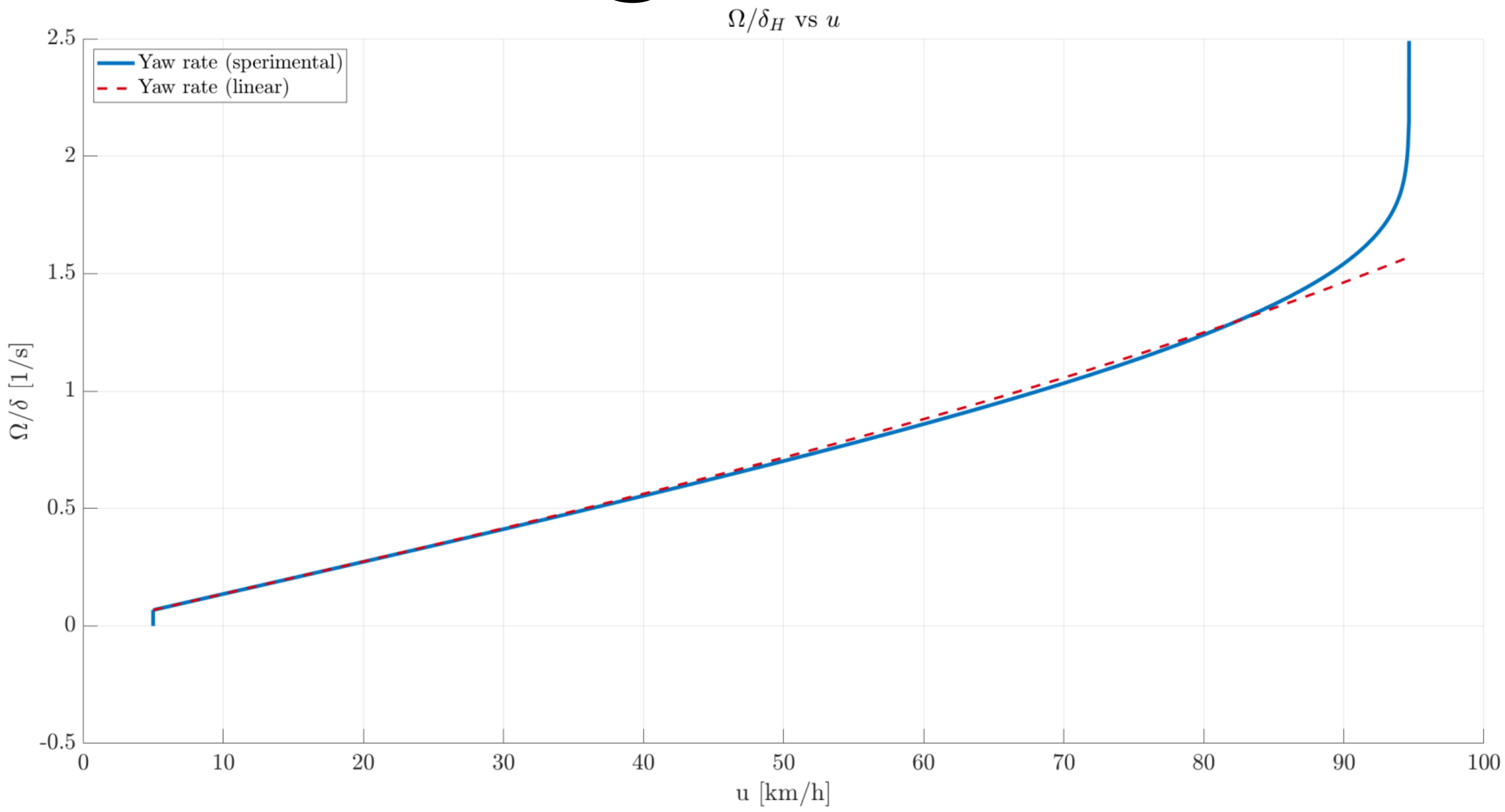
$$K_{us\,fitted} = -g \cdot L \cdot \frac{\delta \rho}{\delta a_y}$$

