ACTIVE VIBRATION CONTROL FOR ELECTRIC VEHICLE COMPLIANT DRIVELINES

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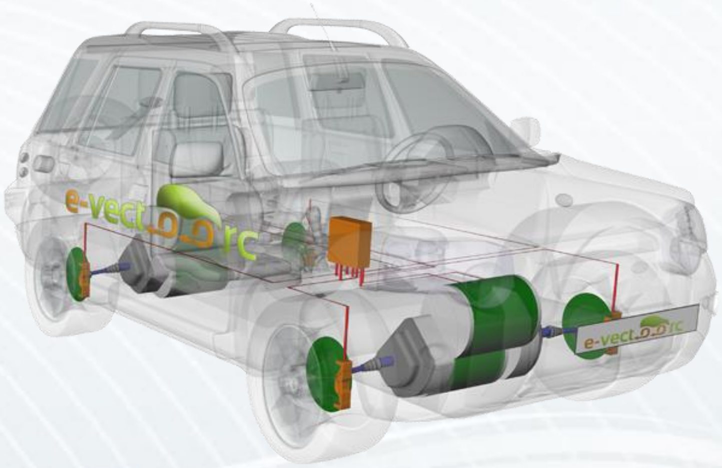

TT06-6: Control of electrical drives

IECON 2013

39th Annual Conference of the IEEE Industrial Electronics Society

November 10-13 2013, Vienna, Austria

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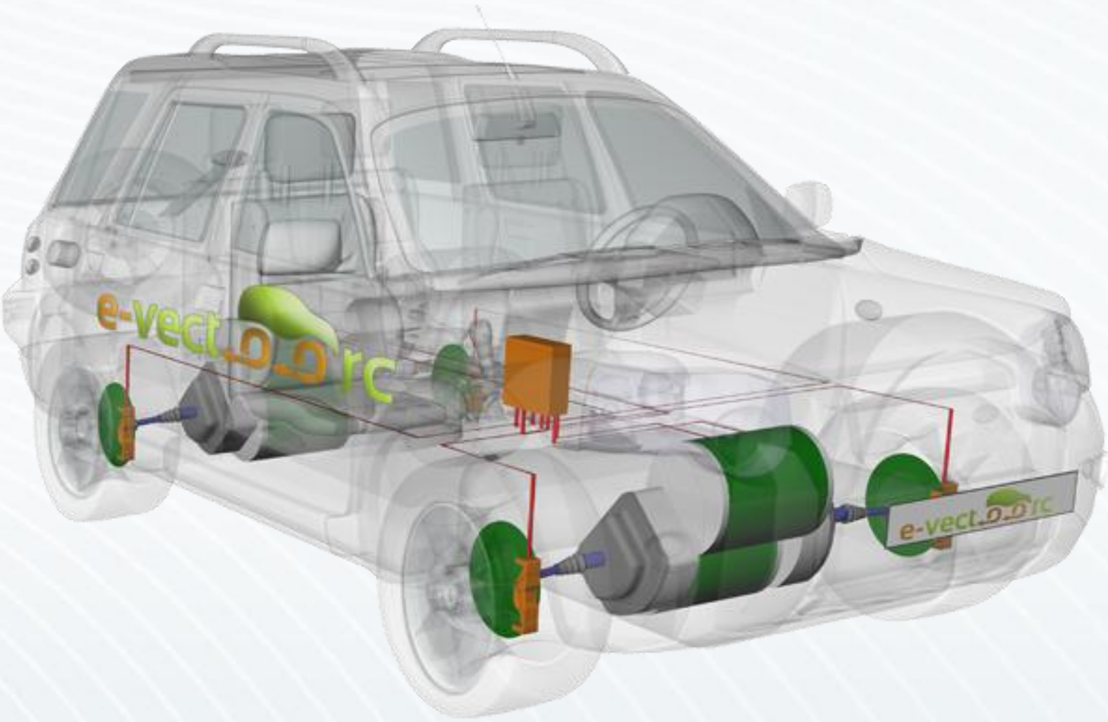
INTRODUCTION



The present work is part of the **E-VECTOORC project**

- Development and demonstration of yaw rate and sideslip angle control algorithms based on the combination of front/rear and left/right torque vectoring to improve overall vehicle dynamic performance.

- Development and demonstration of novel strategies for the modulation of the torque output of the individual electric motors to enhance brake energy recuperation, Anti lock Brake function and Traction Control function.

INTRODUCTION

The vehicle configuration in the project uses in-board motors. The elements of the transmission are:

- Switch Reluctance motors.
- Gearbox.
- Halfshaft

Compliant elements affected by low frequency resonances!!

INTRODUCTION

The **appearance of torsional oscillations** could be motivated by:

- Fast response of the electric motor actuated by the driver.
- In the case of Switched Reluctance Motors (SRM) or Permanent Magnet Synchronous Motors (PMSM), as they are controlled using position feedback, the closed loop could encompass unmodeled torsional resonance modes.
- Perturbations coming from the road.
- Backlash and other nonlinear behaviour in the powertrain.
- Friction brake torque, as a variable load applied to the wheel inertia.

The **effect of the oscillations** are:

- Driver comfort can be affected by the vibrations induced by the drivetrain oscillations.
- Oscillations in the torque can cause wheel blockage or slip.
- If the modulation of the torque in ABS and TC actuations is done by the electric motors, resonant responses in the frequency range close to the expected TC and ABS demands could lead to destabilization of the controllers.
- Oscillations in the powertrain torque will result in accelerated fatigue of mechanical components

INTRODUCTION

Active Vibration Control (AVC) of compliant a drive train is a problem extensively analyzed in the industry with well established damping solutions:

- State feedback
- Speed/acceleration/torque/relative speed feedback
- Speed tracking combined with damping algorithms

However, the drive train of an electric vehicle has special characteristics:

- The control command is not the speed of the shaft but the tire reaction on the road,
- The perturbation is related to a highly nonlinear time varying element: the contact tire-road.

DESCRIPTION OF THE MODEL

The evaluation of the system has been arranged using a detailed simulation model including:

- The delayed response of the motor:

$$T_{EM} = \frac{1}{\tau s + 1} T_{dem}$$

- The torque equilibrium in the motor:

$$T_{EM} - \frac{r_t T_{shaft}^{in}}{\eta_{eq}} = J_{eq} \ddot{\theta}_{EM}$$

$$T_{shaft}^{in} = k_s \left(r_t \theta_{EM} - \theta_w \right) + d_s \left(r_t \dot{\theta}_{EM} - \dot{\theta}_w \right)$$

