Integrated components, systems and architectures for efficient adaption and conversion of commercial vehicle platforms to 3rd generation BEVs for future CO2-free city logistics

Advanced Control

Webinar 1

Assoc.Prof.Dr. Ahu Ece Hartavi Karcı

University of Surrey 30.09.2022

Table of contents

Aim and Objectives

AIM: Develop sustainable city logistics and improve mobility, accessibility, and quality of life of European citizens by taking a transdisciplinary approach

- Control functions to ensure energy efficiency, safety and performance.
- Control functions that are modular, programmable and configurable
- Controllers embedded within the vehicle supervisor, the so-called VMCU, fitting to the available computational power, communication links
  - Torque-vectoring controller→ Tracking the yaw rate and minimise the drivetrain input power for given levels of vehicle speed and lateral acceleration
  - Regenerative braking controller→ Special focus on energy efficiency consideration of limitations related to battery SOC
  - Integrated TV and traction controller
  - Hitch angle controllers→ Caused by the higher torque of e-motors from stand-still for start-stop conditions of delivery vans in urban areas, HWT sensors are to be integrated into the tires of the demonstrator vehicle to continuously measure the tread depth.
  - Robust TV controller through parameter scheduling → Through the use of HiWiTronics sensor outputs fed back to the controller to adaptively modify the gains of the TV controller

Non-Linear Model Predictive Control

- NMPC is an optimization-based method for the feedback control of nonlinear systems → Stabilization and tracking problems.
- The basic idea of predictive control is to use a model that approximates the process to predict and optimize future behaviour.
- A quadratic function is used for the optimization:

$$\ell(x_u(k), u(k), k) = \left\| x_u(k) - x_{ref}(k) \right\|^2 + \lambda \left\| u(k) - u_{ref}(k) \right\|^2$$

- Key features are:
  - Desired feedback value is obtained by applying the first element of the optimal control sequence to the plant at each time instant and the feedback law is obtained by an iterative online optimization over the predictions generated by the model;
  - Capability to consider the constraints in the optimal control problem.

Development of Prediction Model

Rigid vehicle config. in MATLAB

Adding equations for hitch dynamics

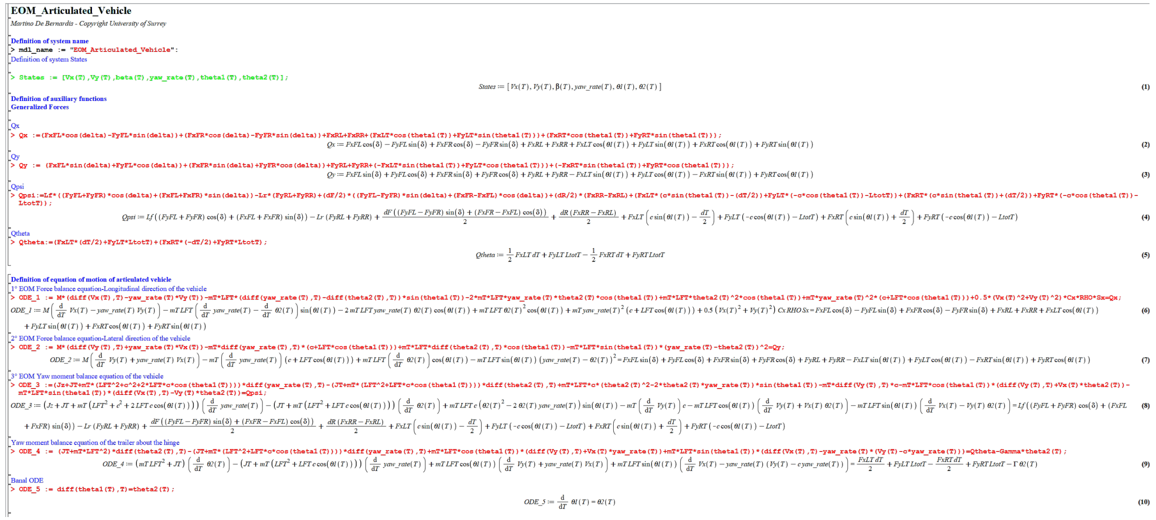
EOM in canonical form

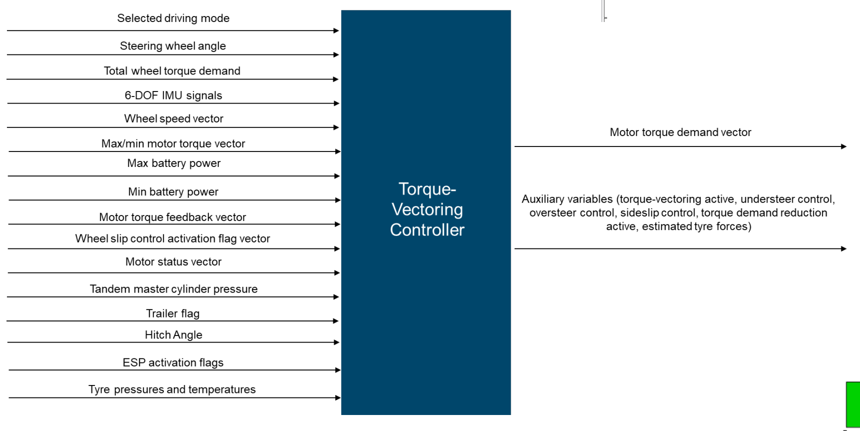
Transfer of Art. Vehic. Model in MATLAB

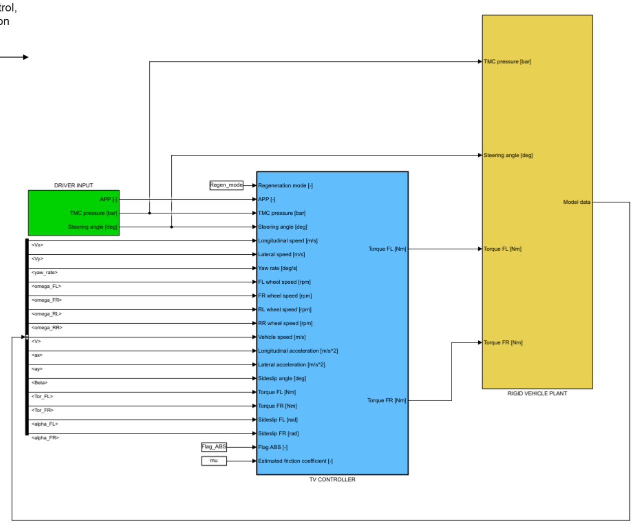
Optimal Control Problem

Simulink implementation

Tests and results



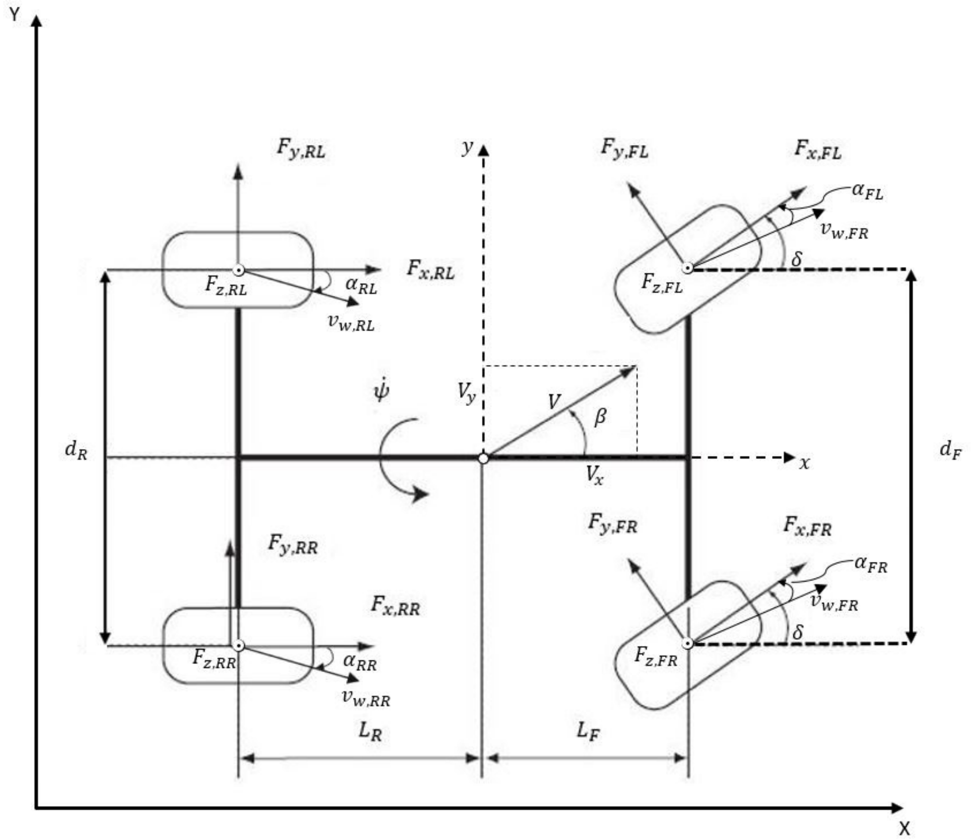




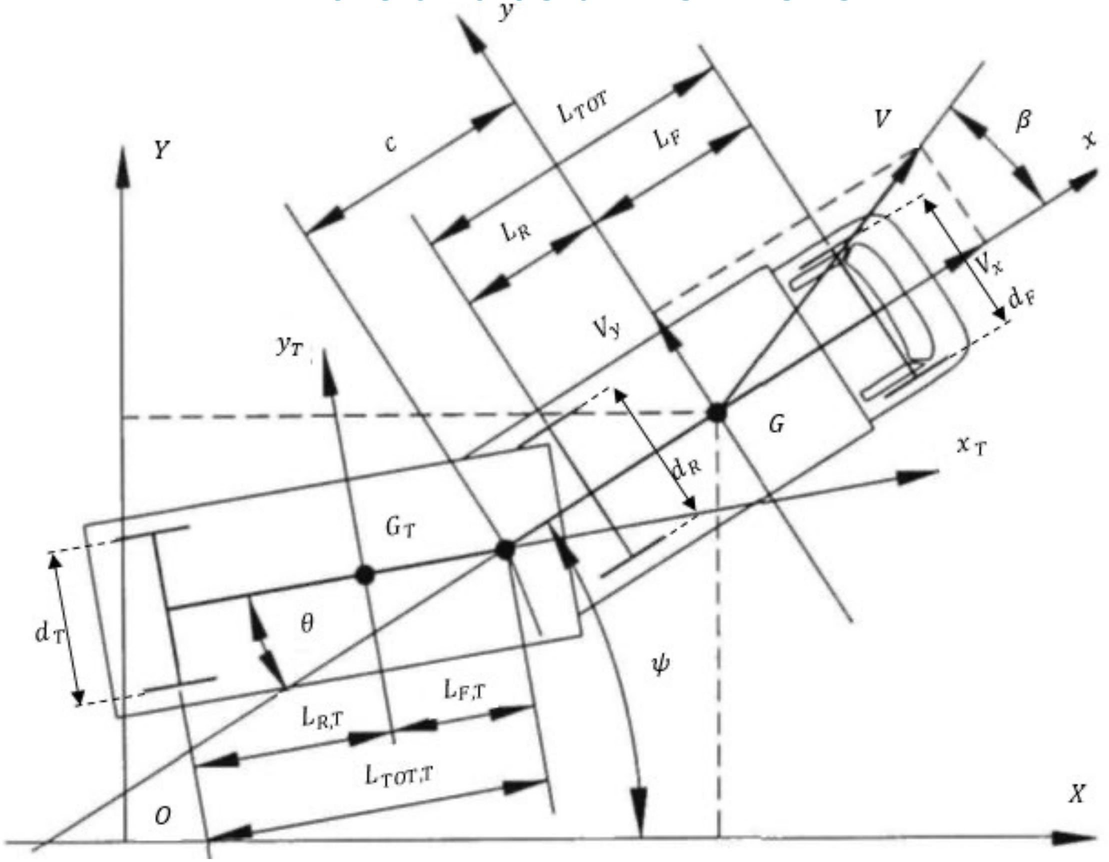
Prediction Model

- The development of the controller for both vehicle configurations start from the mathematical implementation of the prediction model;
- A non-linear 7DoF rigid vehicle configuration is used in the internal model, whilst for the articulated vehicle an additional degree-of-freedom (i.e. hitch angle) is considered, bringing the total DoF to 8.

Rigid vehicle



Articulated vehicle



Formulation of NMPC problem

- An articulated vehicle model in state-space form is developed by combining the vehicle dynamics equations, the wheel dynamics equations and the hitch dynamic equation.
- A state space form is an analytical model of a physical system and is composed by an input array, a parameter array and state array.

$$\dot{X} = f(X(t), W(t), U(t))$$

Rigid vehicle

$$X = [V_x, V_y, \dot{\psi}, \omega_{FL}, \omega_{FR}, \omega_{RL}, \omega_{RR}]^T$$

Articulated vehicle

$$X = [V_x, V_y, \theta, \dot{\theta}, \dot{\psi}, \omega_{FL}, \omega_{FR}, \omega_{RL}, \omega_{RR}]^T$$

$$W = [\tau_{Fj}^{min}, \tau_{Fj}^{max}, P_{BATTERY}^{min}, P_{BATTERY}^{max}]^T$$

$$U = [\tau_{FL}, \tau_{FR}]^T$$

X: state vector, composed of the longitudinal speed, lateral speed, yaw rate, hitch rate, hitch angle and the four wheels' speed;

W: parameter vector, are data used in the controller such as the minimum and the maximum torque value and battery power;

U: control input vector, are the controlled variables which act on the plant such as the torques.

