Nonlinear Model Predictive Control for Preview-Based Traction Control

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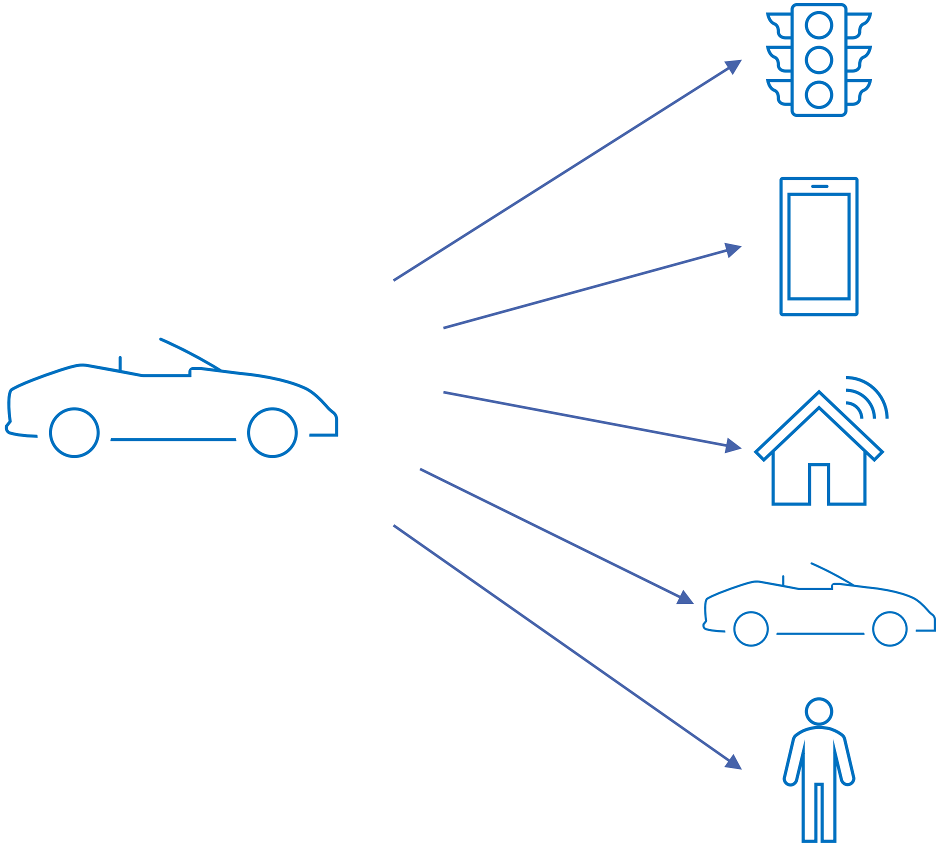
Introduction