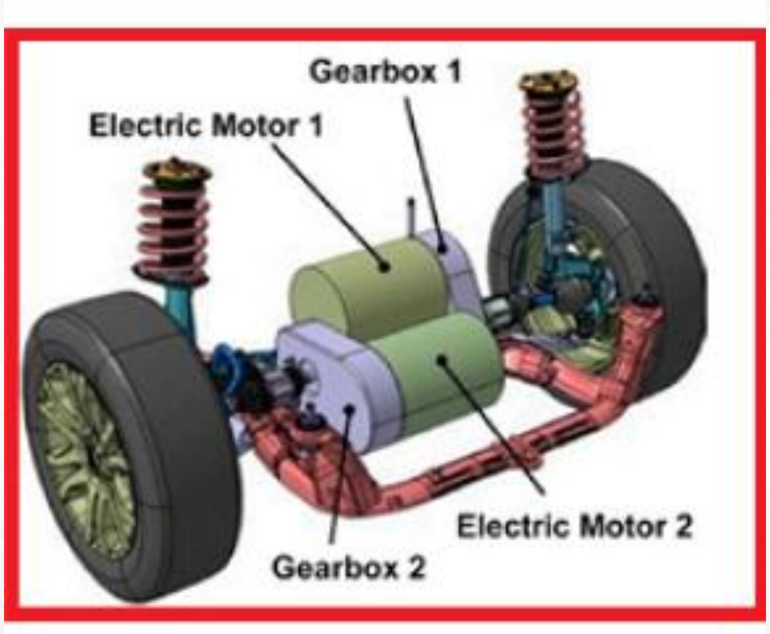
$$T_{shaft}^{out} = \left(T_{shaft}^{in} - \frac{J_{fhs}}{2} \ddot{\theta}_w \right) \eta_s$$

- The transmission to the wheel:

$$T_{shaft}^{out} - T_d - T_{roll} = J_{wheel} \ddot{\theta}_w$$

- The vehicle coupling:

$$T_d - T_{drag}\left(v_{car} \right) = M_v \dot{v}_{car} R_w^2$$



- The tire delayed reaction:

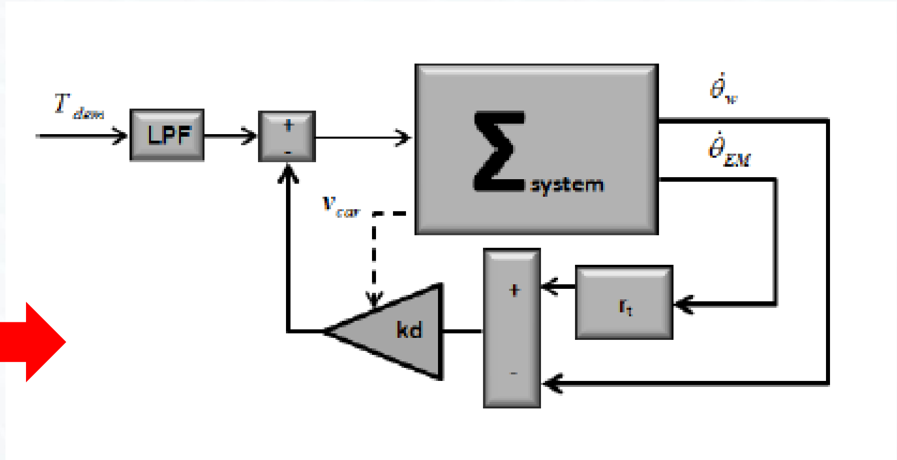
$$\frac{L_{fw}}{v_{car}} \dot{T}_d + T_d = T_{tyre}$$

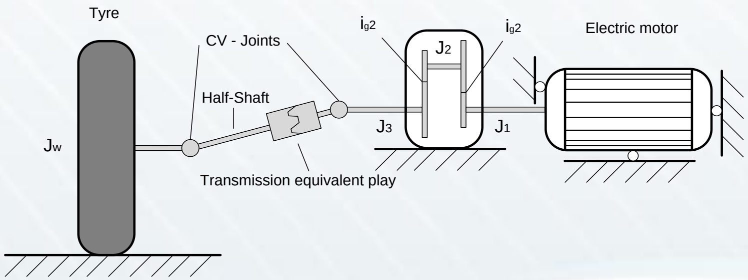
DESIGN OF THE CONTROLLER

Typical approaches for damping torsional oscillations in compliant transmissions in vehicles are mainly:

- Damping feedback laws:
  - Speed.
  - Acceleration.
  - Force.
  - Relative speed.
- State feedback.
- Tracking closed loops.
- Others:
  - Perturbation observers.
  - Sliding controllers.
  - …

For comparison





DESIGN OF THE CONTROLLER

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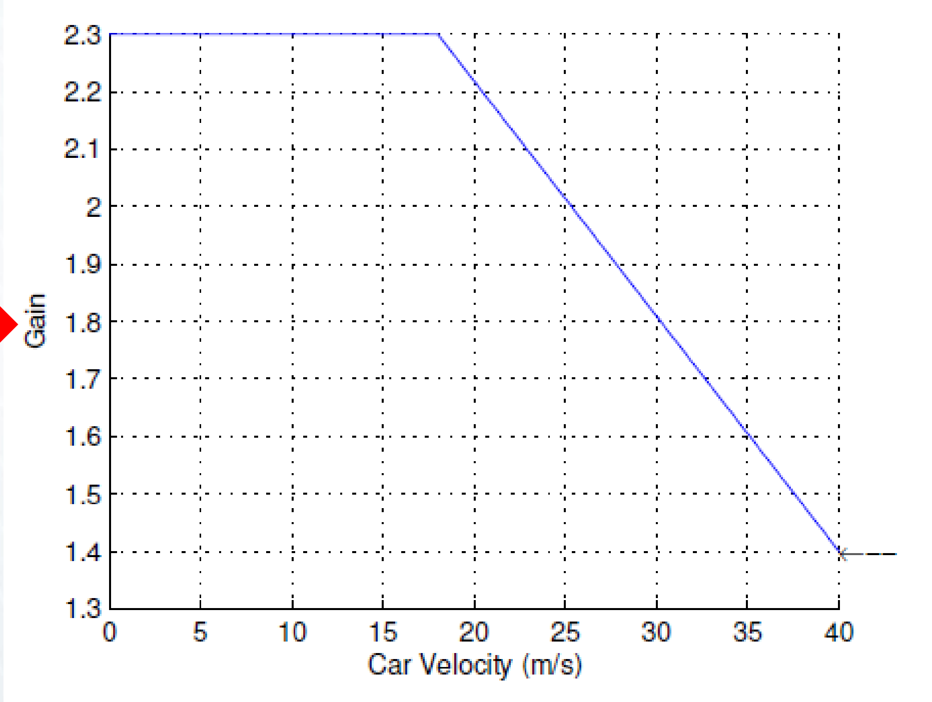
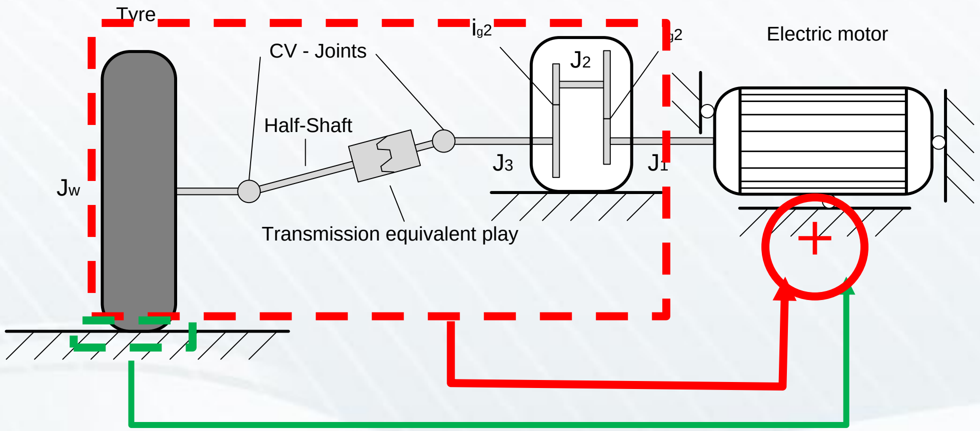
Optimized gain schedule