Cost Function Formulation

- The optimal control input is determined solving a constrained quadratic optimization problem

Cost function: $$J = \frac{1}{2}\left\|Z_V^N - Z_{V,d}^N\right\|_{Q_x}^2 + \frac{1}{2}\sum_{k=0}^{N-1}\left(\left\|Z_V^k - Z_{V,d}^k\right\|_{Q_x}^2 + \left\|U^k\right\|_R^2\right)$$

Output array:

$$Z_V = [\tau_{tot}, \dot{\psi}, s_\alpha, P_{loss,xslip}^{tot}, P_{loss,yslip}^{tot}, P_{loss,PWT}]^T$$

Desired output array:

$$Z_{V,d} = \left[\tau_{tot,d}\,, \dot{\psi}_d, 0\,, 0\,, 0, 0\right]^T$$

- Constraints are used to set the working limits of the controller

Constraints: $$-min\left(F_{x,ij}^{max}R, \tau_{Fj}^{min}\right) \leq \tau_{Fj}^k \leq min\left(F_{x,ij}^{max}R, \tau_{Fj}^{max}\right)$$

$$s_\alpha \geq 0$$

$$-\alpha_{Rj}^{max}(1+s_\alpha) \leq \alpha_{Rj}^k \leq \alpha_{Rj}^{max}(1+s_\alpha)$$

$$P_{BATTERY}^{min} \leq P_{BATTERY}^k \leq P_{BATTERY}^{max}$$

Controller's flexibility was tested by changing these boundaries

Qx: weight matrix on controlled variable

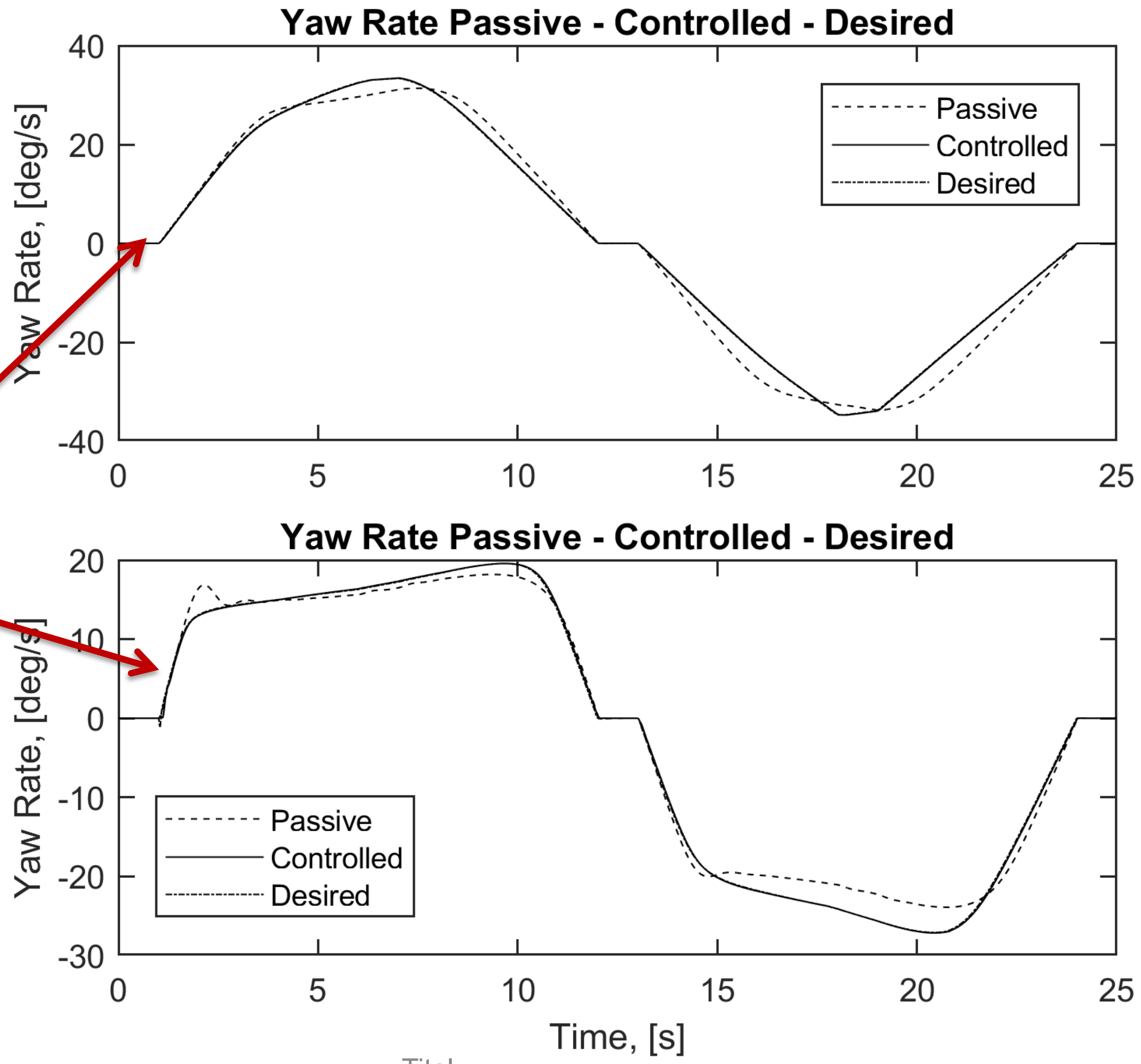
R: weight matrix on control input

- C1:motor torque limit on each wheel;
- C2:rear sideslip angle limited between two boundaries as a function of slack variable;
- C3:operation range of the battery.

Controller Performance in Nominal Condition - Yaw rate tracking

- Yaw rate tracking achieved, with different vehicle speed
- 60 km/h and 120 km/h in the first and second Figure respectively

Yaw rate of controlled vehicle is overlapped with desired yaw rate

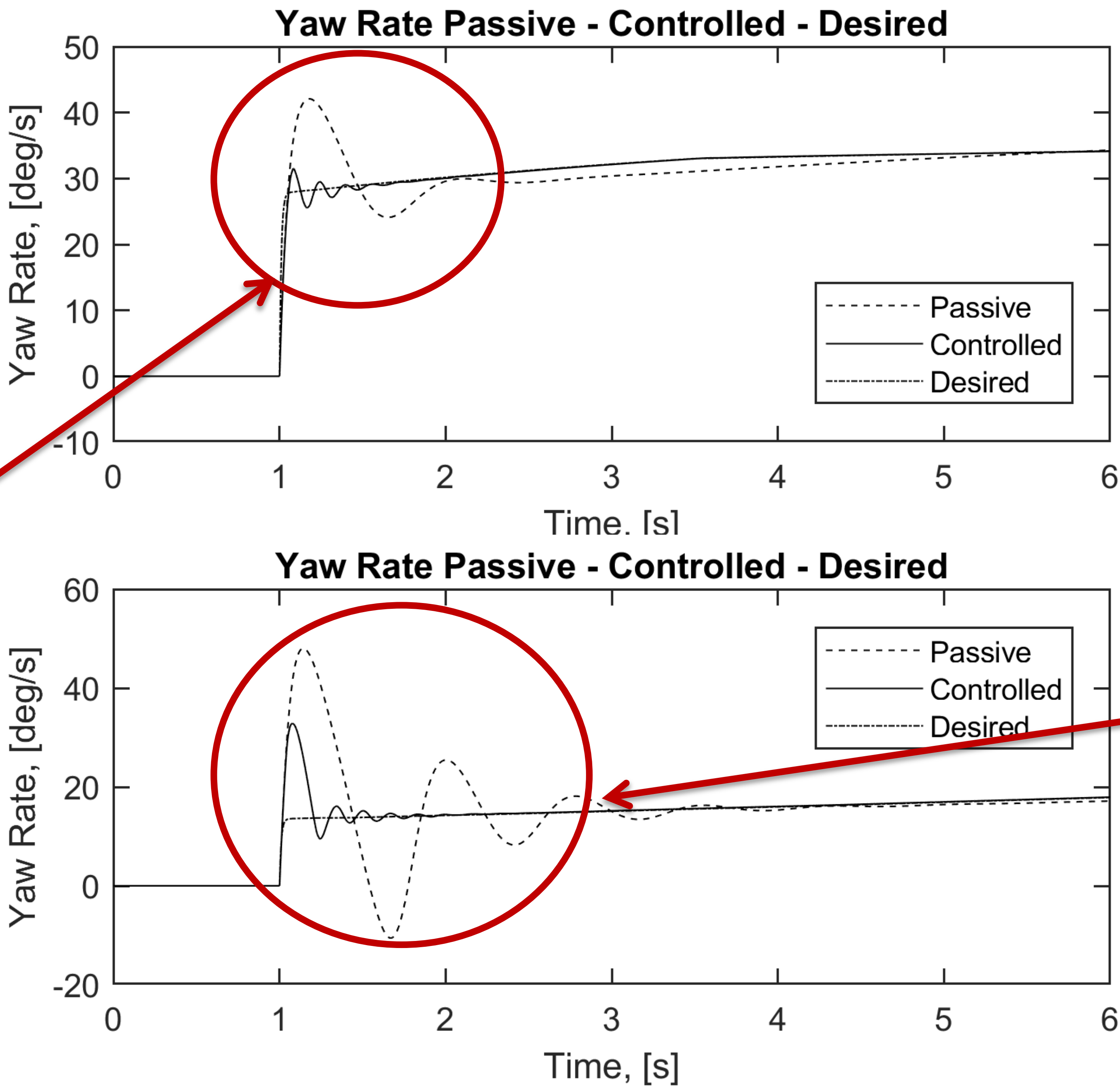


SLOW STEERING MANOEUVRE

Controller Performance: Emergency Condition – Yaw rate tracking

- Yaw rate tracking in a step steer manoeuvre with different vehicle speeds
- 60 km/h and 120 km/h in the first and second figure respectively

Damping effect of the controller on the yaw rate at 60 km/h



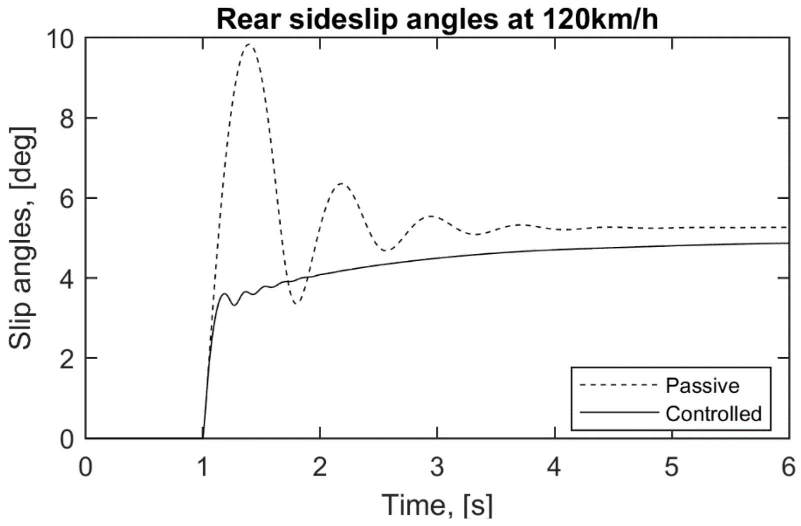
SINGLE STEP STEER MANOEUVRE

With higher speed, the damping effect of the controller is fundamental for vehicle stabilization

Simulations with Controller: Emergency Condition

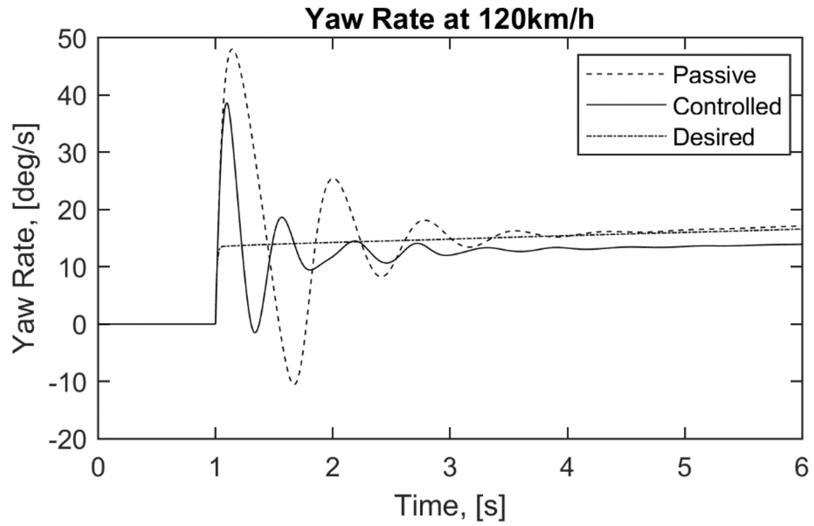
Rear sideslip angle slack variable control

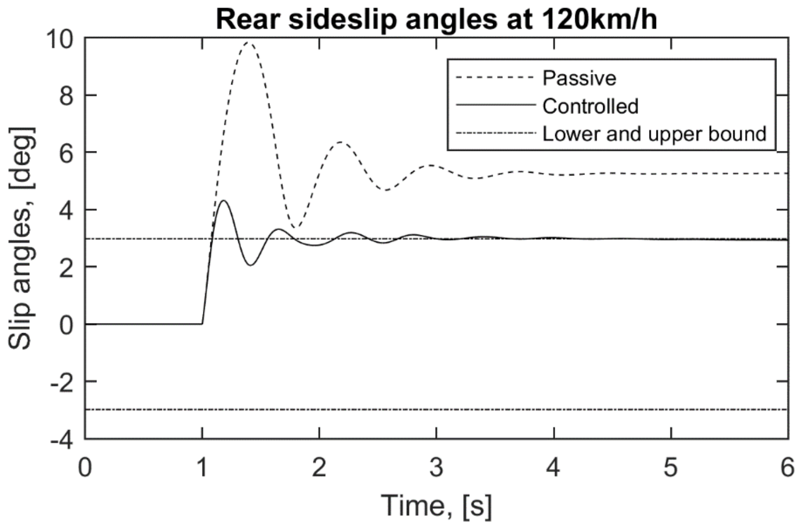
- Rear sideslip angle can be controlled, acting on the slack variable used to define the soft-constraint.