- Vehicle connectivity – V2X



Infrastructure – V2I

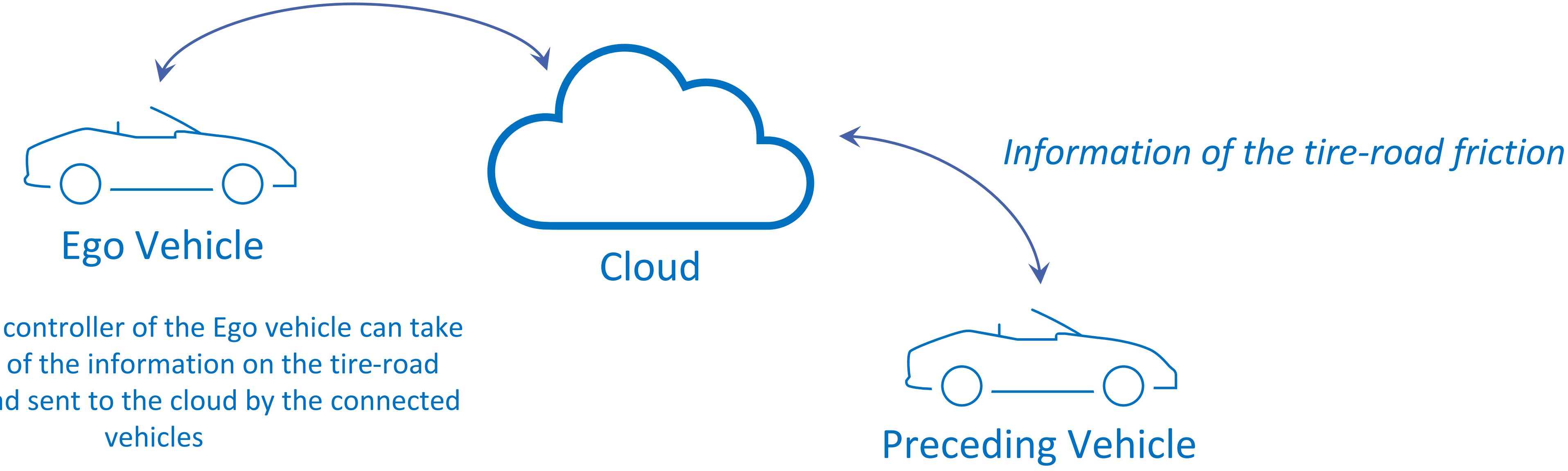
Devices – V2D

Smart Home – V2H

Vehicles – V2V

Pedestrians – V2P

- Vehicle to vehicle – V2V



The traction controller of the Ego vehicle can take advantage of the information on the tire-road friction ahead sent to the cloud by the connected vehicles

Our study presents a nonlinear model predictive control (NMPC) formulation for preview-based traction control, which uses the information on the expected tire-road friction coefficient ahead to enhance the wheel slip control performance.

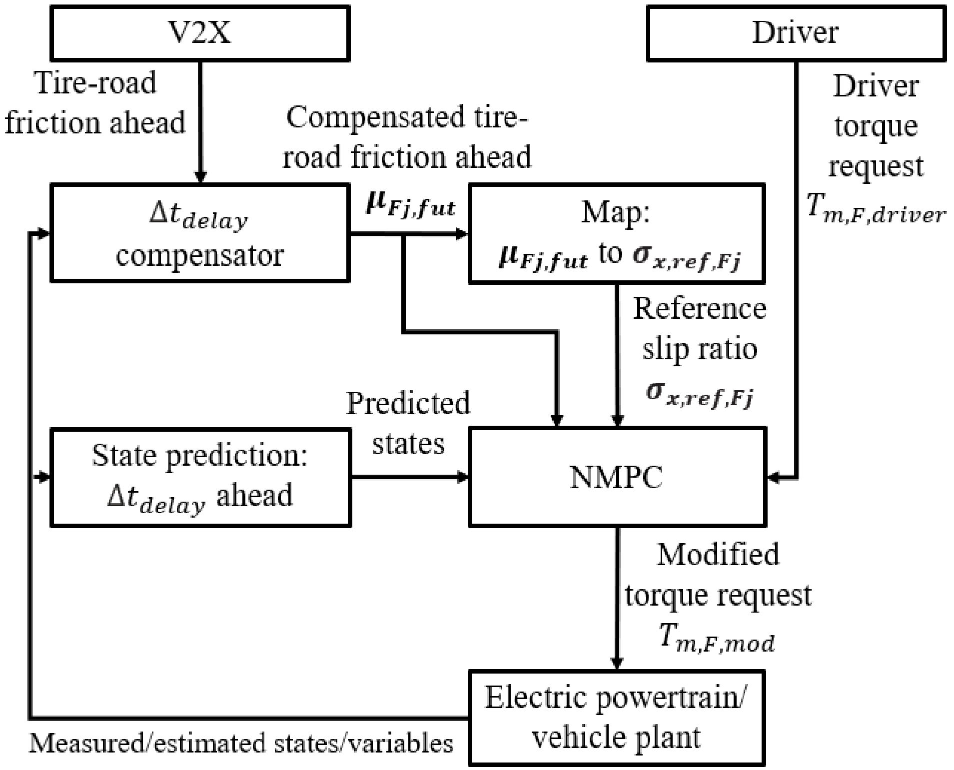
Introduction

- Proof-of-concept experiments on an electric vehicle prototype highlight the real-time capability of the controller, and the wheel slip control performance improvement brought by the tire-road friction coefficient preview.
- An experimentally validated simulation model is used in sensitivity analyses, to evaluate the performance benefit of the preview-based controller for different powertrain characteristics, such as time constants and/or pure time delays.