DESIGN OF THE CONTROLLER

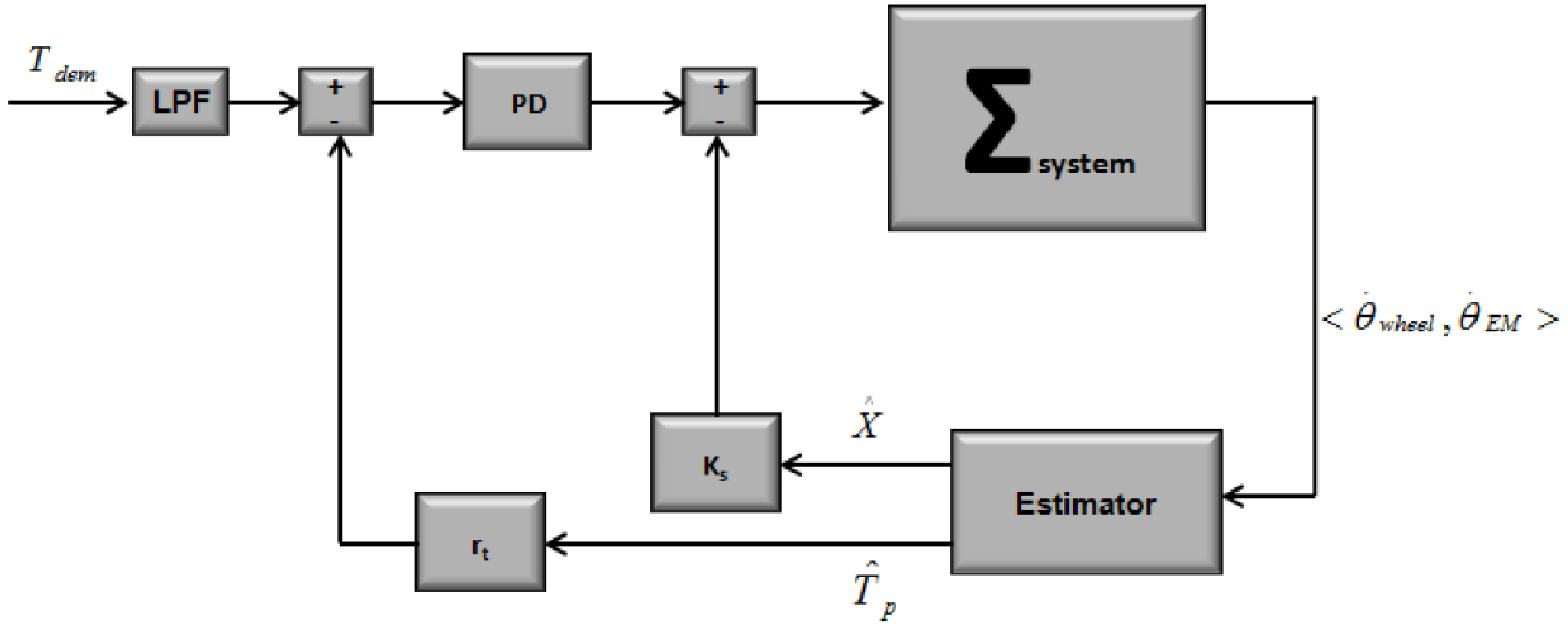
The proposed vibration control (**E-AVC**) includes:

- A **fast state feedback loop** for damping the resonance frequency of the elastic transmission.
- An **outer loop for tracking the torque reaction** at the wheel and therefore eliminating the oscillations at frequencies below the resonance frequency, which are not affected by the state feedback damping.



DESIGN OF THE CONTROLLER

A block diagram can be observed below:



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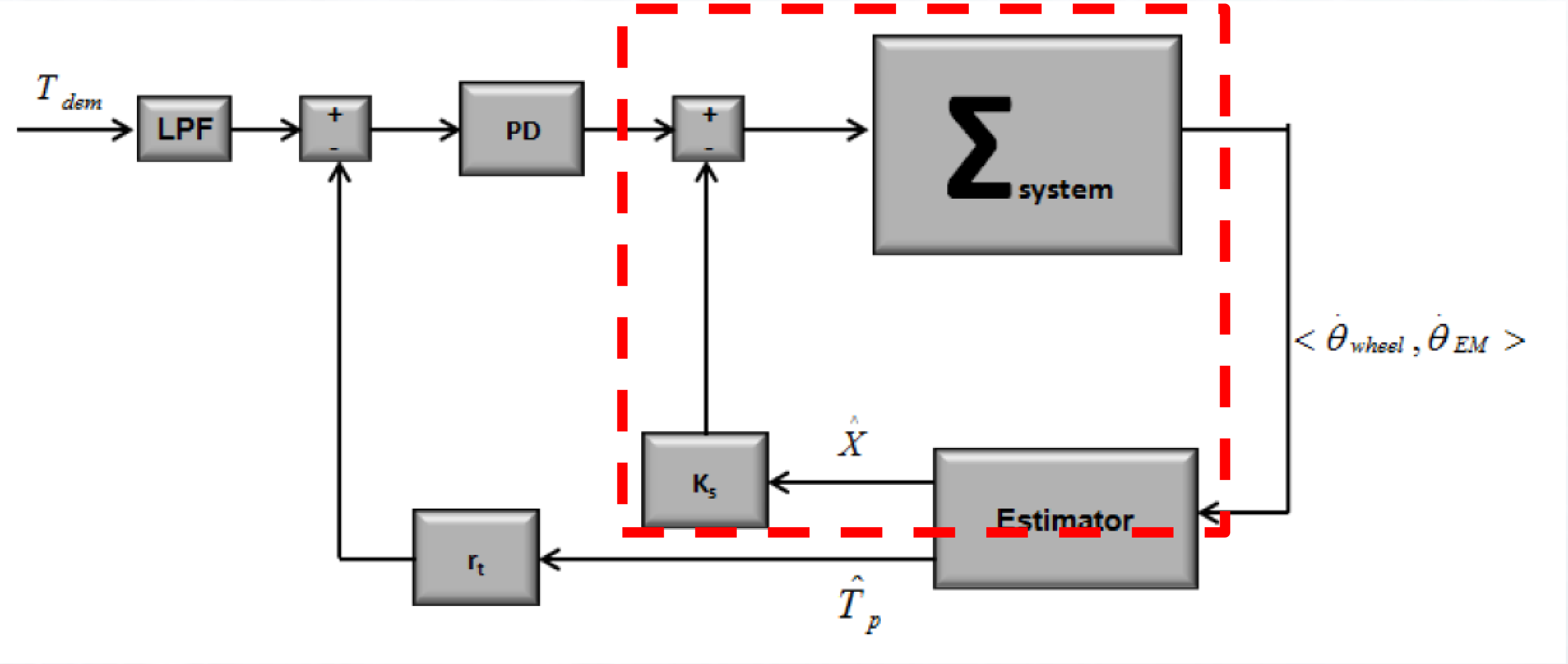
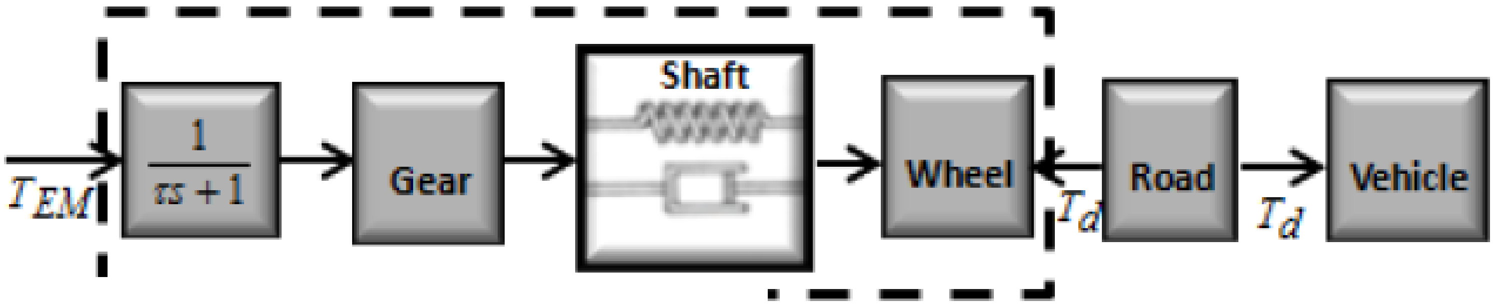