In this scenario, the slack variable is not taken into account in the cost function. Controlled rear sideslip angle is damped with respect to the passive, but not limited.

SINGLE STEP STEER MANOEUVRE



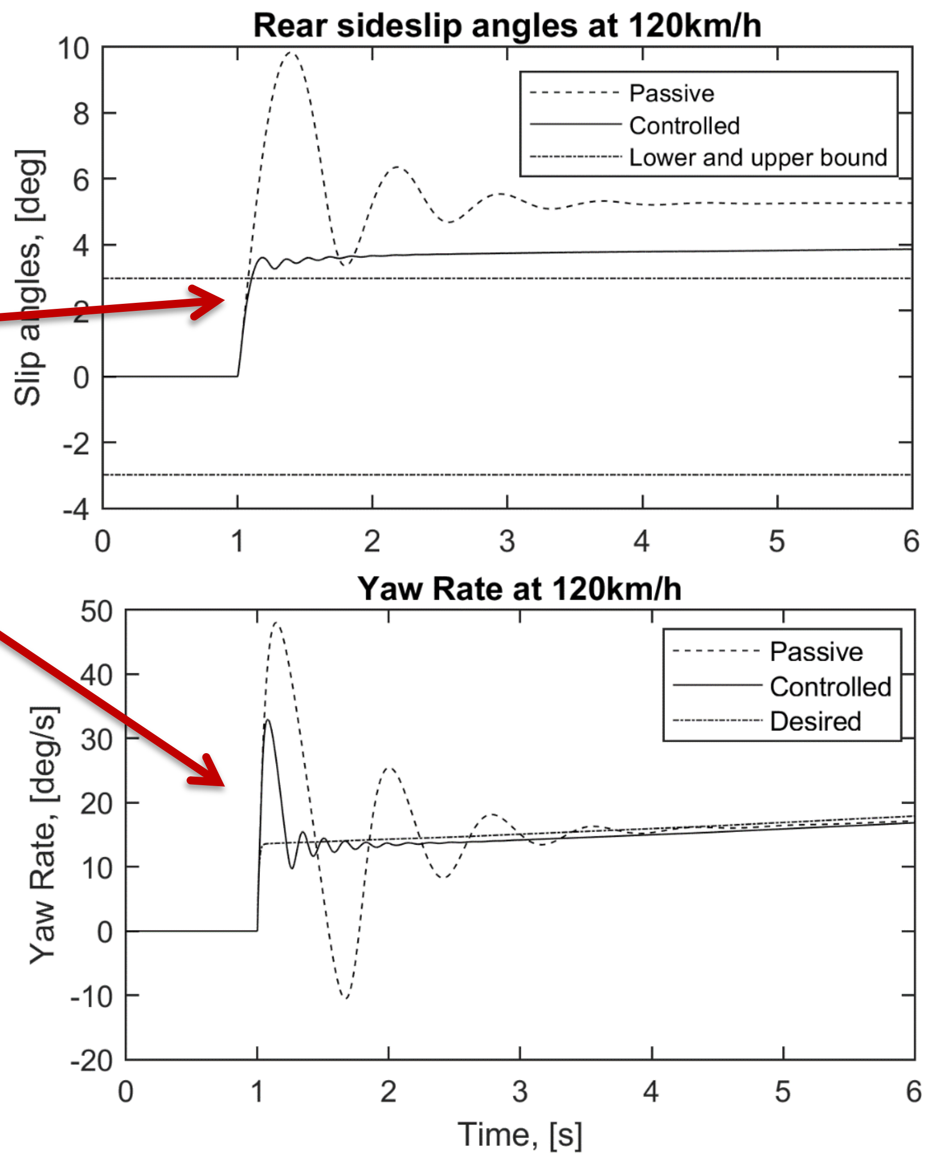


In this scenario, only the slack variable is taken into account in the cost function. Controlled rear sideslip angle is damped and within the boundary. The yaw rate is not tracked on purpose.

Simulations with Controller: Emergency Condition

Rear sideslip angle slack variable control

- Controller is now acting on both rear axle sideslip angle and yaw rate
- Both terms are taken into account in the cost function
- Yaw rate is tracked
- Rear axle sideslip angle is constrainted



Key Performance Indicators

SINGLE STEP STEER MANOEUVRE KPIs	PASSIVE VEHICLE	CONTROLLED: YR + TRQ	CONTROLLED: REAR SIDESLIP ANGLE + TRQ	CONTROLLED: YR + TRQ + REAR SIDESLIP ANGLE	MEAS. UNIT
RMSE YAW RATE	8.87	3.82	4.35	3.88	deg/s
YAW RATE PEAK VALUE	48.02	32.95	33.96	32.95	deg/s
REAR SIDESLIP ANGLE PEAK VALUE	9.84	4.88	4.87	4.88	deg
VEHICLE SPEED END MANOEUVRE	97.27	97.26	100.55	98.48	km/h
IACA	0	92.69	99.18	98.49	Nm

YR + TRQ: Yaw rate tracking and torque in cost function

REAR SIDESLIP ANGLE + TRQ: Slack variable and torque in cost function

YR + TRQ + REAR SIDESLIP ANGLE: Yaw rate tracking, torque, slack variable in cost function

$$RMSE = \sqrt{\frac{1}{t_f - t_i}\int_{t_i}^{t_f}\left(r_{ref}(t) - r(t)\right)^2 dt}$$

$$IACA = \sqrt{\frac{1}{t_f - t_i}\int_{t_i}^{t_f}|u(t)|dt}$$

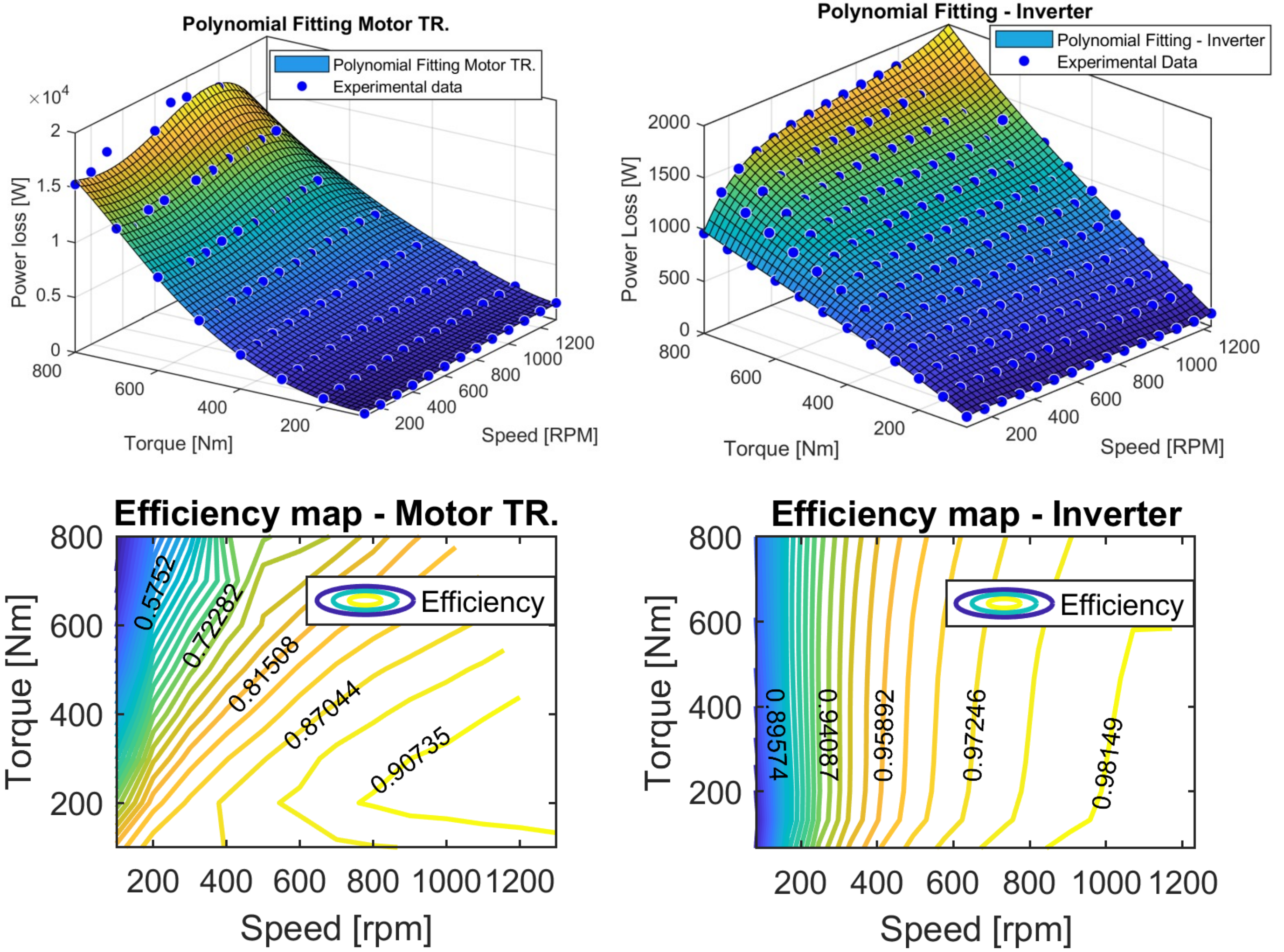
Power losses

❖ In the controller formulation, both powertrain power losses and tyre slip power losses are taken into account

Powertrain power losses

$$P_{loss,PWT} = \sum_{i=1}^{N} \left(P_{loss,MOT} + P_{loss,INV}\right)$$

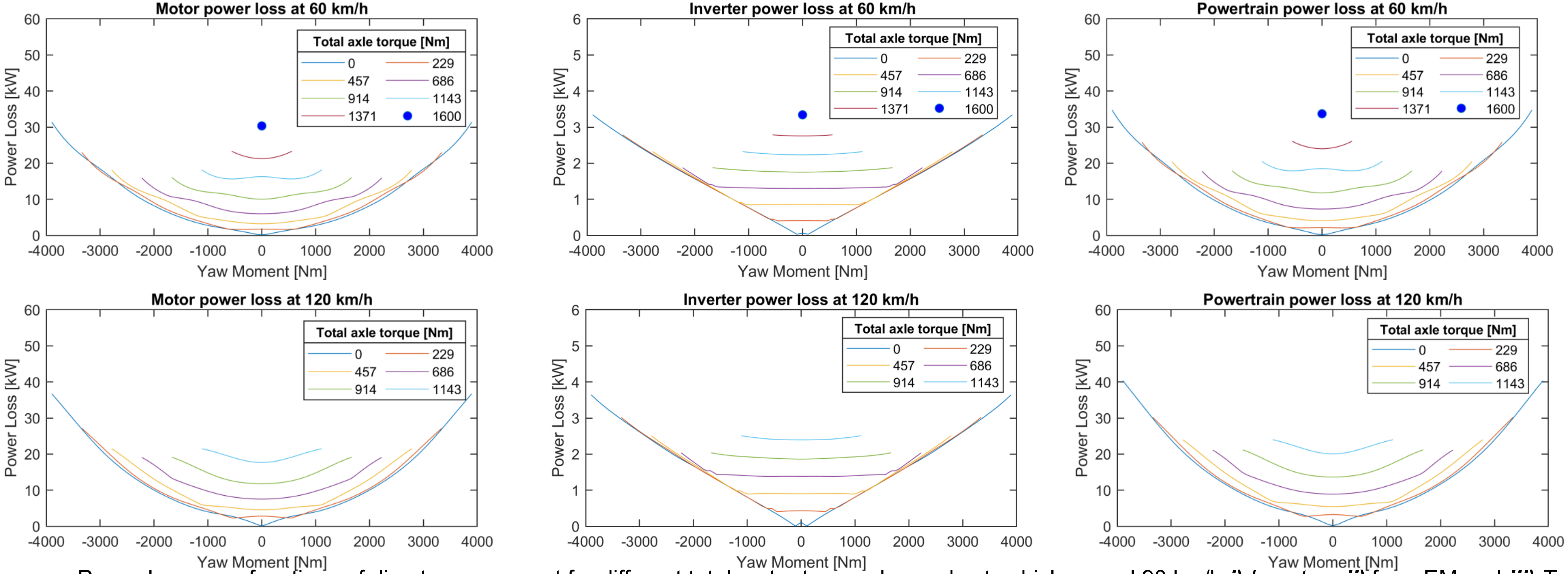
Where N is the number of motors and inverters



Tyre slip power losses

$$\begin{cases} P_{loss,xslip} = \sum_{\substack{i=F,R \\ j=R,L}} \left(F_{x,ij} v_{slip,x,ij}\right) \\ P_{loss,yslip} = \sum_{\substack{i=F,R \\ j=R,L}} \left(F_{y,ij} v_{slip,y,ij}\right) \end{cases}$$

Preliminary Analysis



Power losses as functions of direct yaw moment for different total motor torque demands at vehicle speed 90 km/h ***i)*** *Inverter* , ***ii)*** from EM and ***iii)*** *Total power-loss*