$$K_{us} = -0.003320$$





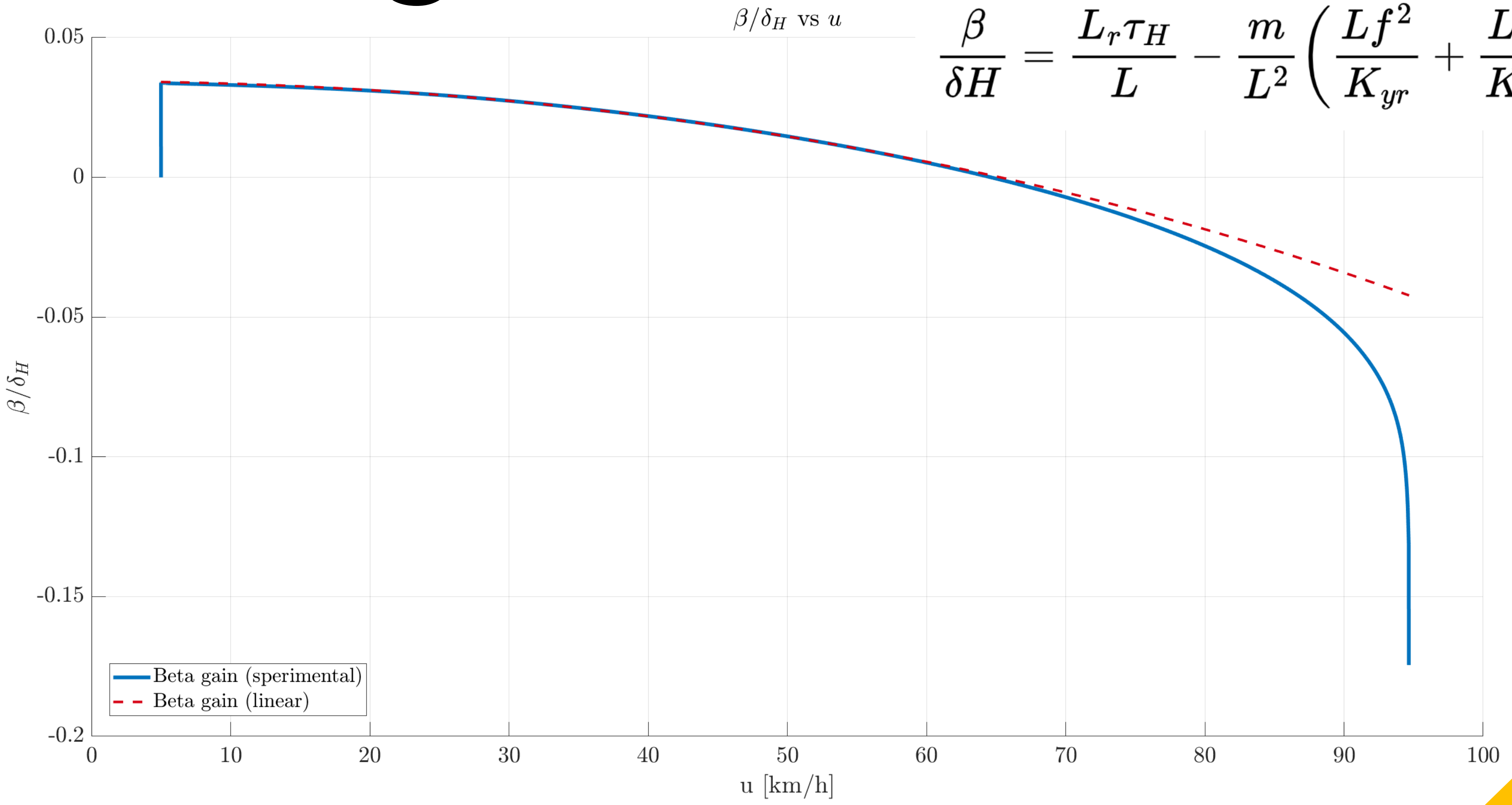
Yaw rate gain



$$\frac{\Omega}{\delta H} = \frac{\frac{U}{L}\tau_H}{1 + \frac{u^2}{L}K_{us}}$$

Beta gain rate

$$\frac{\beta}{\delta H} = \frac{L_r \tau_H}{L} - \frac{m}{L^2}\left(\frac{Lf^2}{K_{yr}} + \frac{Lr^2}{K_{yf}}\right)\tau_H\left(\frac{u^2}{L + K_{us}u^2}\right)$$



Variations applied on the model

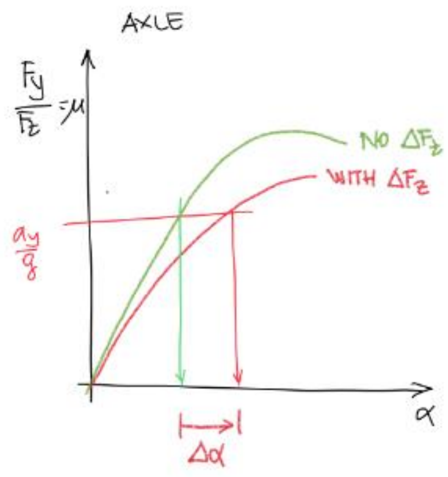
- Variation on stiffness effect
- Variation on toe effect
- Variation on camber angle