Control architecture

Two traction controllers were developed:

- a pre-emptive NMPC with preview of the tire-road friction ahead in the context of V2X;
- a benchmarking non-pre-emptive NMPC, which is only aware of the instantaneous tire-road friction condition.



NMPC formulation

Continuous time formulation

$$\dot{\boldsymbol{x}}(t) = f(\boldsymbol{x}(t), \boldsymbol{u}(t))$$

States

$$\boldsymbol{x} = [T_{m,F}, \omega_{FL}, \omega_{FR}, s_{FL}, s_{FR}, e_{int,FL}, e_{int,FR}]$$

Control action

$$\boldsymbol{u} = [T_{m,F,mod}, \varepsilon_{\sigma_{x,FL}}, \varepsilon_{\sigma_{x,FR}}]$$

$$\dot{T}_{m,F} = \frac{T_{m,F,mod} - T_{m,F}}{\tau}$$

$$\dot{\omega}_{Fj} = \frac{T_{wh,Fj} - F_{x,Fj} R_F}{J_{\omega,F}}$$

$$\dot{s}_{Fj} = \dot{\omega}_{Fj} R_F - \dot{V} = \left[-\frac{R_F^2}{J_{\omega,F}} - \frac{2}{m} \right] F_{x,Fj} + \frac{T_{wh,Fj} R_F}{J_{\omega,F}}$$

$$\dot{e}_{int,Fj} = e_{Fj} = \sigma_{x,ref,Fj} - \sigma_{x,Fj}$$

$$s_{Fj} = \omega_{Fj} R_F - V \qquad \sigma_{x,Fj} = \frac{s_{Fj}}{\omega_{Fj} R_F}$$

$$\dot{V} = \frac{F_{x,FL} + F_{x,FR}}{m} \approx \frac{2F_{x,Fj}}{m}$$

Pacejka magic formula

$$F_{x,Fj} = \mu_{x,Fj} F_{z,Fj}$$

$$\mu_{x,Fj} = D_{Fj} \sin\left(C_{0,F} \tan^{-1}\left(B_{Fj} \sigma_{x,Fj}\right)\right)$$

$$B_{Fj} = B_{0,F} / \mu_{Fj,fut}$$

$$D_{Fj} = D_{0,F} \mu_{Fj,fut}$$

NMPC formulation

Reference slip ratio along the prediction horizon

$$\sigma_{x,ref,Fj} = f_{\sigma_{x,ref,F}}\left(\mu_{Fj,fut}, F_{z,Fj}\right)$$

$$\boldsymbol{\mu}_{\boldsymbol{Fj,fut}}(k) = f_{\mu_{Fj,fut}}\left[\boldsymbol{S}_{\boldsymbol{fut}}(k) + \Delta x_{delay}(k)\mathbf{1}\right]$$

$$\boldsymbol{S}_{\boldsymbol{fut}}(k) = S(k)1 + V(k)\left[\boldsymbol{t}_{\boldsymbol{fut}} - t_{fut,0}\mathbf{1}\right] \qquad \Delta x_{delay}(k) = V(k)\Delta t_{delay}$$

For the non-pre-emptive NMPC implementation, $\boldsymbol{\mu}_{\boldsymbol{Fj,fut}}$ is a vector of identical components, equal to the current tire-road friction condition, and $\Delta t_{delay} = \Delta x_{delay} = 0$.

Constraints

$$0 \leq T_{m,F,mod,n} \leq T_{m,F,driver}$$

$$e_{Fj,n} + \varepsilon_{\sigma_{x,Fj},n} \geq 0$$

$$\varepsilon_{\sigma_{x,Fj},n} \geq 0$$

Controller parameter	Experiments	Simulations
Prediction horizon H_P (ms)	250	250
Time step T_s (ms)	25	5
No. of steps N	10	50
Integration time step (ms)	1	1