- Direct yaw moment limits varying with the total torque demand
- Identification of the optimal direct yaw moment

Torque demands on each side

$$\tau_{FR} = 0.5\tau_{tot,d} - M_{z,ref}\frac{R_w}{d_F}$$

$$\tau_{FL} = 0.5\tau_{tot,d} + M_{z,ref}\frac{R_w}{d_F}$$

Power loss in Traction

$$P_{loss,TR} = \tau_{mot}\omega(\frac{1}{\eta^{TR}} - 1)$$

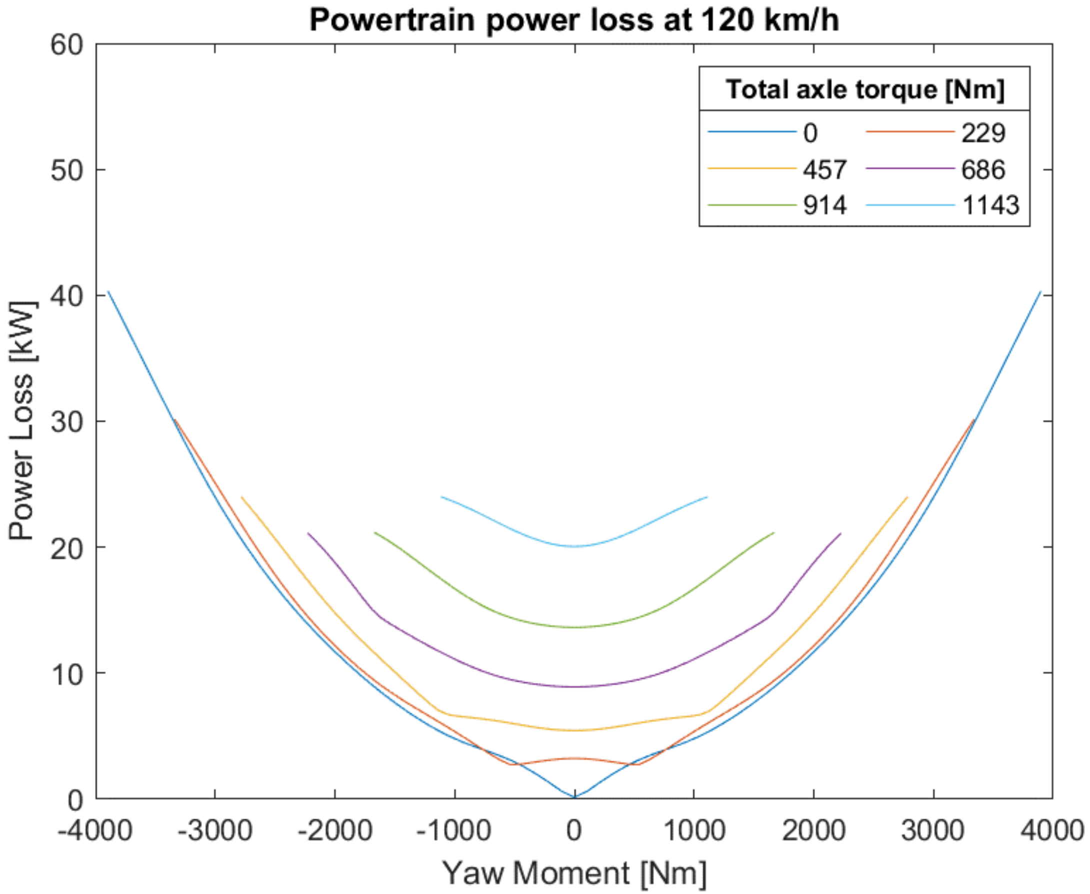
Power loss in Regen

$$P_{loss.REG} = \tau_{mot}\omega(1 - \eta^{REG})$$

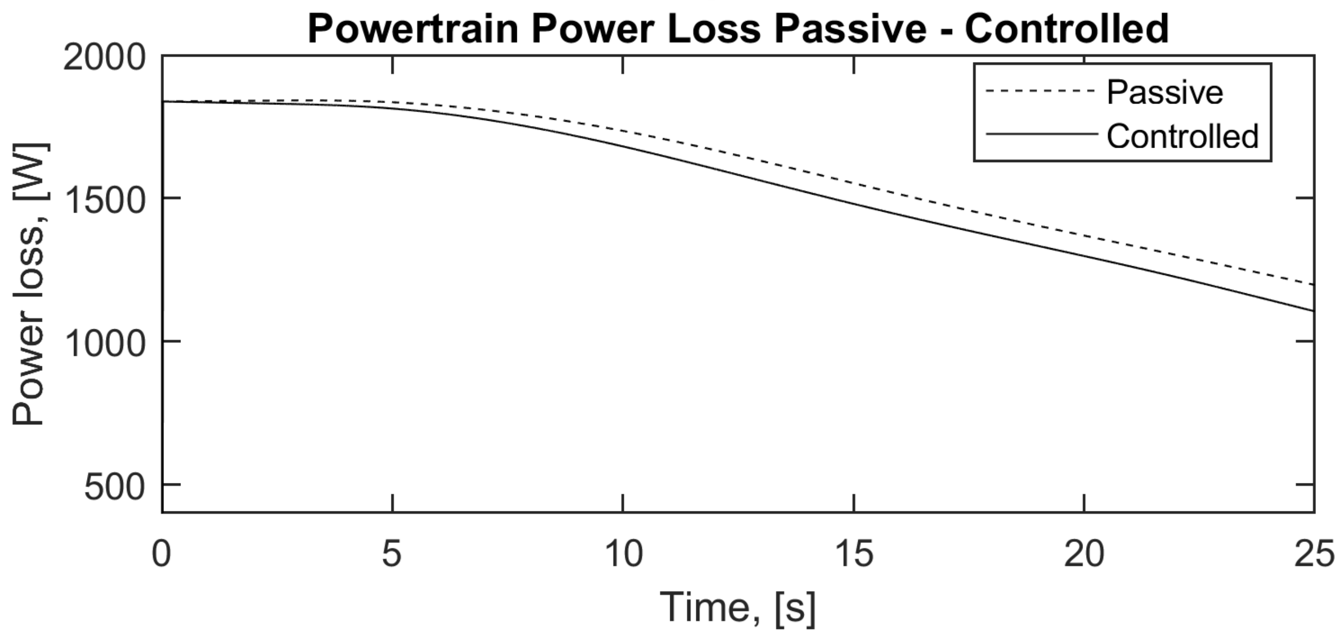
Simulations with Controller: Powertrain Power Loss

Preliminary test on powertrain power loss reduction

Acting on the cost function to control the powertrain power loss term it is possible to notice that there is a reduction in the energy consumption



Early test at constant torque demand

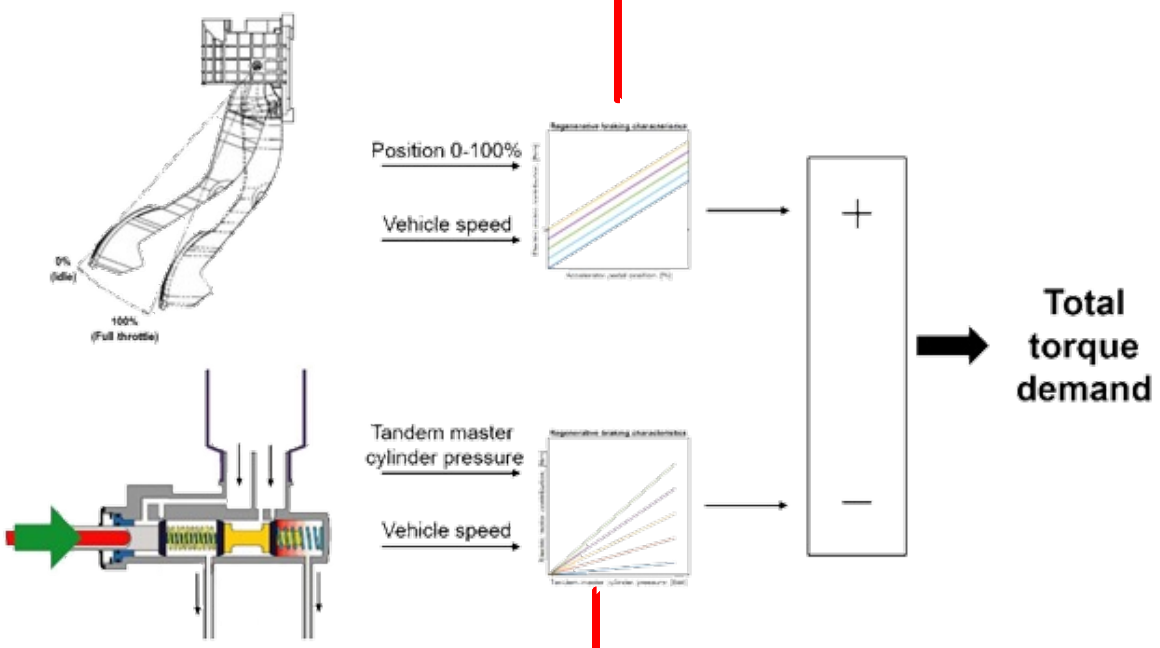


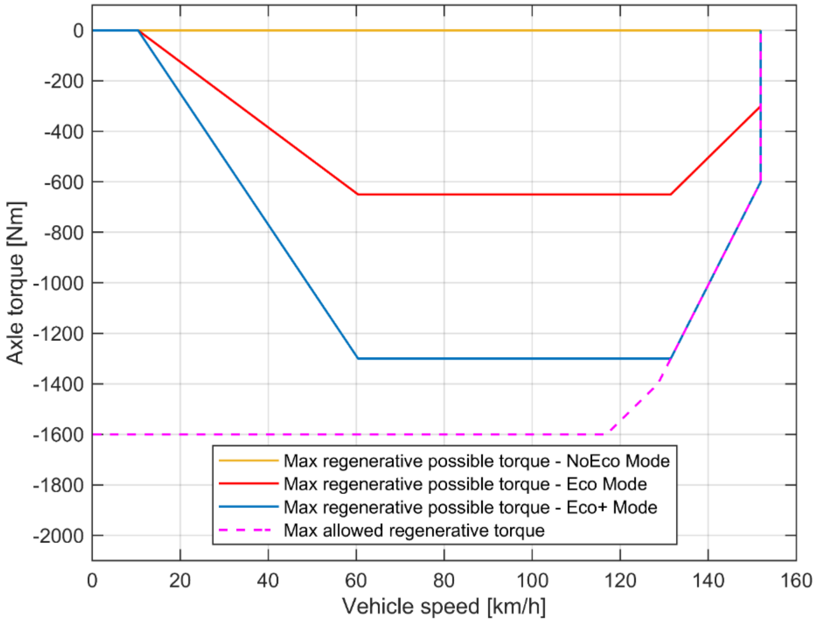
Regenerative braking

Regenerative braking controller scheme:

The regenerative braking controller works around the constraints of the physically available braking system.

Driveability map based on the accelerator pedal position and on the vehicle speed → calculate the **accelerator-pedal-related part** of the total regenerative braking torque demand.





Low accelerator pedal positions (0-20%) → regenerative braking system is active → **negative torque** is provided.

Additional map based on the measured **pressure in the tandem master cylinder** → **regenerative braking torque** is added.

The **total torque demand** is applied to the vehicle through the electric powertrains in braking conditions.

If interventions of the **conventional ABS** occur → use of the **flag** variable from the **ABS unit** to reduce the regenerative braking contribution.

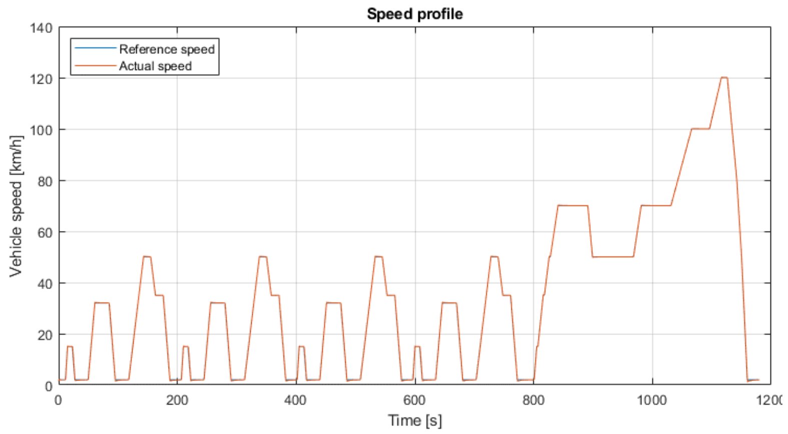
Regenerative braking

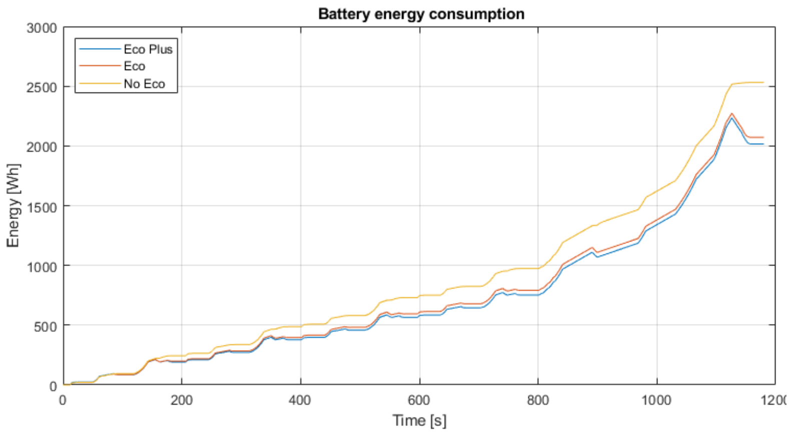
Preliminary results on regenerative braking:

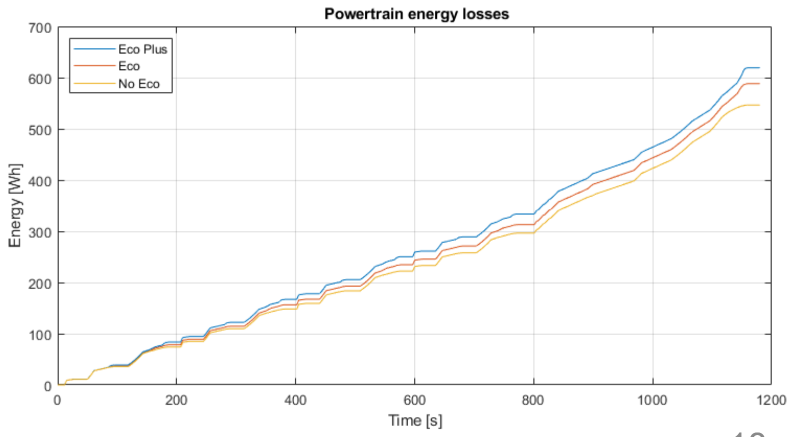
- Standard cycles have been used to test the controller;
- Three different regenerative modes available, from the absence of regeneration to the most regenerative, namely: **No Eco**, **Eco** and **Eco+**;
- **Sensible reduction** in the battery energy consumption with both **Eco+** and **Eco** modes with respect to the case where no regenerative braking is used (No Eco);
- Despite the lower energy consumption, the Eco+ and Eco modes show an **higher powertrain energy loss** due to the efficiency η^{REG} of the powertrain lower than one.