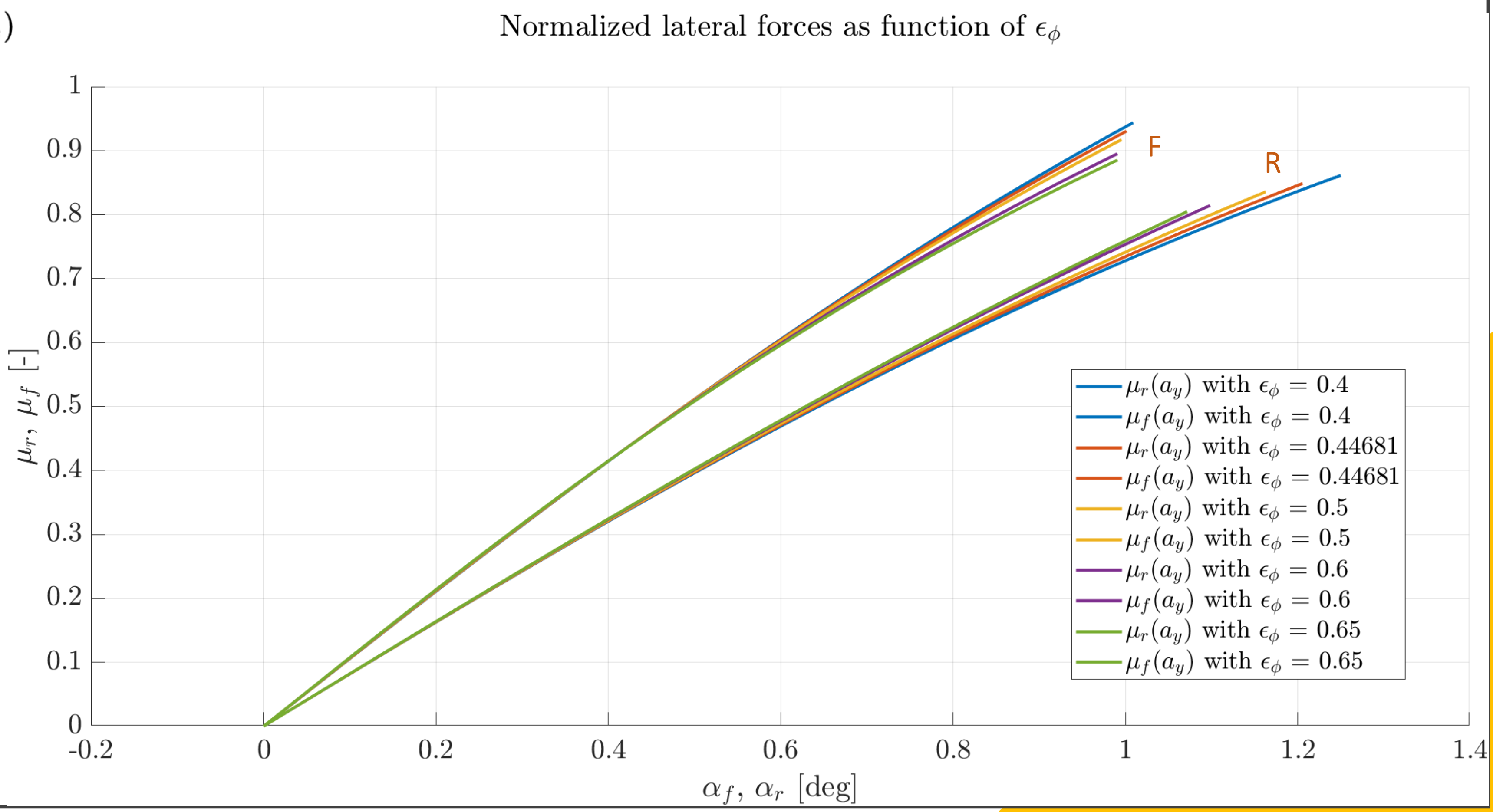
Effect of suspensions stiffness

$$\Delta F z_r = \frac{m a_y}{w_f}\left(\frac{Lf}{L} h_{rr} + (1-\epsilon_\phi) h_s\right)$$

$$\Delta F z_f = \frac{m a_y}{w_f}\left(\frac{Lr}{L} h_{rf} + \epsilon_\phi h_s\right)$$