DESIGN OF THE CONTROLLER

The fast state feedback is focused on well characterized elements:



$$\begin{pmatrix} \dot{\theta}_{motor} \\ \ddot{\theta}_{motor} \\ \dot{\theta}_{wheel} \\ \ddot{\theta}_{wheel} \\ \dot{T}_{EM} \end{pmatrix} = \dot{\mathbf{x}}_s = \mathbf{A}_s \mathbf{x}_s + \mathbf{B}_s T_{dem}$$

$$\mathbf{A}_s = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ \frac{-k_s r_t^2}{J_{eq}\hat{\eta}_{eq}} & \frac{-d_s r_t^2}{J_{eq}\hat{\eta}_{eq}} & \frac{k_s r_t}{J_{eq}\hat{\eta}_{eq}} & \frac{d_s r_t}{J_{eq}\hat{\eta}_{eq}} & \frac{1}{J_{eq}} \\ 0 & 0 & 0 & 1 & 0 \\ \frac{k_s r_t}{J_{wheel}} & \frac{d_s r_t}{J_{wheel}} & \frac{-k_s}{J_{wheel}} & \frac{-d_s}{J_{wheel}} & 0 \\ 0 & 1 & 0 & 0 & \frac{-1}{\tau} \end{pmatrix}$$

$$\mathbf{B}_s = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{\tau} \end{pmatrix}$$

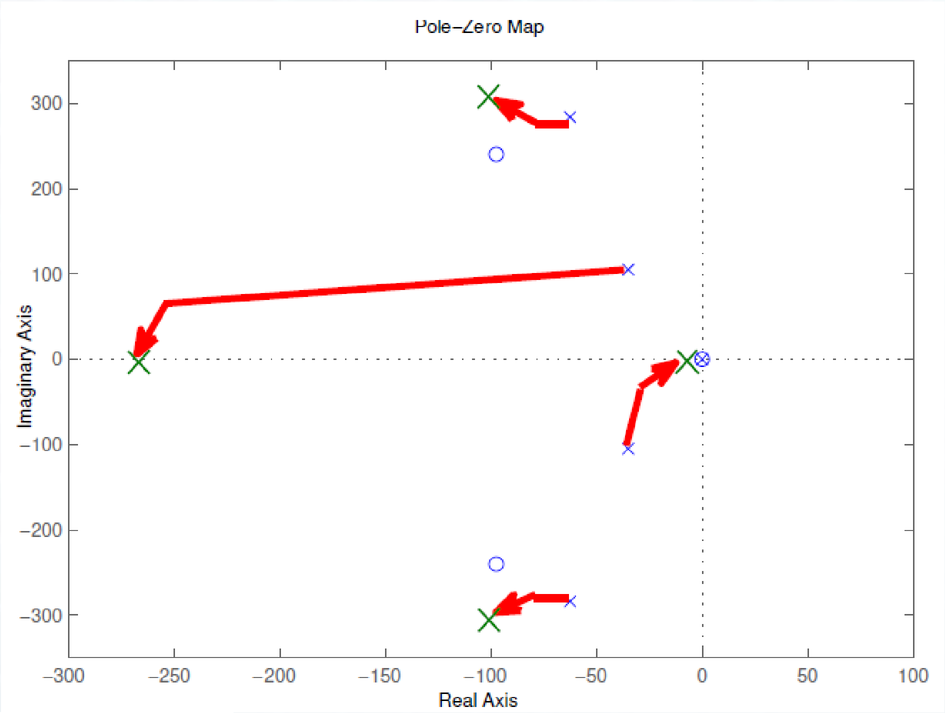
This representation is highly simplified with regards to the simulation model.

DESIGN OF THE CONTROLLER

The fast state feedback is focused on well characterized elements:

$$\begin{pmatrix} \dot{\theta}_{motor} \\ \ddot{\theta}_{motor} \\ \dot{\theta}_{wheel} \\ \ddot{\theta}_{wheel} \\ \dot{T}_{EM} \end{pmatrix} = \dot{\mathbf{x}}_s = \mathbf{A}_s \mathbf{x}_s + \mathbf{B}_s T_{dem}$$