		Energy cons. [Wh]	En. cons. reduct. (%)	Avg. cons. [Wh/km]	Powertrain losses [Wh]	Percentage incr. (%)
NEDC (10.93 km)	NoEco	2535.4	-	231.94	546.63	-
	Eco	2076.4	18.10	189.95	588.22	7.61
	Eco+	2021.4	20.27	184.92	619.05	13.25
WLTP 3b (23.20 km)	NoEco	6281.7	-	269.99	1314.9	-
	Eco	5258.8	16.28	226.03	1387.6	5.53
	Eco+	5035.6	19.83	216.44	1495.5	13.74
FTP-75 (17.77 km)	NoEco	5453.2	-	306.89	1426.3	-
	Eco	4615.0	15.37	259.72	1501.1	5.24
	Eco+	4354.3	20.15	245.05	1615.7	13.27
HWFET (16.45 km)	NoEco	3173.3	-	192.25	531.48	-
	Eco	2902.9	8.52	175.86	552.57	3.97
	Eco+	2882.8	9.15	174.65	570.10	7.27

NEDC







Integrated torque-vectoring and traction controller

Novel points:

- Novel strategy, to **reduce** the high **computational cost** of an NMPC formulation and to make the **controller implementable in real-time** using an external **PI** with a **feedback** which limits the maximum value of the torque usable based on the difference between the reference and the actual slip value

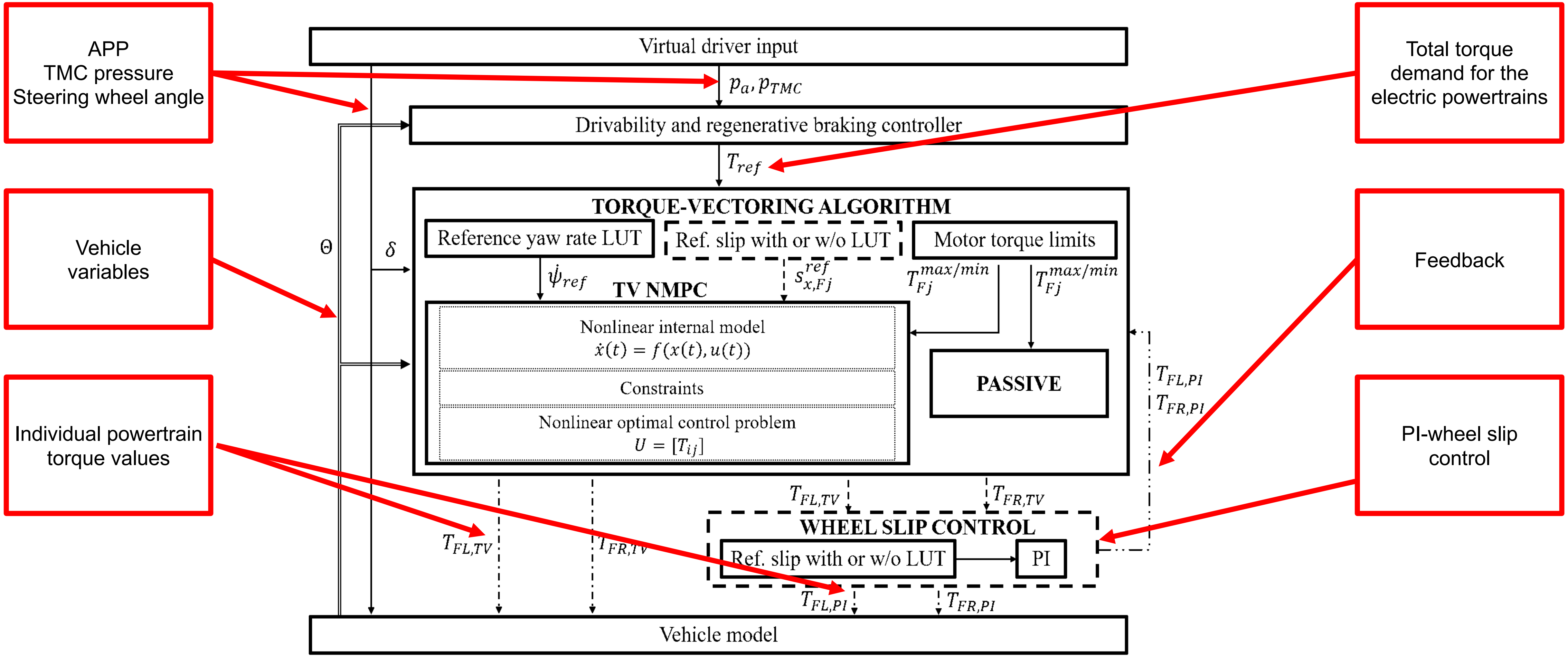
- **Centralized NMPC** which includes a **soft constraint** on the longitudinal slip in addition to the control of lateral dynamics

- **Sensitivity analysis**, with constant and optimized fixed weights, about the influence of the **time step**, of the prediction carried out by internal model, with different **prediction horizon** $(\boldsymbol{H_p})$ on control performances

- **Objective comparison**, with constant and optimized fixed weights, among **five real-time implementable NMPC** strategies

Integrated torque-vectoring and traction controller

Composed scheme of the proposed controllers:



- The **main target** was the development of traction control function using three different approaches.
- The Nonlinear Model Predictive Control (NMPC) approach is employed in this study to develop the **integrated control** and NMPC+PI with or w/o feedback structure.

Integrated torque-vectoring and traction controller

Formulation of the NMPC problem:

- The **internal NMPC model** is expressed through the following continuous time formulation:

$$\dot{X} = f(X(t), U(t))$$

Centralized NMPC	NMPC+PI with and w/o feedback	NMPC+PI with and w/o feedback without wheel dynamics
$X_1 = [V_x, V_y, \dot{\psi}, \omega_{FL}, \omega_{FR}, \omega_{RL}, \omega_{RR}, T_{FL,EM}, T_{FR,EM}]^T$	$X_2 = [V_x, V_y, \dot{\psi}, \omega_{FL}, \omega_{FR}, \omega_{RL}, \omega_{RR}]^T$	$X_3 = [V_x, V_y, \dot{\psi}]^T$
$U_1 = [T_{FL}, T_{FR}, s_\alpha, s_{sx,FL}, s_{sx,FR}]^T$	$U_2 = [T_{FL}, T_{FR}, s_\alpha]^T$	$U_3 = [F_{x\,FL}, F_{x\,FR}, s_\alpha]^T$

- **Output array** definition of the proposed controllers:

$Z_V = [\tau_{tot}, \dot{\psi}, s_\alpha, s_{sx,FL}, s_{sx,FR}]^T$	$Z_V = [\tau_{tot}, \dot{\psi}, s_\alpha]^T$	$Z_V = [F_{x,tot}, \dot{\psi}, s_\alpha]^T$
$Z_{V,d} = [\tau_{tot,d}, \dot{\psi}_d, 0, 0, 0]^T$	$Z_{V,d} = [\tau_{tot,d}, \dot{\psi}_d, 0]^T$	$Z_{V,d} = [F_{x,tot,d}, \dot{\psi}_d, 0]^T$

- X: state array; U: control input array; Z_V: output vector; $Z_{V,d}$: output vector with the desirable values

Integrated torque-vectoring and traction controller

Controller tuning routine:

A unified **tuning routine**, using the ***fmincon*** Sequential Quadratic Programming (**SQP**) algorithm of Matlab, **optimizes the weights** in the OCP of the best controller formulations, i.e. the **centralized NMPC** and the **NMPC+PI with feedback**.

The weights to optimize are on the **yaw rate tracking**, on the **slack variable**, to constraint the **rear side sideslip angle**, and, if they are present, on the **slack variables** to constraint the **longitudinal slip** on the front left and front right corner.

The weight on the **torque demand** is held constant and it has been chosen in order to guarantee the torque request during the manoeuvre.

Controller name	$Q_{LB} \leq Q_{opt} \leq Q_{UB}$
Centralized NMPC	$0 \leq Q_{\dot{\psi}} \leq 10^5$ $0 \leq Q_{s_{\alpha,rear}} \leq 10^5$ $0 \leq Q_{s_{sx,ij}} \leq 10^5$
NMPC+PI with feedback	$0 \leq Q_{\dot{\psi}} \leq 10^5$ $0 \leq Q_{s_{\alpha,rear}} \leq 10^5$

In the configuration NMPC+PI with feedback the **PI gains** are kept constant to a value which permits to obtain a good **trade-off** between slip control performance and signal oscillation.

Integrated torque-vectoring and traction controller

Real-time implementation:

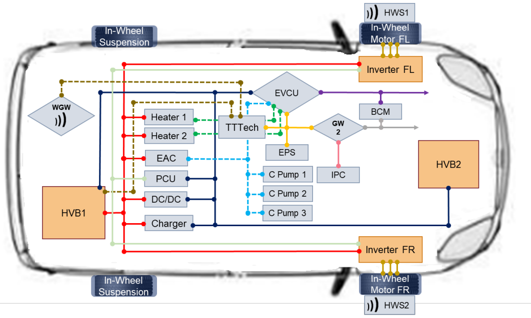
- To select the minimum time step of the controllers a set of simulation have been implemented in real-time on a rapid control prototyping unit, i.e. **dSPACE MicroAutoBox** II 1401/1513, with an IBM 900 MHz processor to **verify the real-time capability** of the considered controllers with different number of steps N_s.
- The **turnaround time** information specifies the **minimum** $\boldsymbol{T_s}$ achievable for a fixed N_s to obtain a real-time implementable controller

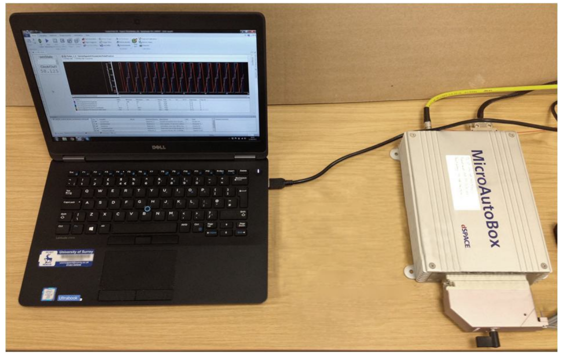
Controllers	T_s [ms]	N_s [-]
Centralized NMPC	27	2
TV NMPC+PI with or w/o feedback	11	2
	16	3
	21	4
	26	5
TV NMPC+PI with or w/o feedback no wheel dynamics	8	2
	12	3
	16	4
	20	5

T_s and N_s controller configurations implementable in real-time

KPIs of controllers runnable in real-time with constant fixed and optimized fixed weights

Controllers	$RMSE_{\Delta\dot{\psi}}$ [deg/s]	$RMSE_{\Delta sx_{FL}}$ [deg]	$RMSE_{\Delta sx_{FR}}$ [deg]	$IACA_{M_z}$ [Nm]	$\lvert\Delta\psi^{max}\rvert$ [deg/s]	$\lvert\alpha_{rear}^{max}\rvert$ [deg]	V_{end}^{norm} [km/h]	J_{KPI} [-]
Constant fixed weights								
Centralized NMPC T_s= 27 ms N_s=2	3.02	0.02	0.02	1086	9.51	3.31	89.54	0.190
TV NMPC+PI with feedback T_s=11 ms N_s=2	2.40	0.01	0.01	1186	5.88	2.94	88.13	**0.160**
TV NMPC+PI w/o feedback T_s=16 ms N_s=3	2.51	0.07	0.07	1072	7.57	3.31	105.44	0.201
TV NMPC+PI with feedback no wheel dynamics T_s=16 ms N_s=4	3.66	0.02	0.02	588	13.29	4.09	104.2	0.189
TV NMPC+PI w/o feedback no wheel dynamics T_s=16 ms N_s=4	3.99	0.06	0.06	730	14.24	4.24	111.81	**0.232**
Optimized fixed weights								
Centralized NMPC T_s= 27 ms N_s=2	2.79	0.02	0.02	1143	9.22	3.17	86.93	0.182
TV NMPC+PI with feedback T_s=11 ms N_s=2	2.24	0.01	0.01	1127	6.37	2.91	88.78	**0.155**
TV NMPC+PI w/o feedback T_s=16 ms N_s=3	2.27	0.07	0.07	923	6.45	2.97	99.82	0.192
TV NMPC+PI with feedback no wheel dynamics T_s=12 ms N_s=3	2.75	0.02	0.02	819	9.47	3.26	107.4	0.159
TV NMPC+PI w/o feedback no wheel dynamics T_s=12 ms N_s=3	3.15	0.05	0.04	1034	11.68	3.37	116.03	**0.195**
Passive configuration								
/	17.19	0.11	0.07	-	56.33	15.95	121.47	0.812