$$\epsilon_\phi = \frac{k_{\phi f}}{k_{\phi f} + k_{\phi r}}$$

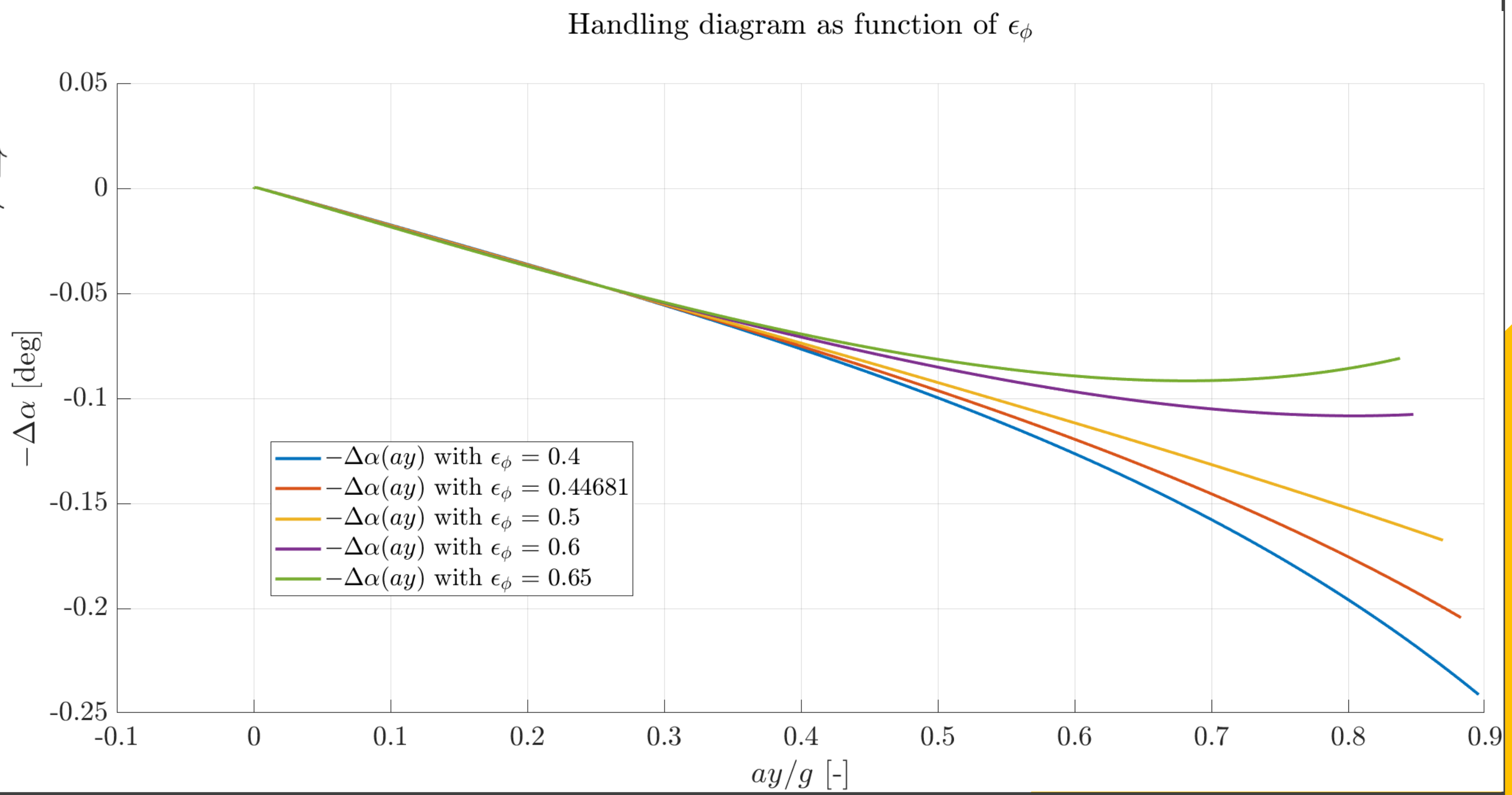




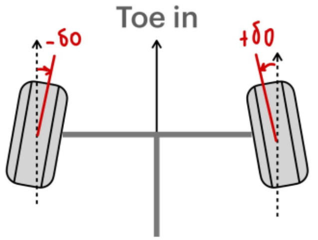
Effect of suspensions stiffness

UNIVERSITÀ DI TRENTO

$$\Delta Fzf \uparrow \;\Rightarrow\; \alpha_f \uparrow \;\Rightarrow\; US \uparrow$$
$$\Delta Fzr \uparrow \;\Rightarrow\; \alpha_r \uparrow \;\Rightarrow\; OS \uparrow$$