Nonlinear optimal control problem

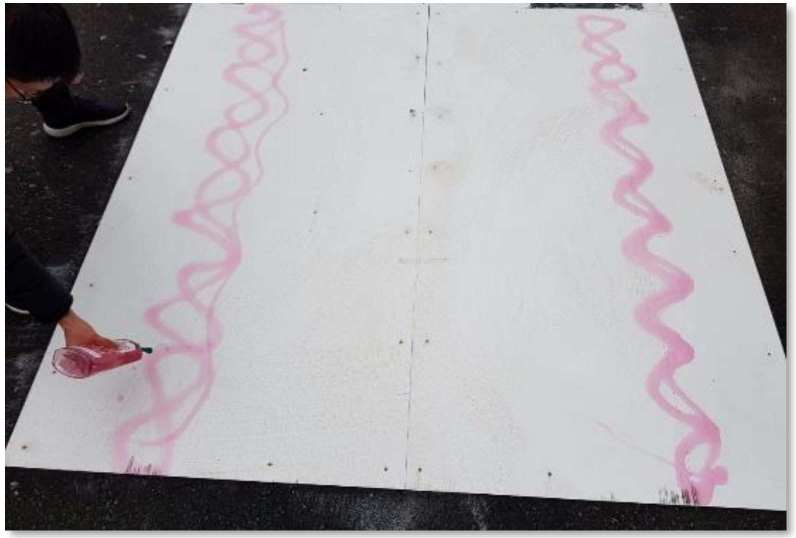
- A generic nonlinear optimal control problem can be defined as the minimization of the following cost function in discrete time form:

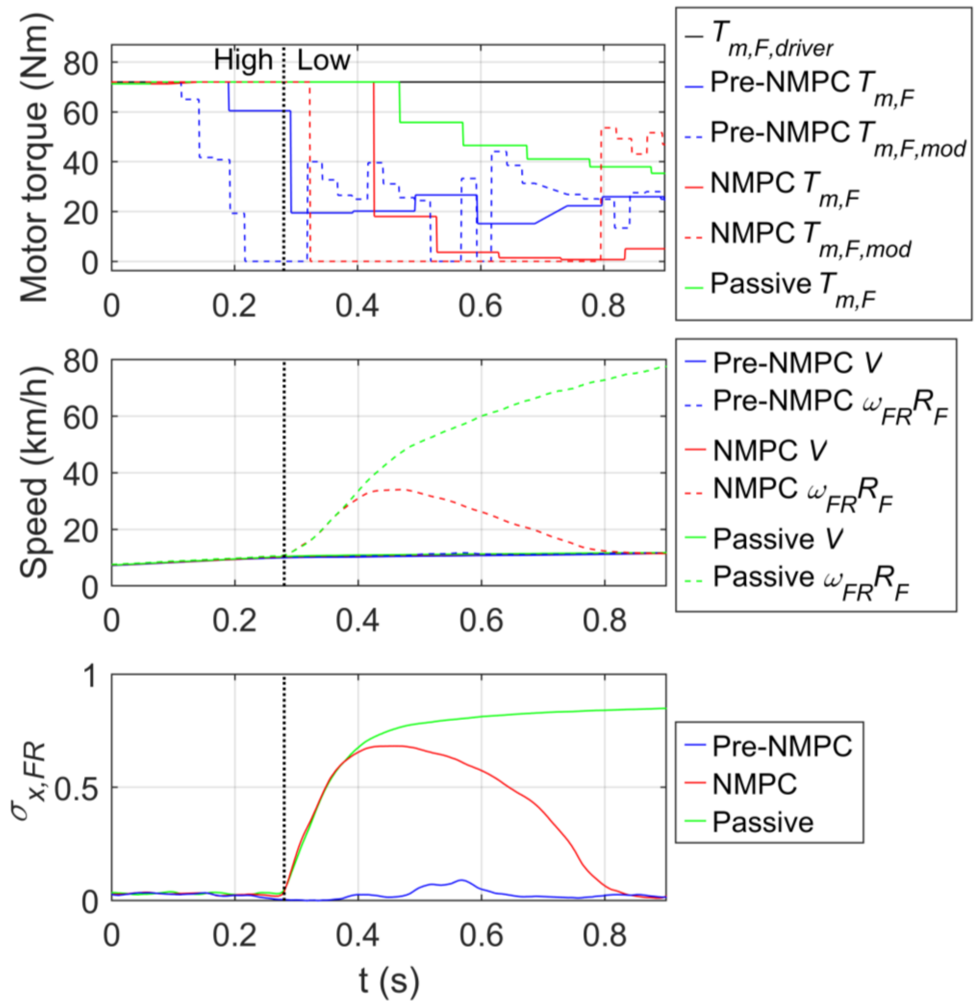
$$\min_{\boldsymbol{u}} J\big(\boldsymbol{x}(0), \boldsymbol{u}(\cdot)\big) \coloneqq \sum_{n=0}^{N-1} l(\boldsymbol{x_n}, \boldsymbol{u_n})$$