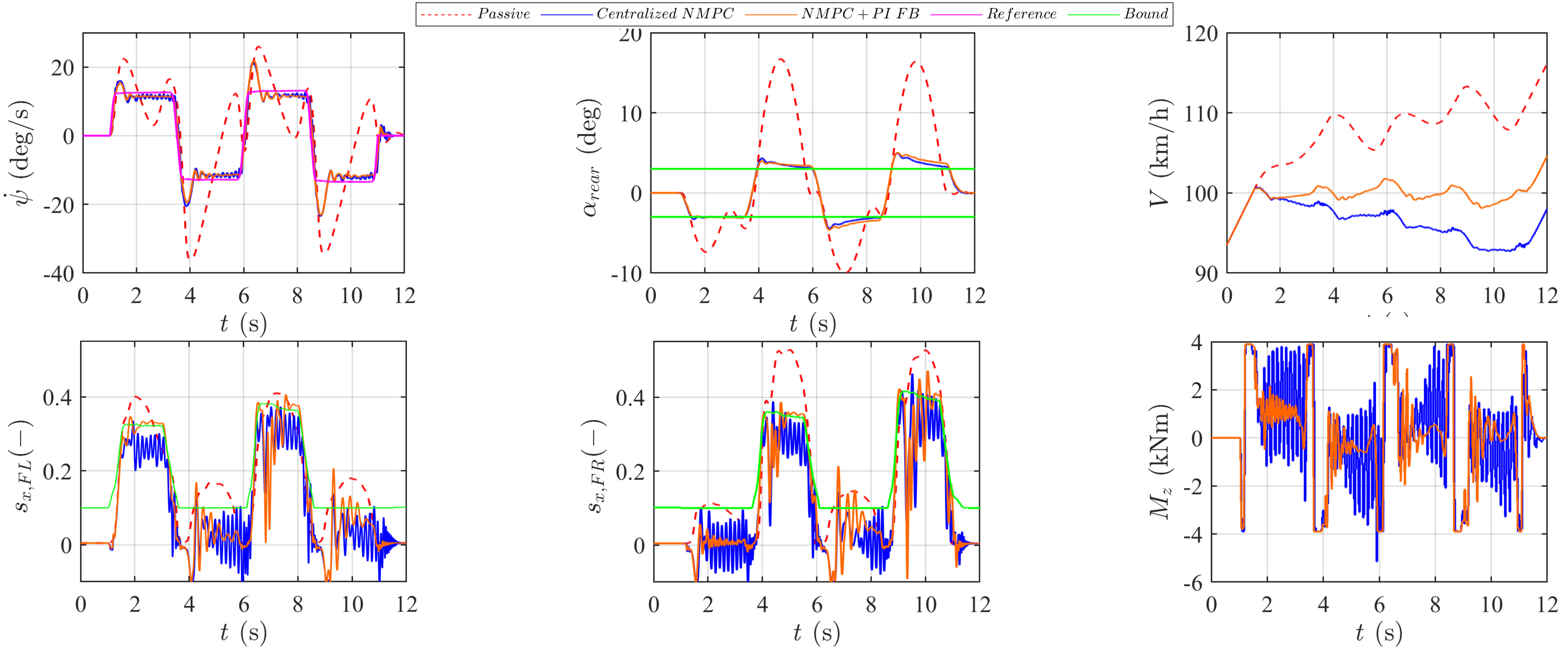




Integrated torque-vectoring and traction controller

Manoeuvre and results:

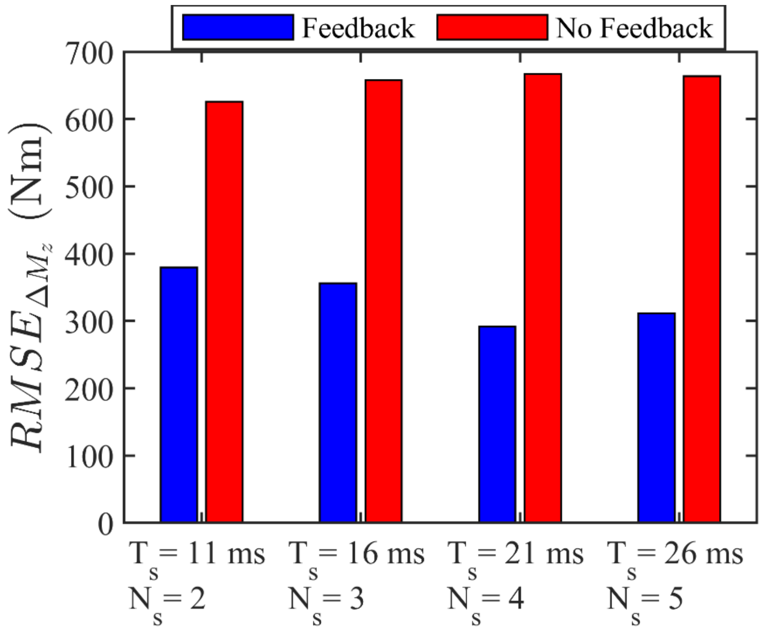
- **Double step steer manoeuvre** is performed to excite the vehicle dynamics. This manoeuvre begins with a steering angle equal to zero at 100 km/h. From 0.5 s to 1 s a tip-in changes the accelerator pedal position from 25% (partially pressed) to 100% (full throttle). A sequence of step steer is performed at the end of the tip-in with maximum steering angle at the wheels of 12 deg.

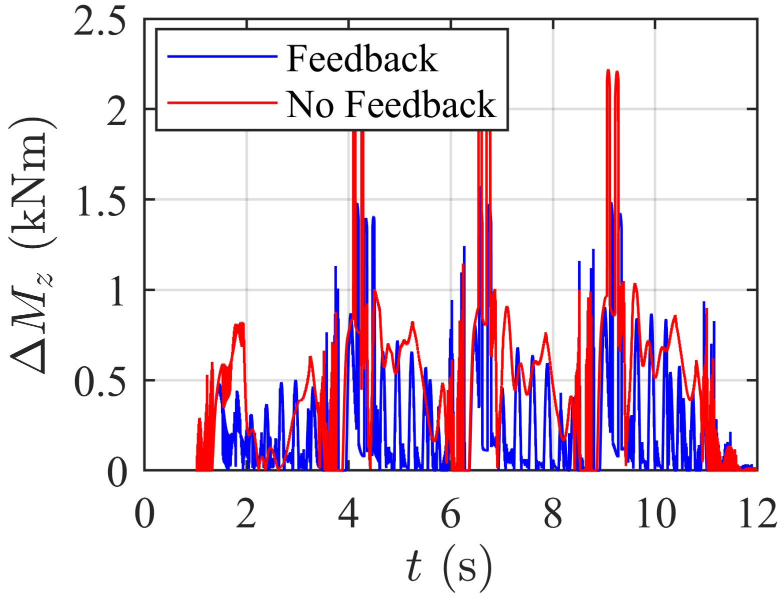


Integrated torque-vectoring and traction controller

Comparison between TV NMPC+PI with and w/o feedback:

- To understand the utility of the novel formulation which includes the feedback an analysis of the KPI $RMSE_{\Delta M_z}$ and of the M_z tracking error with respect to the time was performed.





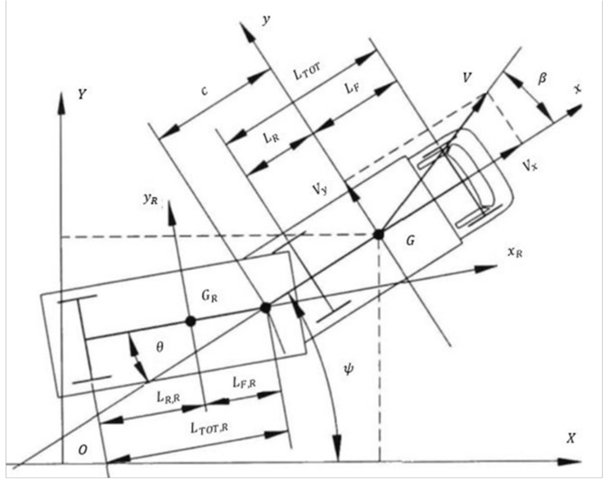
$$M_z^{PRE\ PI} = \frac{(\tau_{FL}^{PRE\ PI} - \tau_{FR}^{PRE\ PI})d_F}{2R} \qquad M_z^{POST\ PI} = \frac{(\tau_{FL}^{POSTPI} - \tau_{FR}^{POSTPI})d_F}{2R} \qquad RMSE_{\Delta M_z} = \sqrt{\frac{1}{t_f - t_i}\int_{t_i}^{t_f}\left(M_z^{POST\ PI}(t) - M_z^{PRE\ PI}(t)\right)^2 dt}$$

- The value of the **KPI $RMSE_{\Delta M_z}$** results to be **lower in the case where the feedback is implemented**. This confirms the utility of the novel formulation which permits to have an intervention of the NMPC on the lateral dynamics limited in a range which depends on the action of the coupled PI.

Hitch angle control

Comparison among baseline controller and 4 different hitch angle control approaches:

- Baseline TV controller formulation for rigid vehicle (YR_{rig})
- Hitch angle controller 1: TV controller for the articulated vehicle based on the modified reference yaw rate formulation $(MYR_{ref,rig})$
- Hitch angle controller 2: Yaw rate and soft constraint on hitch angle error $(YR + SC_{HAE})$
- Hitch angle controller 3: Yaw rate and hitch angle error function $(YR + HAE_{fun})$
- Hitch angle controller 4: Modified yaw rate error $(MYRE)$



Baseline TV controller formulation for rigid vehicle: YR_{rig}

In this formulation the internal model is the rigid vehicle configuration

Z_V is the output vector defined as $Z_V = \left[\tau_{tot}\,, \dot{\psi}\,, s_\alpha\right]^T$

$Z_{V,d}$ is the output vector with the desirable values defined as $Z_{V,d} = \left[\tau_{tot,d}\,, \dot{\psi}_d\,, 0\right]^T$

Constraints:

$$LB_{\tau_{Fj}} \leq \tau_{Fj}^k \leq UB_{\tau_{Fj}}$$

$$s_\alpha \geq 0$$

$$-\alpha_R^{max}(1 + s_\alpha) \leq \alpha_R^k \leq \alpha_R^{max}(1 + s_\alpha)$$

$$P_{Batt}^{min} \leq P_{Batt}^k \leq P_{Batt}^{max}$$

Hitch angle control

Hitch angle controller 1: modified yaw rate reference on the rigid vehicle $(MYR_{ref,rig})$

The internal model is the rigid vehicle configuration and the controller blends the contributions of the yaw rate and the hitch angle error only when the trailer dynamics are deemed critical.

Z_V is the output vector defined as $Z_V = \left[\tau_{tot}, \dot{\psi}, s_\alpha\right]^T$

Same constraints of YR_{rig}

The desired output array $Z_{V,d}$ is $Z_{V,d} = \left[\tau_{tot,d}, \dot{\psi}_{dm}, 0\right]^T$

$$\dot{\psi}_{dm} = \dot{\psi}_d - W_\theta(1 - K_\theta)\Delta\theta_{act}$$

Where:

$$K_\theta = \begin{cases} 1 & if \quad \Delta\theta_{act} \in [-\Delta\theta_{th}; \Delta\theta_{th}] \\ 1 + \dfrac{K_{\theta,min} - 1}{\Delta\theta_{th} - \Delta\theta_{lim}}(\Delta\theta_{th} - |\theta_{des} - \theta|) & if \quad \Delta\theta_{act} \in [-\Delta\theta_{lim}; -\Delta\theta_{th}] \cup [\Delta\theta_{th}; \Delta\theta_{lim}] \\ K_{\theta,min} & if \quad \Delta\theta_{act} \notin [-\Delta\theta_{lim}; \Delta\theta_{lim}] \end{cases}$$

$$\Delta\theta_{act} = \theta_{des} - \theta$$

Hitch angle controller 2: yaw rate control and soft constraint on hitch angle error $(YR + SC_{HAE})$

This approach considers a soft constraint on the hitch angle error and a slack variable s_θ is added in the cost function.