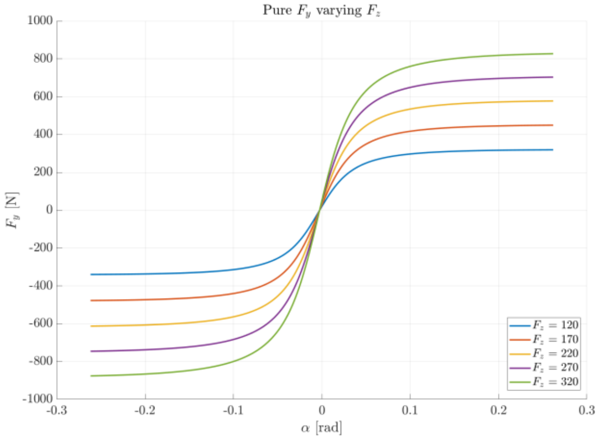


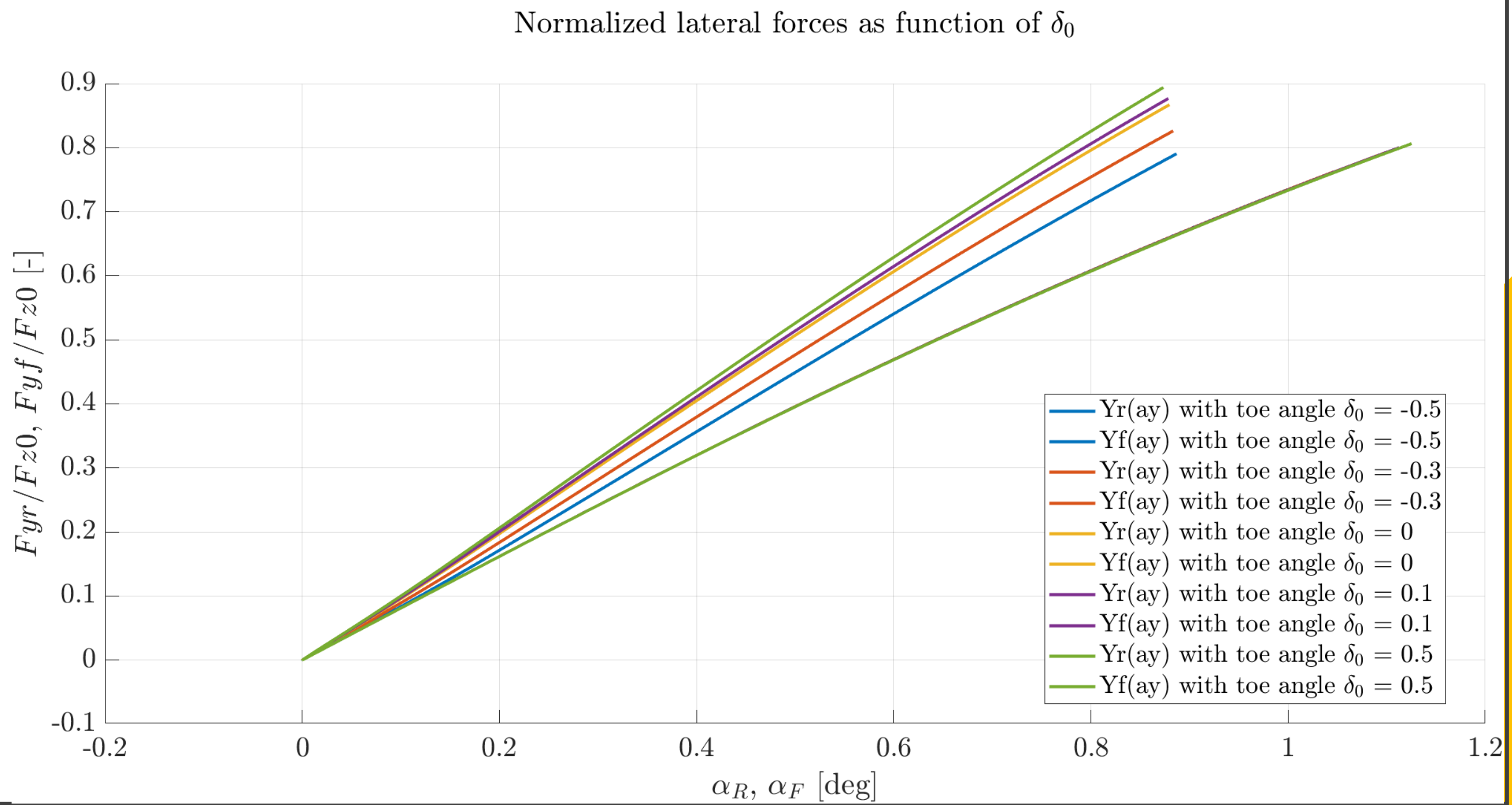
Effect of toe angle



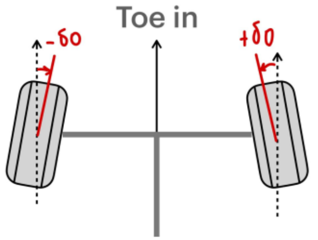

```
function [delta__fr, delta__fl] = perfectAcker(delta,vehicle_data)

    % ----------------------------------------------------------------
    %% Function purpose: compute steering angles for front wheels, with
    %%                    perfect Ackerman steering model
    % ----------------------------------------------------------------

    % Load vehicle data
    Lf = vehicle_data.vehicle.Lf;
    Lr = vehicle_data.vehicle.Lr;
    Wf = vehicle_data.vehicle.Wf;
    delta_0 = vehicle_data.front_wheel.delta_f0*(pi/180);

    % Perfect Ackermann steering law
    delta__fr = atan((2*Lr+2*Lf)*tan(delta)/(Wf*tan(delta)+2*Lr+2*Lf)) + delta_0;
    delta__fl = -atan((2*Lr+2*Lf)*tan(delta)/(Wf*tan(delta)-2*Lr-2*Lf)) - delta_0;

end
```