Where the stage cost function associated with each time step is:

$$l(\boldsymbol{x_n}, \boldsymbol{u_n}) \\ = W_{u,\varepsilon_{\sigma_{x,FL}}} \varepsilon^2_{\sigma_{x,FL},n} + W_{u,\varepsilon_{\sigma_{x,FR}}} \varepsilon^2_{\sigma_{x,FR},n} + W_{u,T_{m,F}} \left[T_{m,F,driver} - T_{m,F,mod,n}\right]^2 + W_{u,e_{int,FL}} e^2_{int,FL,n} + W_{u,e_{int,FR}} e^2_{int,FR,n}$$

Vehicle experiments





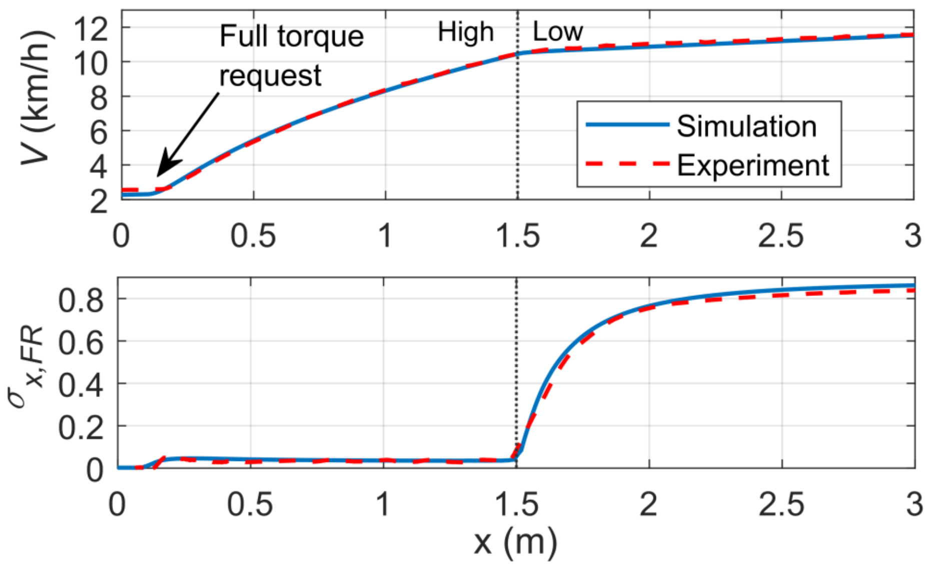
Vehicle experiments

Video presentation
(not included in these slides)