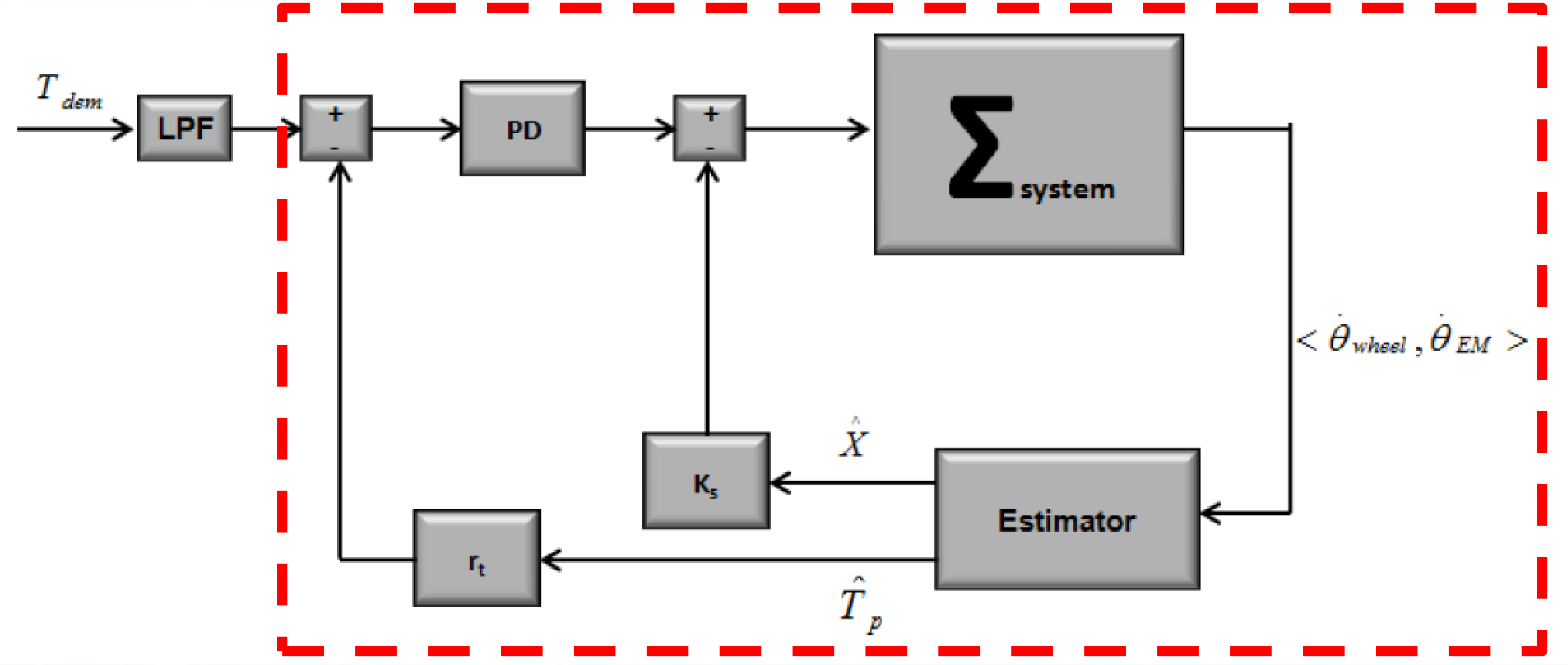
$$\dot{\mathbf{x}}_s = (\mathbf{A}_s - \mathbf{K}_s)\,\mathbf{x}_s + \mathbf{B}_s \mathbf{K}_s T_{dem}$$



$$\dot{\theta}_{wheel} / T_{dem}$$

DESIGN OF THE CONTROLLER

A block diagram can be observed below:



DESIGN OF THE CONTROLLER

The outer loop requires estimating the reaction of the road.

$$\begin{pmatrix} \dot{\theta}_{motor} \\ \ddot{\theta}_{motor} \\ \dot{\theta}_{wheel} \\ \ddot{\theta}_{wheel} \\ \dot{T}_{EM} \end{pmatrix} = \dot{\mathbf{x}}_s = \mathbf{A}_s \mathbf{x}_s + \mathbf{B}_s T_{dem}$$

+

$$\begin{aligned} T_p &= T_{tyre} - T_{roll} \\ \frac{dT_p}{dt} &= 0 \end{aligned}$$

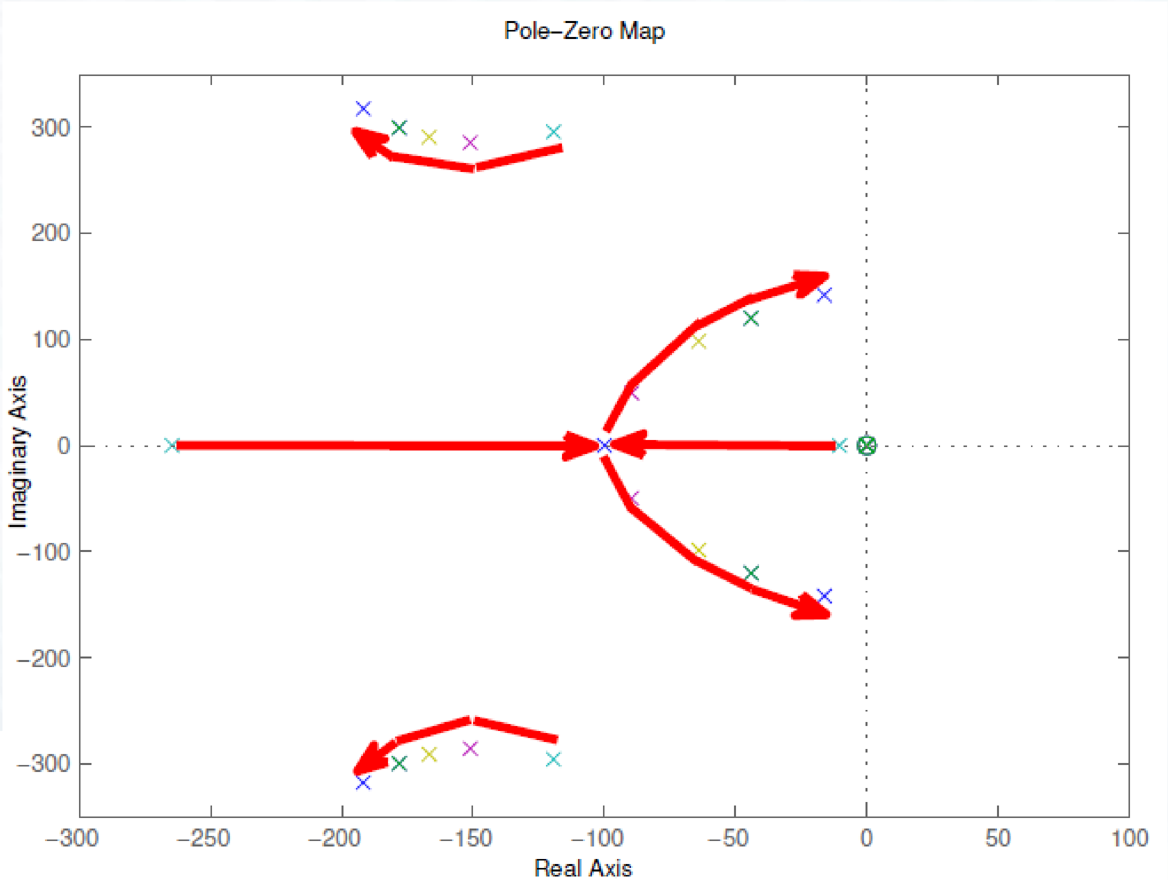
Perturbation Estimator based on Extended Observers:

$$\begin{pmatrix} \dot{\mathbf{x}}_s \\ \dot{T}_p \end{pmatrix} = \begin{pmatrix} \mathbf{A}_s & 0_{5\times 1} \\ 0_{1\times 5} & 0 \end{pmatrix} \begin{pmatrix} \mathbf{x}_s \\ T_p \end{pmatrix} + \begin{pmatrix} \mathbf{B}_s \\ 0 \end{pmatrix} T_{dem}$$