+ effect of the lateral load transfer



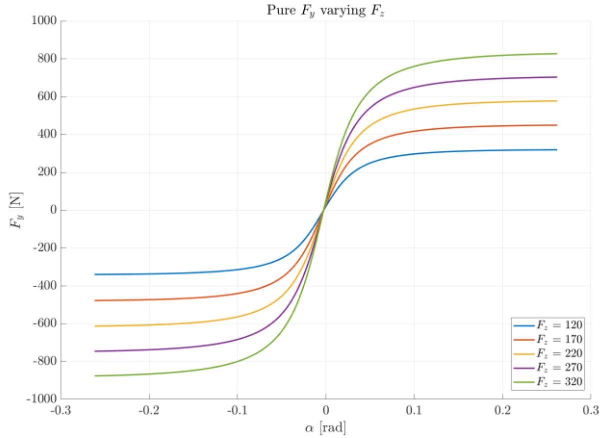


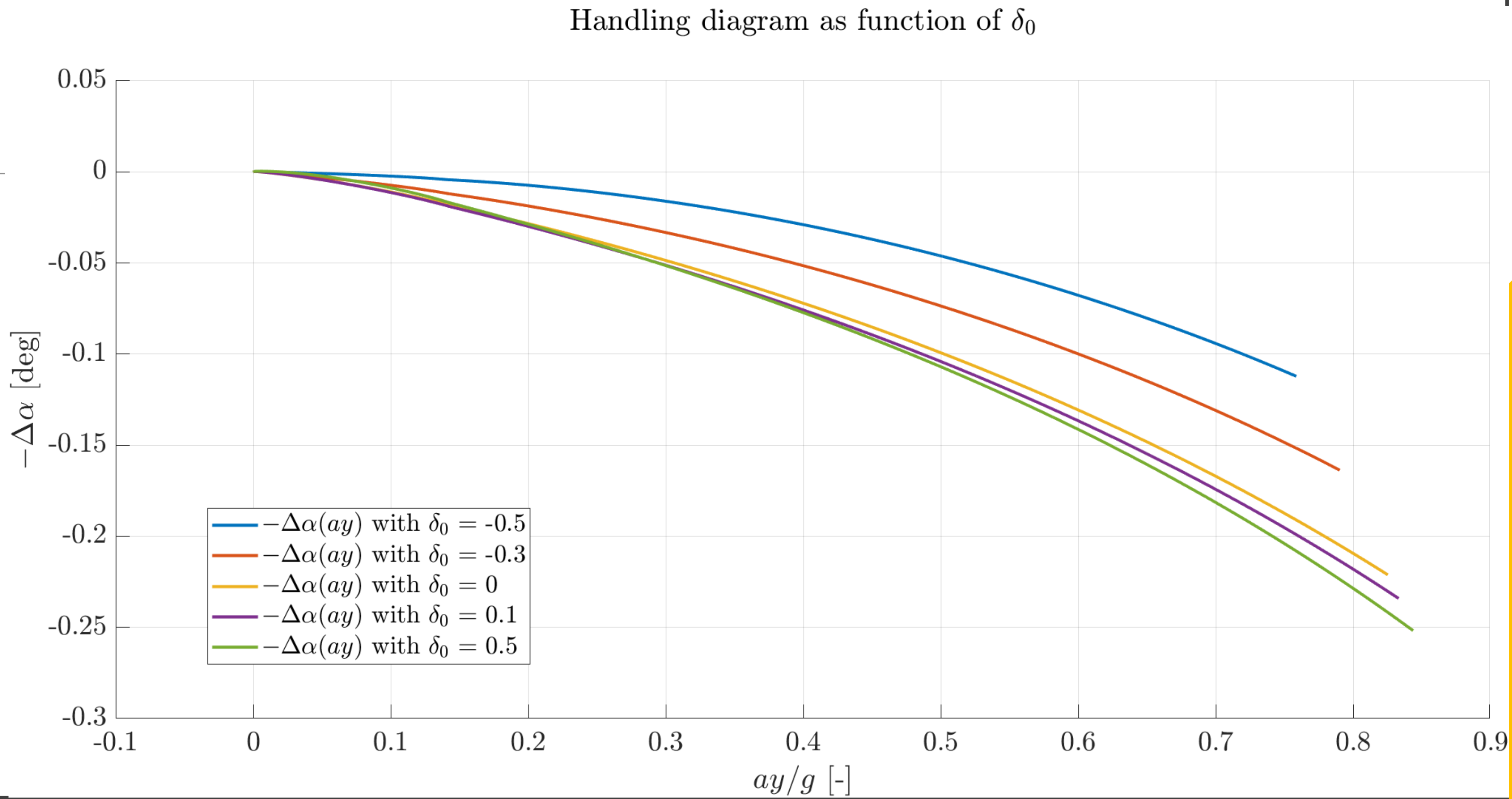
Effect of toe angle



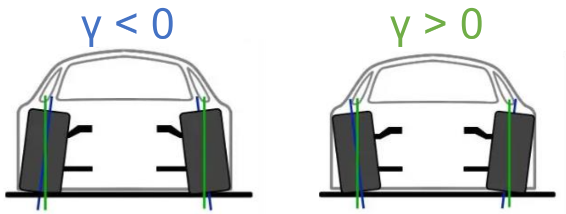

```matlab
function [delta__fr, delta__fl] = perfectAcker(delta,vehicle_data)

    % ---------------------------------------------------------------
    %% Function purpose: compute steering angles for front wheels, with
    %%                   perfect Ackerman steering model
    % ---------------------------------------------------------------

    % Load vehicle data
    Lf = vehicle_data.vehicle.Lf;
    Lr = vehicle_data.vehicle.Lr;
    Wf = vehicle_data.vehicle.Wf;
    delta_0 = vehicle_data.front_wheel.delta_f0*(pi/180);

    % Perfect Ackermann steering law
    delta__fr = atan((2*Lr+2*Lf)*tan(delta)/(Wf*tan(delta)+2*Lr+2*Lf)) + delta_0;
    delta__fl = -atan((2*Lr+2*Lf)*tan(delta)/(Wf*tan(delta)-2*Lr-2*Lf)) - delta_0;

end
```