The main aim is to activate the controller only when the thresholds are overcome. In this approach the output vector Z_V is defined as $Z_V = \left[\tau_{tot}, \dot{\psi}, s_\alpha, s_\theta\right]^T$ and the desired output array $Z_{V,d}$ is $Z_{V,d} = \left[\tau_{tot,d}, \dot{\psi}_d, 0, 0\right]^T$

Additional constraints: $s_\theta \geq 0; -\Delta\theta_{lim}(1 + s_\theta) \leq \left|\Delta\theta^k\right| \leq \Delta\theta_{lim}(1 + s_\theta)$

Hitch angle controller 3: yaw rate control and continuous hitch angle error function $(YR + HAE_{fun})$

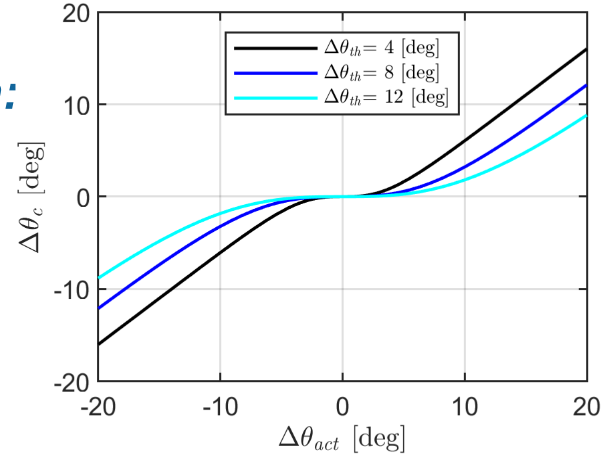
This formulation includes the hitch angle error in the cost function which is taken in account only if the hitch angle actual value overcomes a pre-determined threshold thus, the controller acts only if there is an important oscillation of the articulated vehicle.

In this approach Z_V, which is the output vector, is defined as $Z_V = [\tau_{tot}, \dot{\psi}, \Delta\theta_c, s_\alpha]^T$ and the desired output array $Z_{V,d}$ is $Z_{V,d} = [\tau_{tot,d}, \dot{\psi}_d, 0, 0]^T$

Same constraints of YR_{rig}

Continuous hitch angle error function:

$$\Delta\theta_c = \Delta\theta_{act} - \Delta\theta_{th} \tanh\left(\frac{\Delta\theta_{act}}{\Delta\theta_{th}}\right)$$



Hitch angle controller 4: modified yaw rate error $(MYRE)$

The modified yaw rate formulation is based on the modification of the yaw rate error formulation, by substituting it with a weighted linear combination of the yaw rate error and the hitch angle error where the latter has an influence only when it exceeds pre-determined thresholds. The output vector Z_V is defined as $Z_V = [\tau_{tot}, \Delta\dot{\psi}_\theta, s_\alpha]^T$ and the desired output array $Z_{V,d}$ is $Z_{V,d} = [\tau_{tot,d}, 0, 0]^T$

Weighted linear combination: $\Delta\dot{\psi}_\theta = K_\theta \Delta\dot{\psi} - W_\theta(1 - K_\theta)\Delta\theta_{act}$; $\Delta\dot{\psi} = \dot{\psi}_d - \dot{\psi}$

Same constraints of YR_{rig}

Hitch angle control

Controller tuning routine:

To obtain an **objective assessment** of the proposed hitch angle controllers, a **tuning routine** was implemented to select the values of the main **calibration parameters** of each controller, during a single sinusoidal steering test with a steering wheel angle input of 50 deg amplitude and 3 s duration, from an initial speed of 70 km/h.

Controller name	Acronym	Description	$Lower\ limit \leq Parameter \leq Upper\ limit$
TV controlled vehicle	YR^1_{rig}	Yaw rate tracking of the rigid vehicle	-
Modified yaw rate	$MYR^1_{ref,rig}$	Weighted linear combination of the rigid vehicle yaw rate, and hitch angle error	-100 $s^{-1} \leq W_\theta \leq$ -0.9 s^{-1} $0.1 \leq K_{\theta,min} \leq 0.9$ 3 deg $\leq \Delta\theta_{lim} \leq$ 10 deg
Yaw rate and soft constraint on hitch angle error	$YR + SC_{HAE}$	Yaw rate tracking and soft constraint applied on hitch angle error	$2 \leq W_{s_\theta} \leq 1000$ 3 deg $\leq \Delta\theta_{lim} \leq$ 10 deg
Yaw rate and hitch angle error function	$YR + HAE_{fun}$	Yaw rate tracking and hitch angle error control through continuous function	$200 \leq W_{\Delta\theta_c} \leq 4000$
Modified yaw rate error	$MYRE$	Weighted linear combination of the yaw rate error and hitch angle error	-100 $s^{-1} \leq W_\theta \leq$ -1 s^{-1} $0.1 \leq K_{\theta,min} \leq 1$ 3 deg $\leq \Delta\theta_{lim} \leq$ 10 deg

[1]: rigid vehicle used as internal model

*: hitch angle reaches a threshold value. In this case the simulation is aborted early

-: value not calculated

/: simulation interrupted; value not calculated

Comparison on torque-vectoring controllers

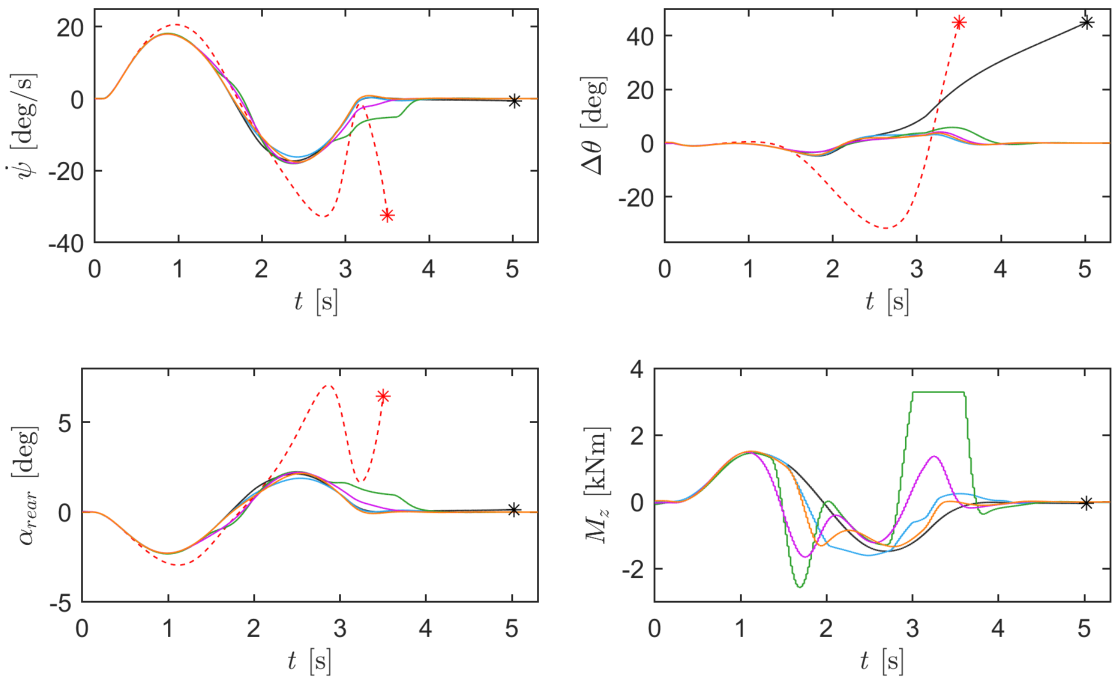
Manoeuvres and results:

The controllers were tested simulating two different manoeuvres performed with constant torque demand:

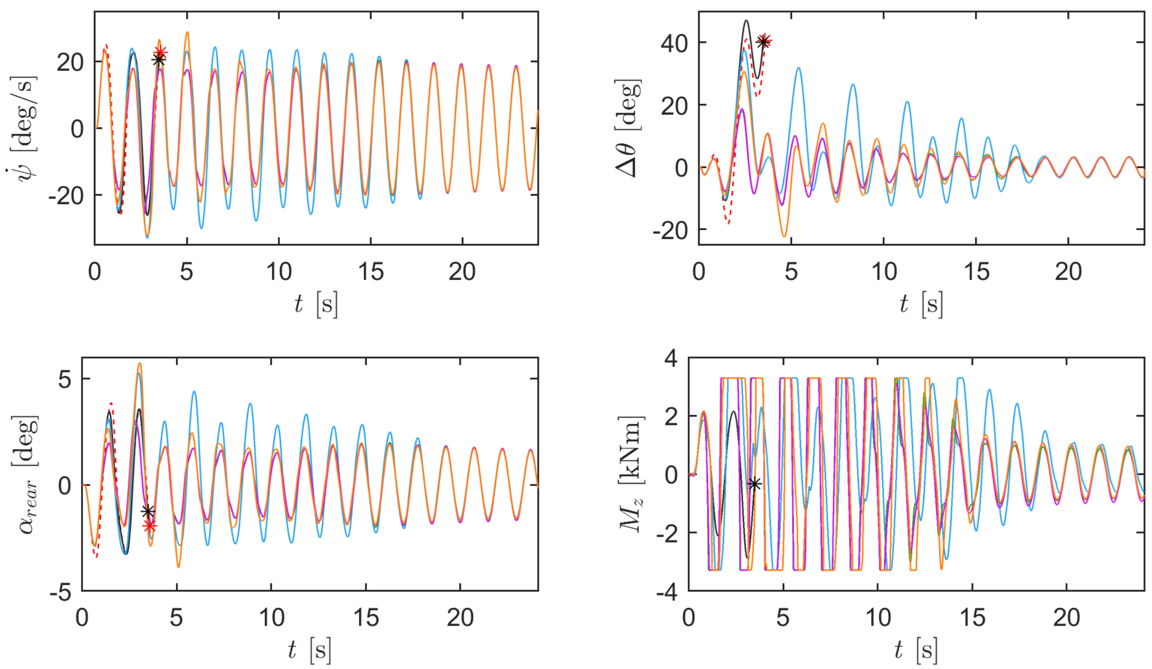
- **Single sinusoidal** steering test with a steering wheel angle input of 50 deg amplitude and 3 s duration, from an initial speed of 70 km/h
- **Prolonged sinusoidal** steering test at constant frequency of 0.67 Hz with a steering wheel angle input of 65 deg amplitude and ~25 s duration, from an initial speed of 70 km/h
- The results show that the best performance are obtained with the articulated vehicle model based controllers ($YR + HAE_{fun}$, $YR + SC_{HAE}$, $MYRE$ sorted by decreasing performance), whilst the worst result is obtained with the $MYR_{ref,rig}$ based on the rigid vehicle. The baseline TV controller YR_{rig} does not prove to be reliable in terms of performance

Pass. — YR_{rig} — $MYR_{ref,rig}$ — $YR + SC_{HAE}$ — $YR + HAE_{fun}$ — $MYRE$

Single sinusoidal



Prolonged sinusoidal



Hitch angle control

Robustness of the controllers

Robustness assessment through tests with **three trailers with different characteristics**

		Trailer A	Trailer B	Trailer C
m_T	Mass [kg]	1400	1000	500
I_T	Yaw mass moment of inertia [kgm^2]	778	646	481
$L_{F,T}$	Hitch joint to trailer CGT [m]	2.666	1.961	2.863
$L_{TOT,T}$	Hitch joint to axle distance [m]	2.800	2.300	2.940

TRAILER A		Manoeuvre	$Pass.$	YR^1_{rig}	$MYR^1_{ref,rig}$	$YR+SC_{HAE}$	$YR+HAE_{fun}$	$MYRE$
$RMSE_{\Delta\dot{\psi}}$	[deg/s]	I	9.90*	1.31*	1.26	3.10	2.10	1.37
		II	9.87*	8.08*	5.98	3.30	3.21	4.24
$RMSE_{\Delta\theta^*}$	[deg]	I	13.00*	15.70*	0.00	0.00	0.00	0.00
		II	16.70	19.85*	6.74	1.49	1.57	4.10
$IACA$	[Nm]	I	-	/	275	443	252	261
		II	-	/	699	746	756	793
$\lvert\alpha_R^{max}\rvert$	[deg]	I	7.06*	2.31*	2.31	2.32	2.29	2.29
		II	3.86*	3.57*	5.28	2.90	3.00	5.75
$\lvert\theta^{max}\rvert$	[deg]	I	45.00*	45.00*	6.51	5.83	5.18	6.19
		II	45.00*	45.00*	35.96	19.43	19.89	29.57
J^*_{KPI}	[-]	I	/	/	1.05	1.39	0.95	1.00
		II	/	/	4.37	2.93	2.97	3.86

TRAILER B		Manoeuvre	$Pass.$	YR^1_{rig}	$MYR^1_{ref,rig}$	$YR+SC_{HAE}$	$YR+HAE_{fun}$	$MYRE$
$RMSE_{\Delta\dot{\psi}}$	[deg/s]	I	5.29*	1.59	1.59	1.62	1.67	1.54
		II	5.97	4.56	4.67	4.09	4.07	3.42
$RMSE_{\Delta\theta^*}$	[deg]	I	8.63*	0.00	0.00	0.00	0.00	0.00
		II	6.44	5.76	5.47	1.57	1.63	2.86
$IACA$	[Nm]	I	-	258	258	257	247	268
		II	-	373	761	708	700	759
$\lvert\alpha_R^{max}\rvert$	[deg]	I	3.04*	2.38	2.38	2.44	2.40	2.40
		II	3.76	3.60	3.48	2.92	2.89	2.89
$\lvert\theta^{max}\rvert$	[deg]	I	45.00*	3.33	3.33	3.41	3.38	3.39
		II	40.33	36.56	31.06	19.26	20.15	28.44
J^*_{KPI}	[-]	I	/	0.77	0.77	0.78	0.76	0.79
		II	3.49	3.75	4.05	2.90	2.94	3.62