DESIGN OF THE CONTROLLER

The reaction of the road is tracked with respect to the driver command:

PD controller



T_p/T_{dem}

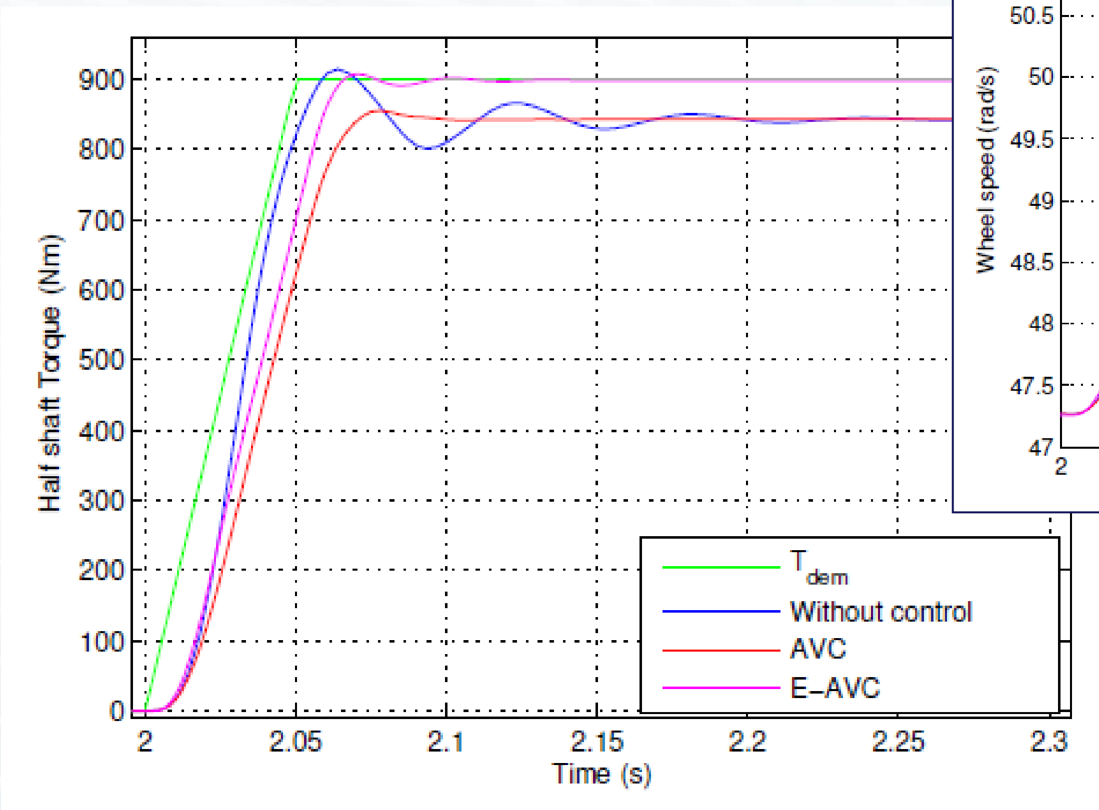
VIRTUAL VALIDATION

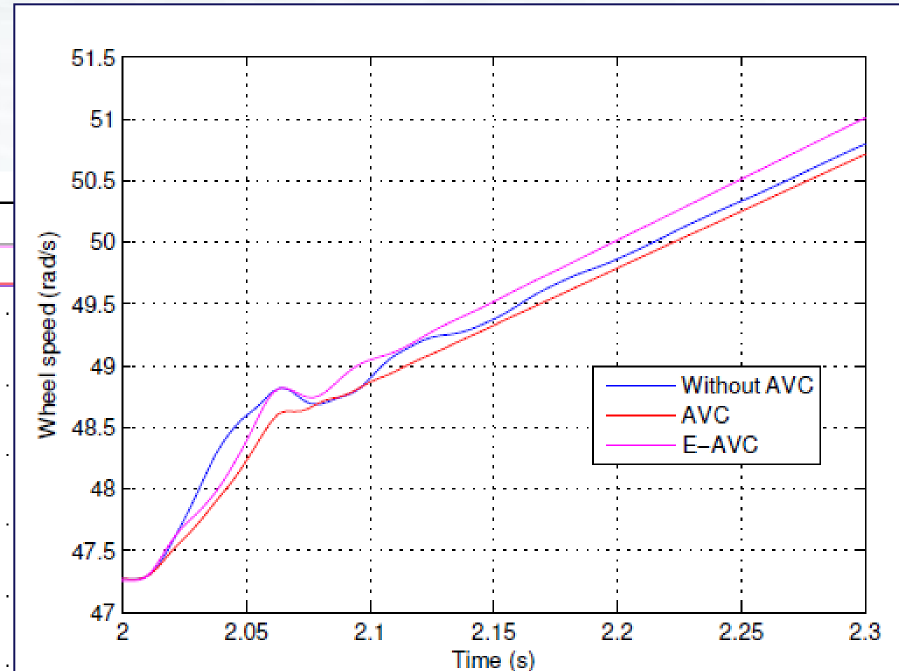
The validation is done in two different conditions:

- Acceleration step in a dry road.
- Acceleration step in snowy conditions.

VIRTUAL VALIDATION

- Acceleration step in a dry road.