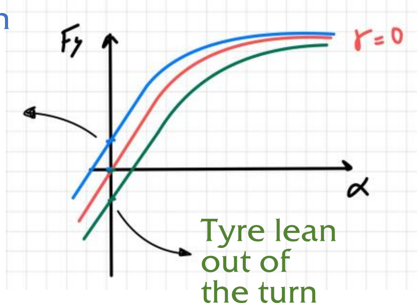
+ effect of the lateral load transfer



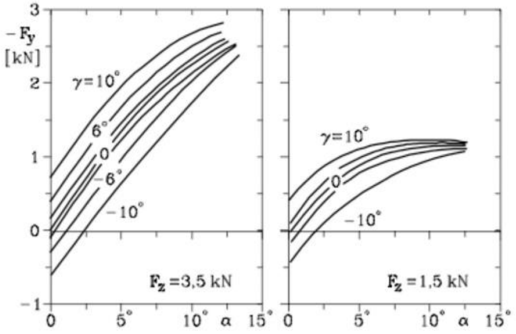


Effect of camber angle

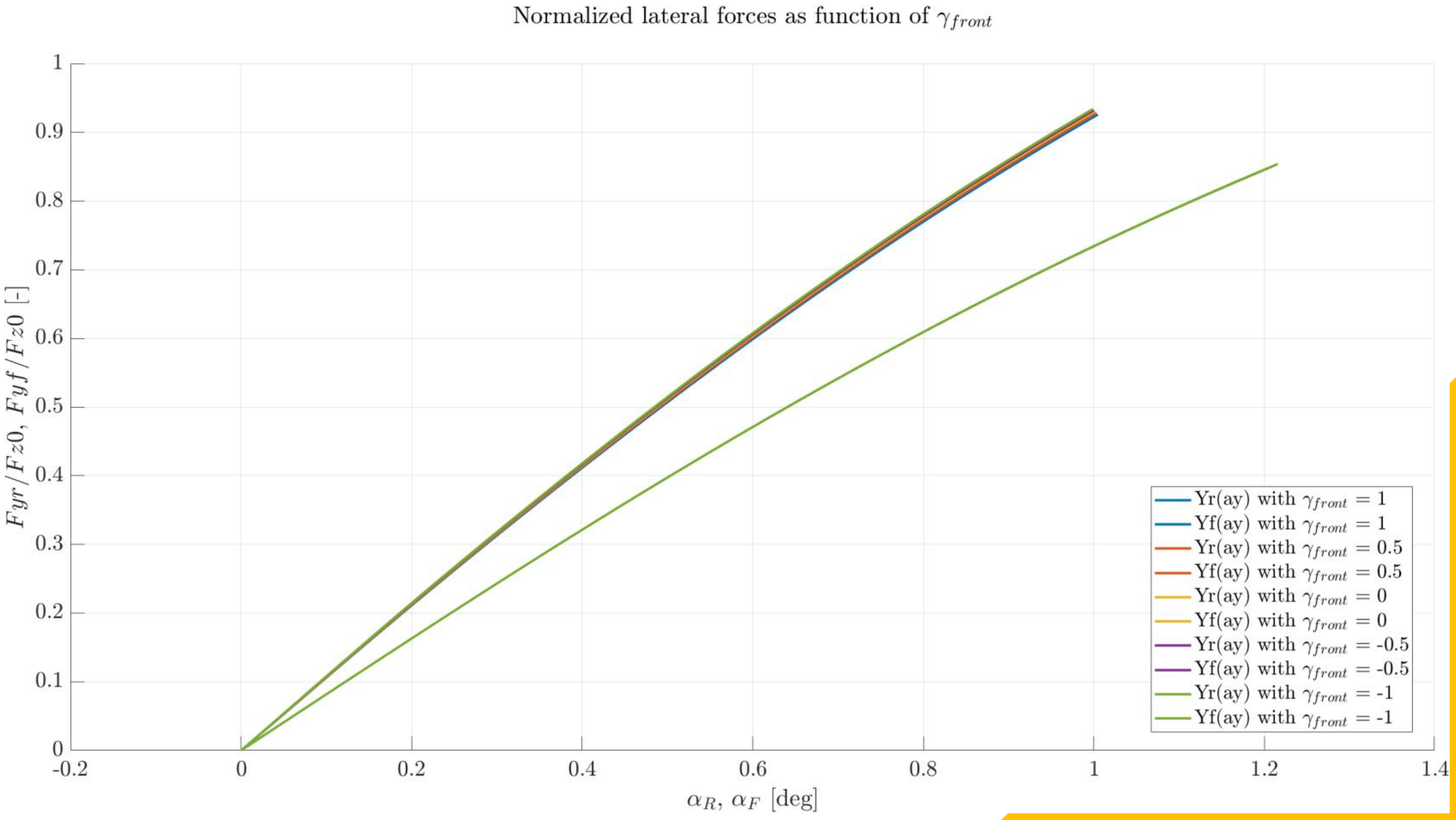




+ effect of lateral
load transfer

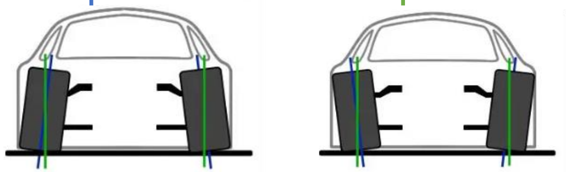


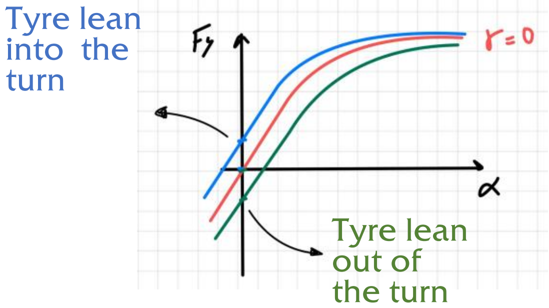
Note: different sign
convention in the picture