TRAILER C		Manoeuvre	$Pass.$	YR^1_{rig}	$MYR^1_{ref,rig}$	$YR+SC_{HAE}$	$YR+HAE_{fun}$	$MYRE$
$RMSE_{\Delta\dot{\psi}}$	[deg/s]	I	2.71	1.08	1.08	1.08	1.02	1.02
		II	8.96*	5.57*	9.97*	3.32	3.2	2.87
$RMSE_{\Delta\theta^*}$	[deg]	I	0.00	0.00	0.00	0.00	0.00	0.00
		II	17.58*	12.35*	11.55*	0.56	0.53	1.67
$IACA$	[Nm]	I	-	142	142	140	144	146
		II	-	/	/	682	692	763
$\lvert\alpha_R^{max}\rvert$	[deg]	I	2.84	2.23	2.23	2.33	2.2	2.2
		II	3.98*	3.31*	6.26*	2.84	2.81	3.31
$\lvert\theta^{max}\rvert$	[deg]	I	5.03	4.03	4.03	4.05	4.00	4.03
		II	45.00*	45.00*	45.00*	14.51	14.54	20.89
J^*_{KPI}	[-]	I	0.52	0.57	0.57	0.56	0.56	0.57
		II	/	/	/	2.44	2.45	3.04

[1]: rigid vehicle used as internal model

*: hitch angle reaches a threshold value. In this case the simulation is aborted early

-: value not calculated

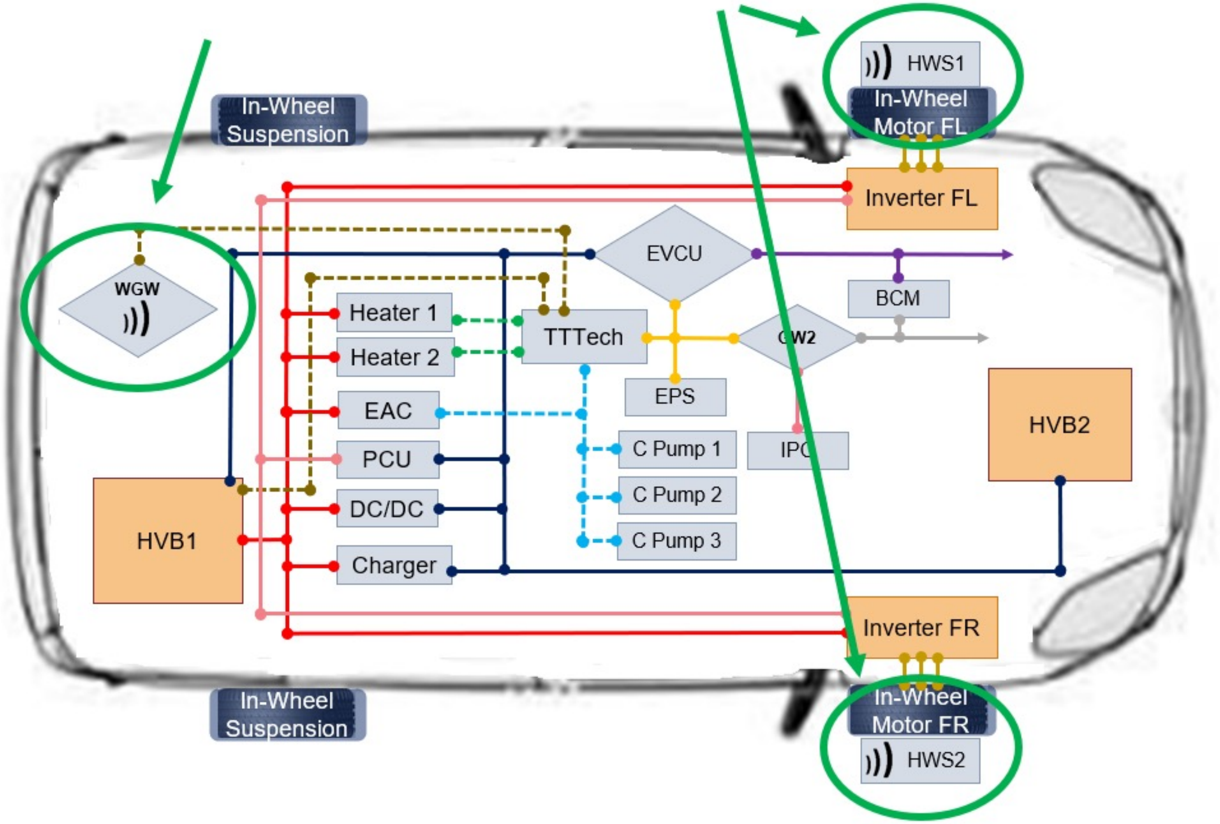
/: simulation interrupted; value not calculated

In-wheel sensor with energy harvester

For HiWiTronics the main objective was to develop a fully functional in-wheel sensor-system including an energy-harvesting device which is capable of gathering data at a high sample rate.

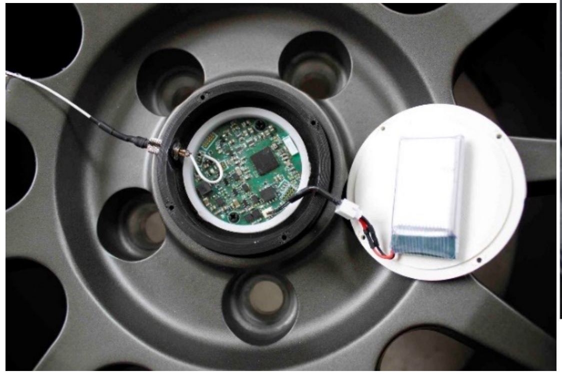
This sensor-data is provided by a wireless gateway to the control-system of the vehicle and allows an increase of efficiency by integrating accurate and fast recurring data to the control-function of the system.

HiWiTronics: in-wheel sensor-system (HWS) and wireless gateway (WGW)



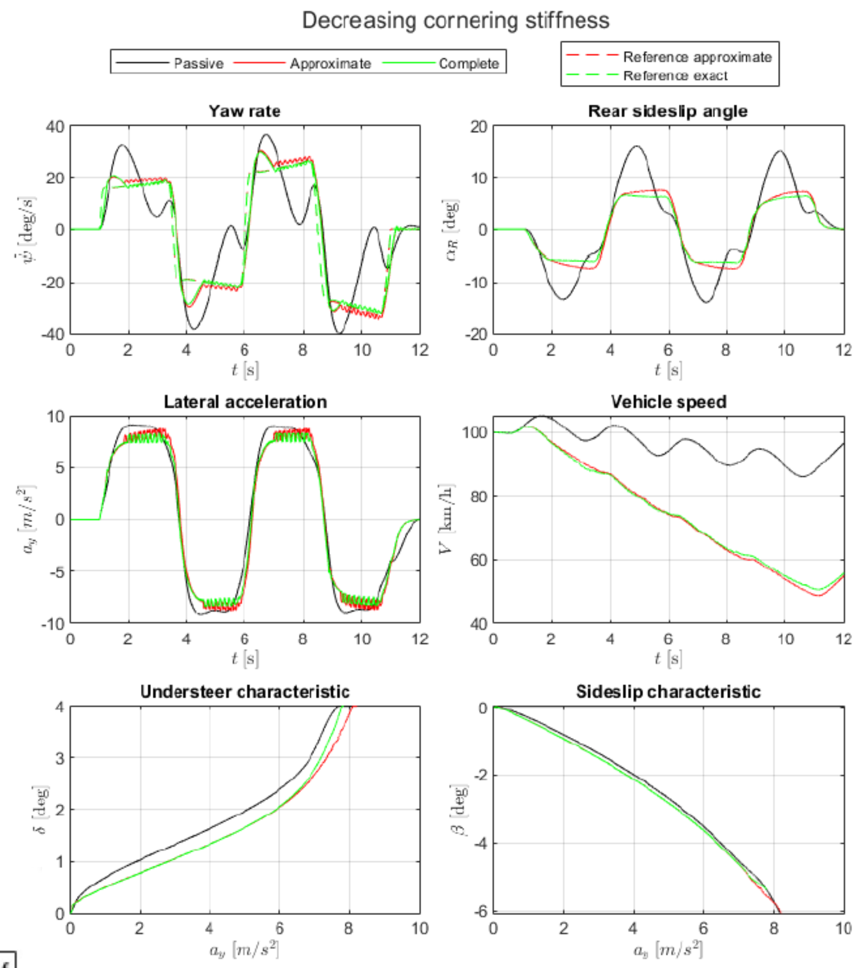
Robust TV controller with parameters scheduling

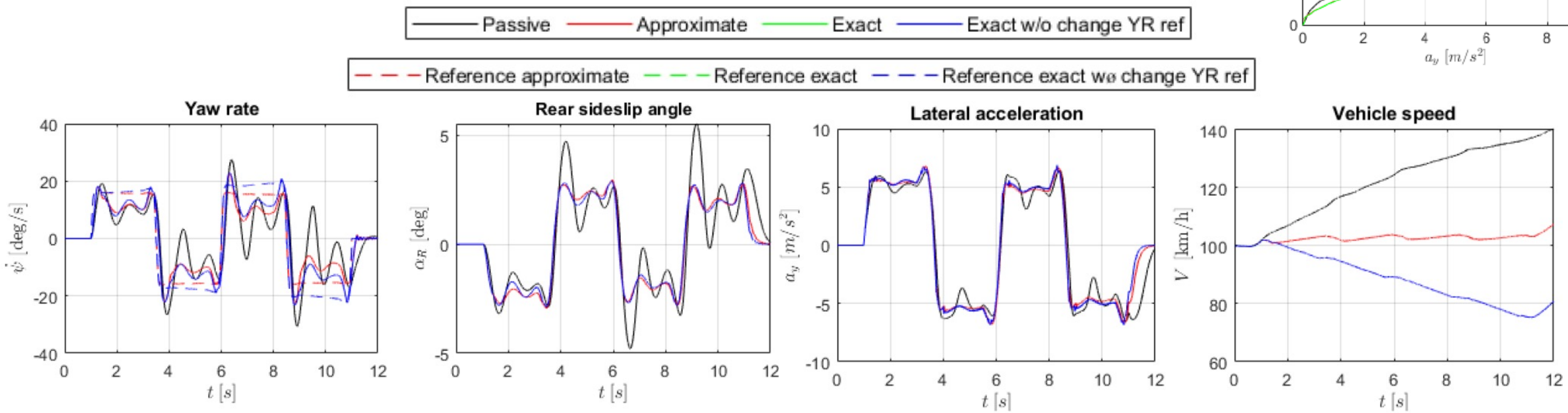
- HiWiTronics, has developed a patented system capable of harvesting energy from rotating parts.
- The In-Wheel Energy Harvesting Device allows signals detected in the wheel to be transmitted to a control unit in the chassis at very high data rates.
- The signals are transmitted at a frequency of 433 MHz due to the higher penetration depth. They are used to control smoother acceleration of electrified vehicles to avoid unnecessary tire wear and air pollution caused by tire abrasion.
- In 2020, the system including necessary sensors has been integrated into the rims of the in-wheel demonstrator vehicle of Tofas. Data communication and interfaces have been aligned with Tofas and TTTech Auto and have been accordingly implemented.



Robust TV controller with parameters scheduling

- All NMPC controllers use an internal model to make prediction about the future behaviour of the plant model;
- Usually, the parameters of the internal model do not vary along the prediction horizon and along the simulations;
- However, in real-life scenarios, parameters like mass and inertia of the vehicle, wheel parameters etc., are not constant and may vary based on the operating conditions;
- A sensitivity analysis has been carried out on the variation of cornering stiffness and friction coefficient, e.g. based on the tyre temperature and pressure variation provided by HWT sensors, to assess the robustness of the proposed controllers;
- Results show that the controller is robust against the parameter variation (cornering stiffness and friction coefficient) in its internal model.





Conclusions

Conclusions on advanced control for rigid EV :

- The controller was tested in wide range of vehicle speed
- The controller has the capability to follow the desired yaw rate and constrain the rear side-slip angle also at high vehicle speed, enhancing the overall vehicle stability;
- The controller showed enhanced vehicle performance in emergency safety manoeuvres like the single-step steer;
- The controller is capable to reduce the high amplitude damping and the peeks of the yaw rate and the rear side-slip angle;
- The regenerative braking controller proved to be effective in the reduction of battery energy consumption by up to 20%;
- A sensitivity analysis has been carried out on the variation of cornering stiffness and friction coefficient, e.g. based on the tyre temperature and pressure variation provided by HWT sensors, to assess the robustness of the proposed controllers;
- The reparameterization of the controller is possible and the analysis showed that the controller is robust against the cornering stiffness and friction coefficient tyre parameter variations.

Conclusions

Conclusions on advanced control for articulated electric vehicles:

- The inclusion of the trailer dynamics in the internal model significantly enhances the performance
- The **best performances** are obtained with $YR + HAE_{fun}$ showing an **88%** and **56%** reduction in the peak value of the hitch angle, whilst for the yaw rate tracking there is an improvement of about **79%** and **68%** in the first and second manoeuvre respectively, with respect to the passive.
- The **novel formulation** $YR + SC_{HAE}$ achieves **good results** in terms of hitch angle damping effect, e.g. **87%** and **57%** of hitch angle peak reduction in the first and second manoeuvre respectively, whilst the yaw tracking performance, shows an **improvement** of approximately **68%** in both manoeuvres, with respect to the passive. The main **advantage** is that the hitch angle contribution is active only when predefined thresholds are exceeded.
- The $MYRE$ is good only when optimized, but does not show robustness with respect to the trailer parameters.
- The $MYR_{ref,rig}$ shows **excellent** results in terms of **yaw rate tracking** but, as **drawback**, the other **KPI values** are not as good as the previous controller formulations. This can be attributable to the use of the **rigid vehicle as internal model**.
- The YR_{rig} is the **simplest** controller based on the **rigid vehicle** and **does not show good robustness** with respect to the trailer parameters variation.
- Short prediction horizons do not represent a performance limitation.
- The algorithms developed are real-time implementable

Thank You for Your Attention!

The authors would like to acknowledge the European Union to fund the SYS2WHEEL (Grant Agreement No: 824244) project under the Horizon 2020 Research and Innovation Program.