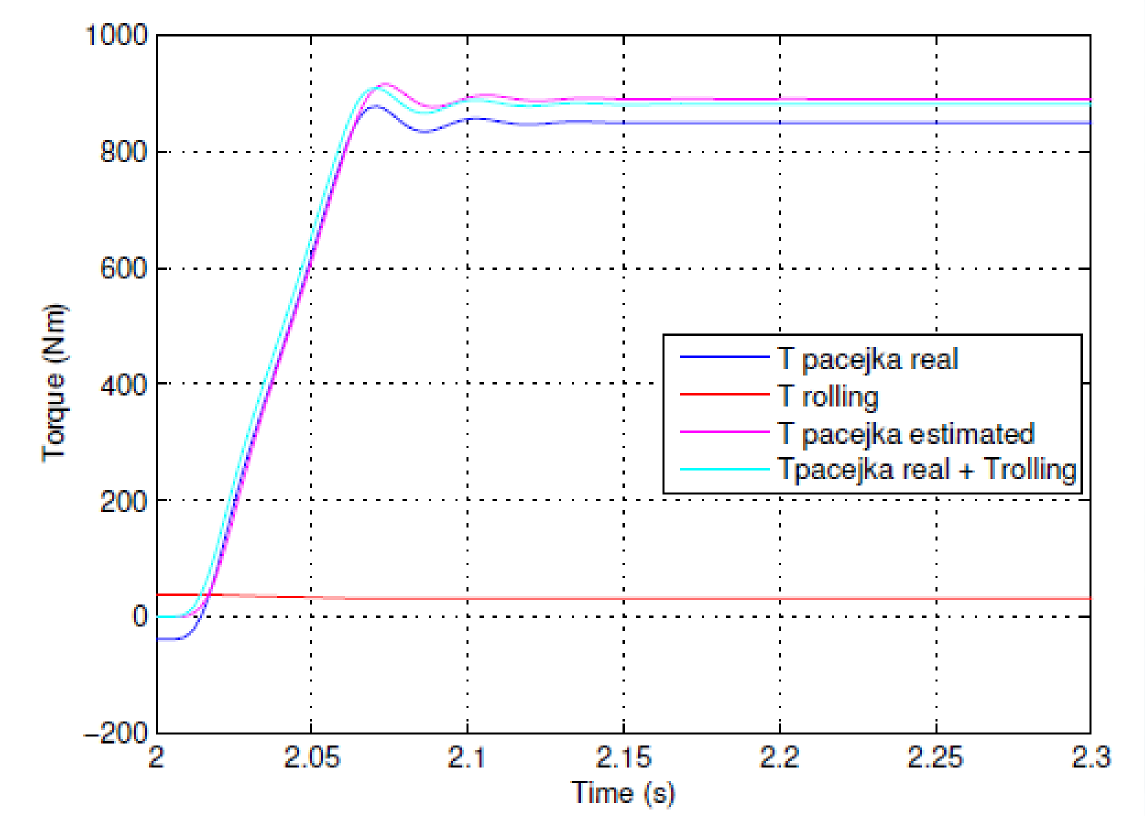




VIRTUAL VALIDATION

- Acceleration step in a dry road.

Even with a simplified representation, the estimator succeeds in approaching the response at the road!

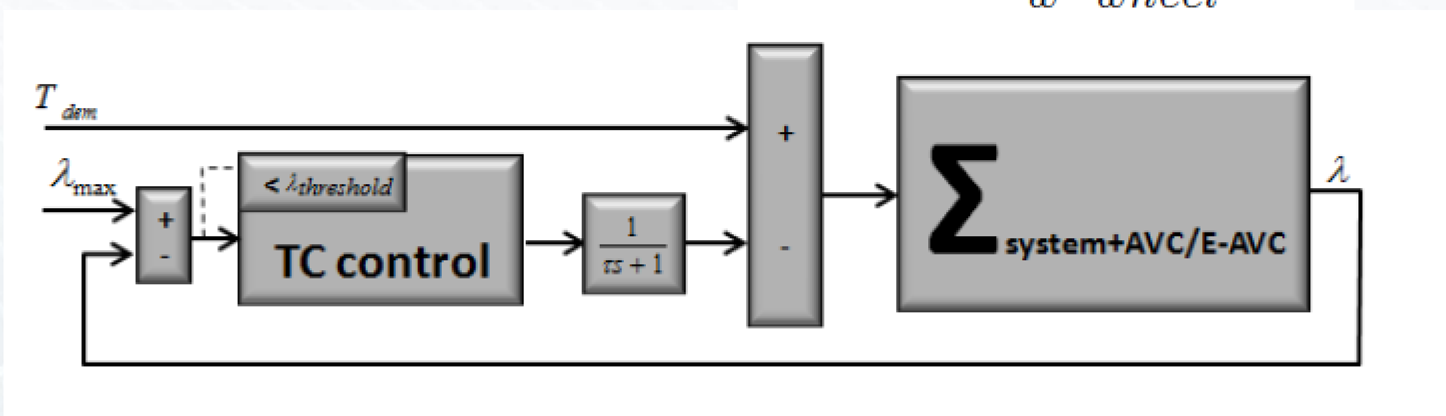


VIRTUAL VALIDATION

- Acceleration step in snowy conditions.

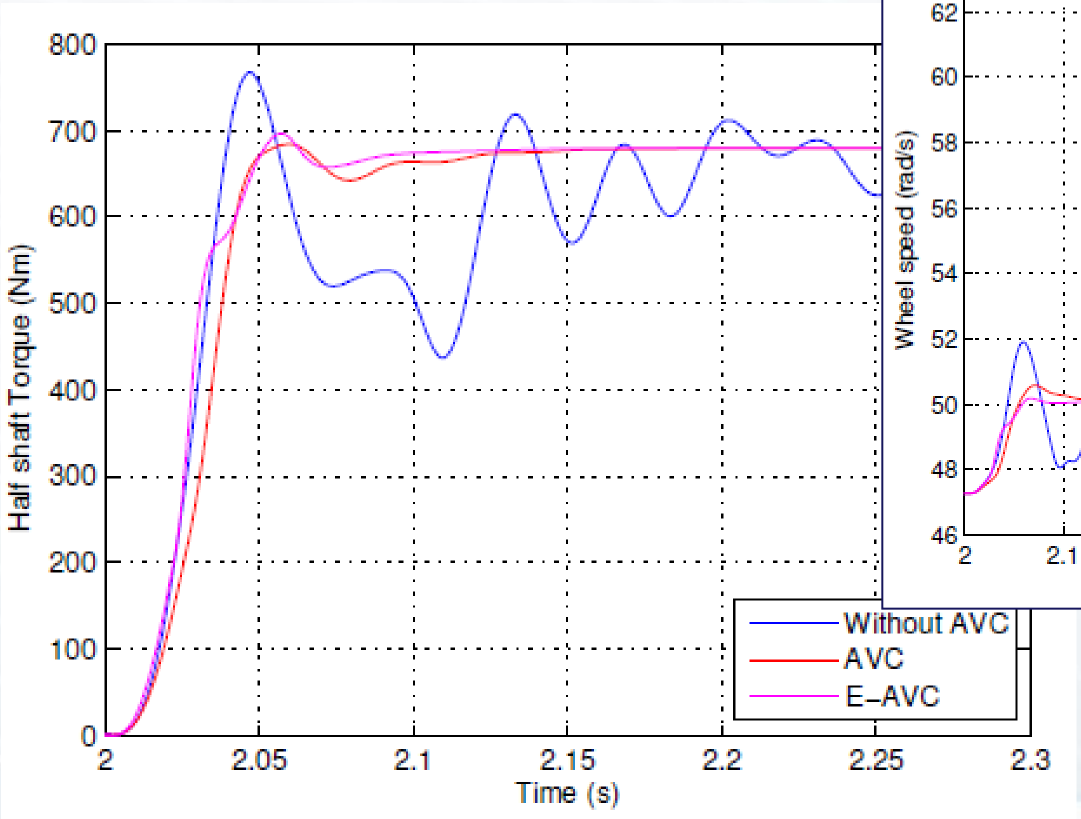
The low friction conditions result in saturation effects in the wheel, and the activation of the **slip control**.