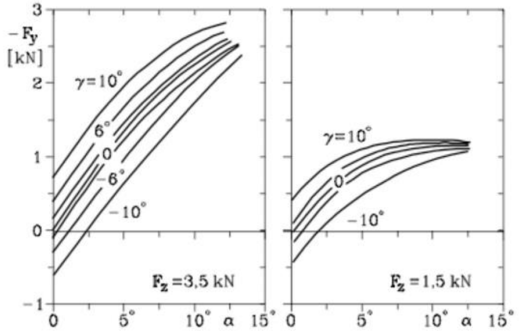
Effect of camber angle

$\gamma < 0$ $\gamma > 0$

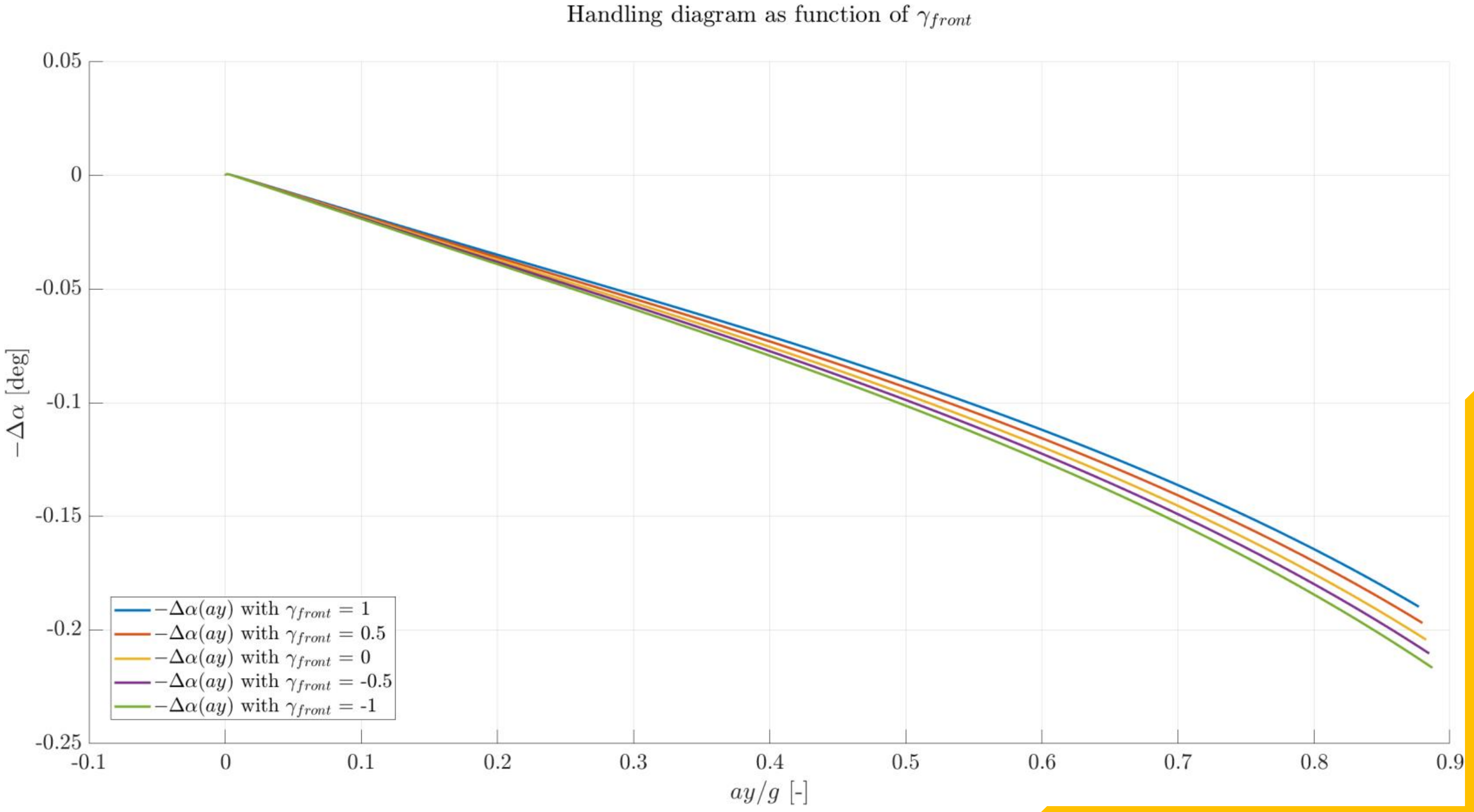


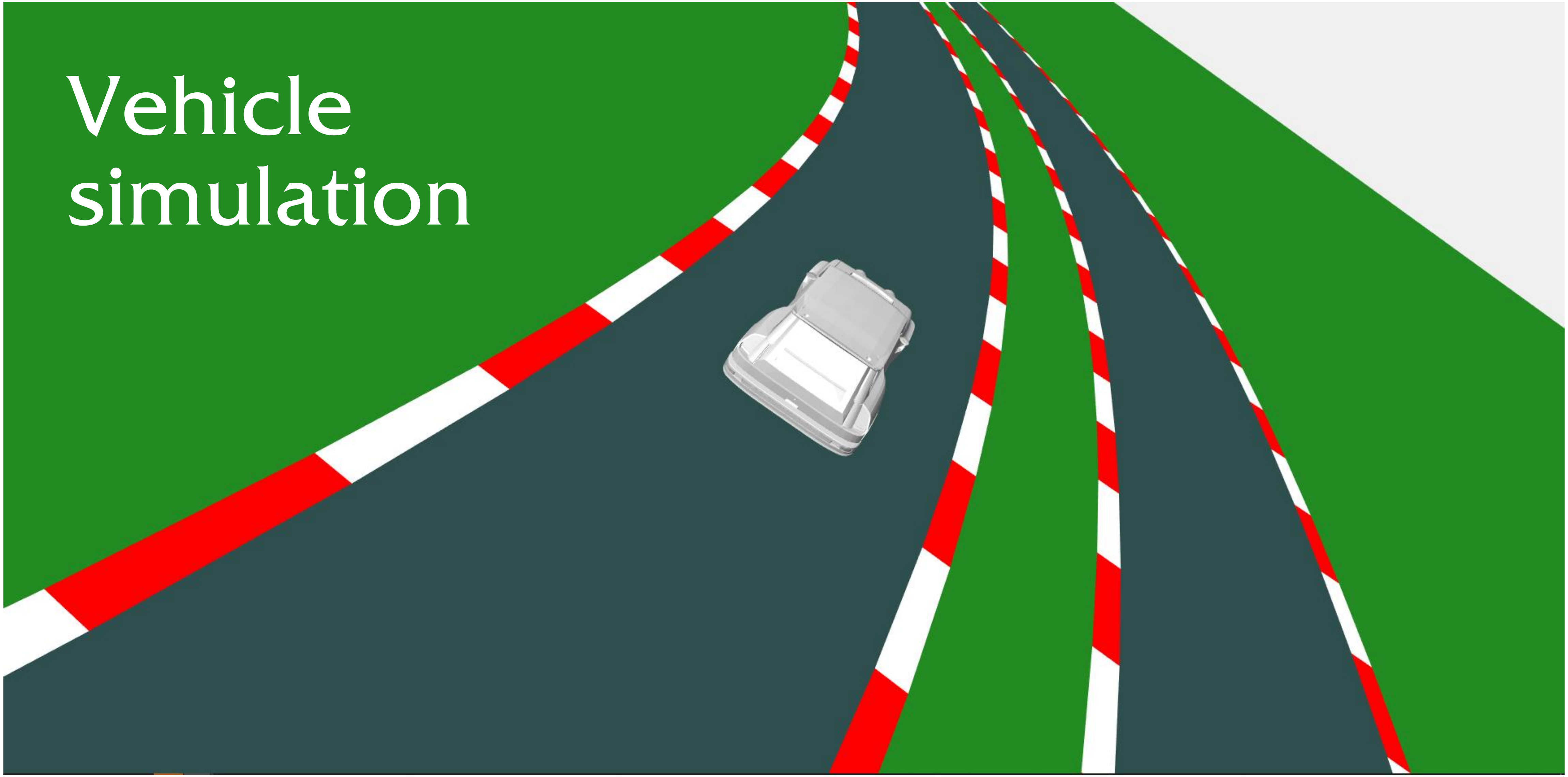


+ effect of lateral load transfer



Note: different sign convention in the picture




Vehicle
simulation

Vehicle simulation

UNIVERSITÀ DI TRENTO