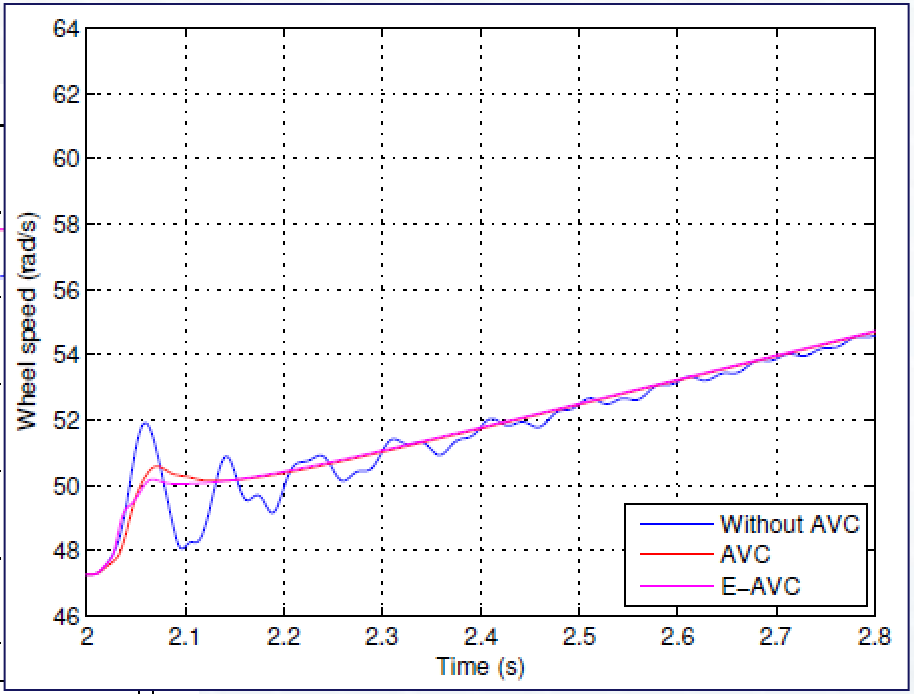
$$\lambda = \frac{R_w \dot{\theta}_{wheel} - v_{car}}{R_w \dot{\theta}_{wheel}}$$



VIRTUAL VALIDATION

- Acceleration step in snowy conditions.

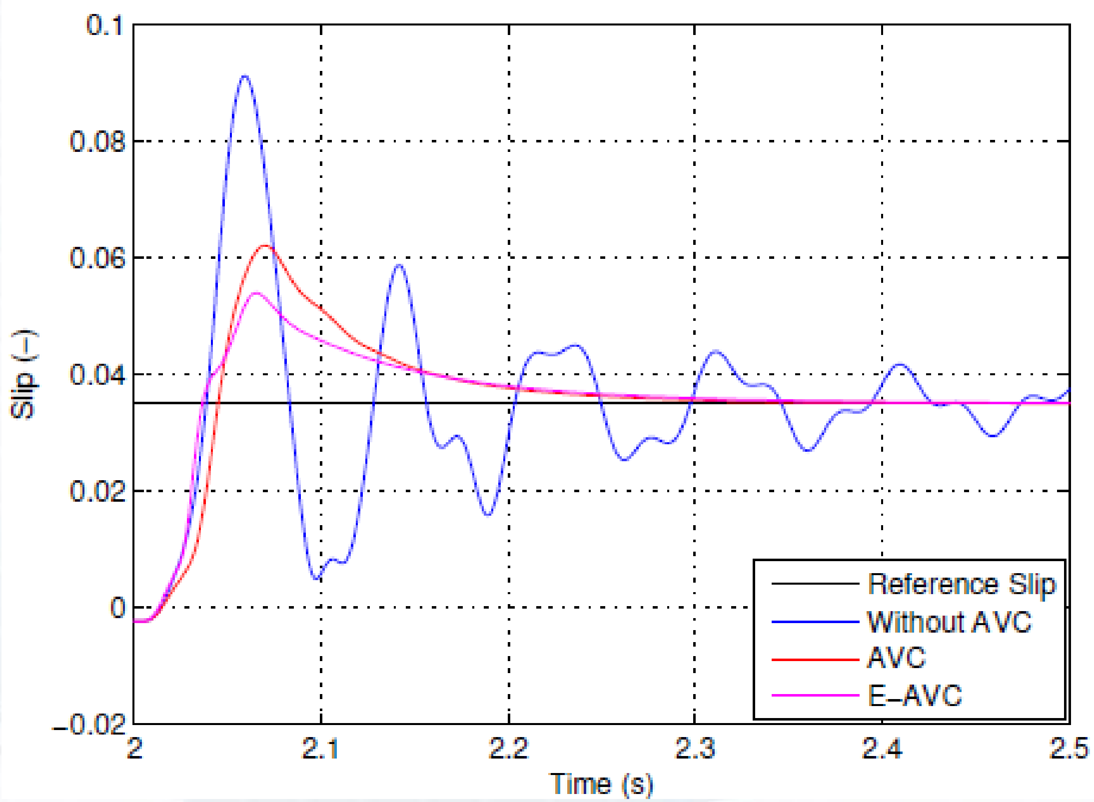




VIRTUAL VALIDATION

➢ Acceleration step in snowy conditions.

The control slip ratio is also improved with the E-AVC.



CONCLUSIONS AND FURTHER ACTIVITIES

The proposed algorithm permits:

- To increase the low frequency performance, which cannot be afforded by simple active damping methods more focused on a definite resonance frequency.
- To assure the force transmission between wheel and road.
- To estimate the reaction force of the tire which can be used for other modules of the vehicle (TC or ABS).

Compared with a classical tachometric method, the proposed controller shows:

- A higher response speed.
- Better torque tracking by the compensation of efficiency effects which reduce the effective reaction on the road.

CONCLUSIONS AND FURTHER ACTIVITIES

Further activities include the implementation in the prototype which is being prepared in the e-Vectoorc project.

THANK YOU FOR YOUR ATTENTION!

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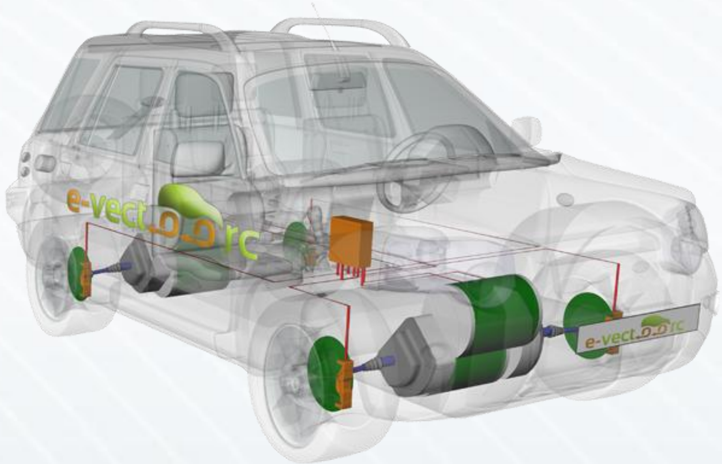

More information of the e-Vectoorc project can be found in:

http://www.e-vectoorc.eu/