Simulation analysis

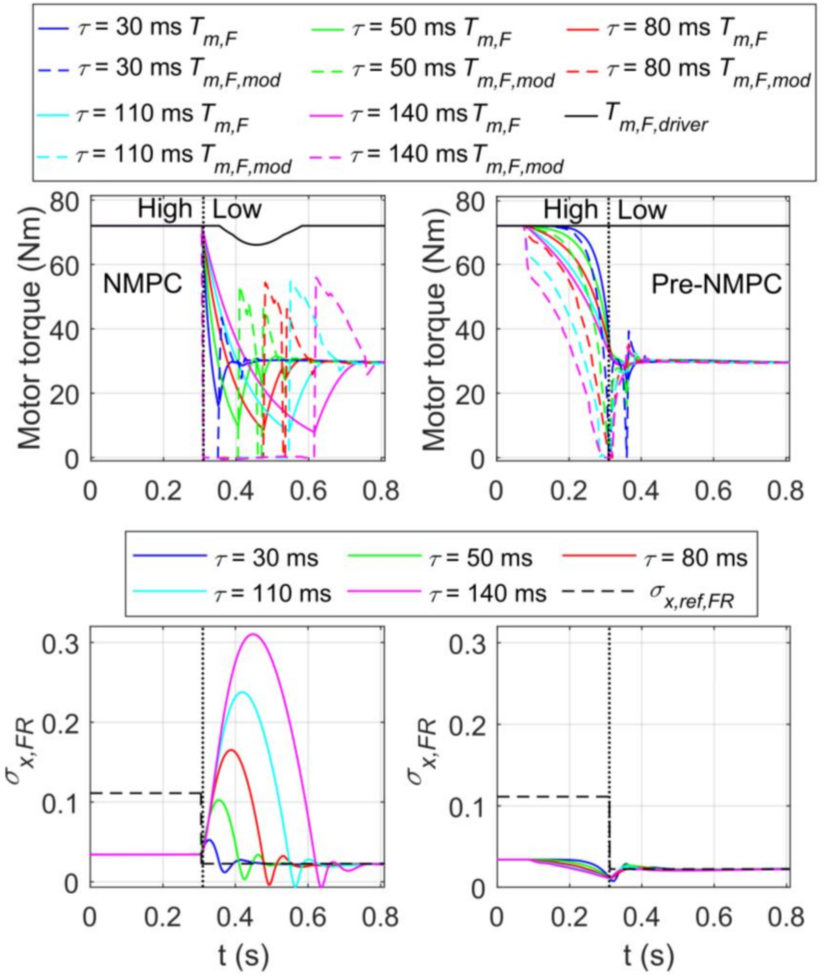
- Simulation-based sensitivity analyses were conducted to evaluate the performance of the preview-based NMPC for different characteristics of the electric powertrain, in terms of: i) motor time constant τ; and ii) pure time delay Δt_{delay} from the torque request to the corresponding torque response.

Simulation model validation against experimental results

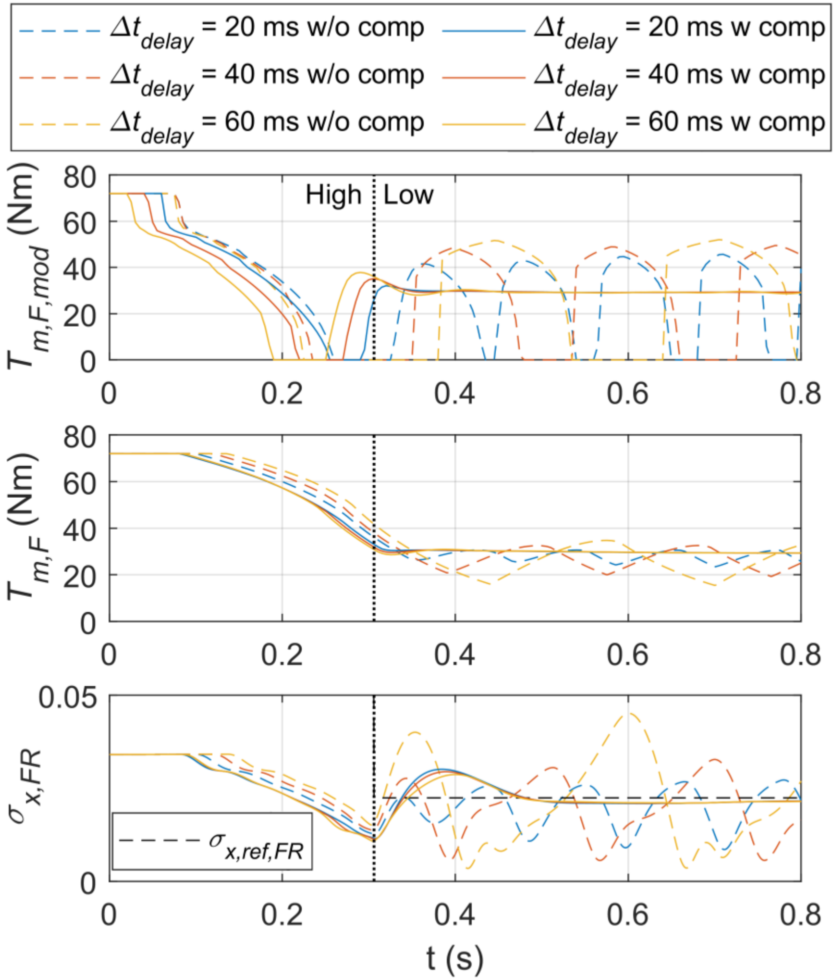


Simulation analysis results

- Effect of the powertrain time constant ($\Delta t_{delay} = 0$)

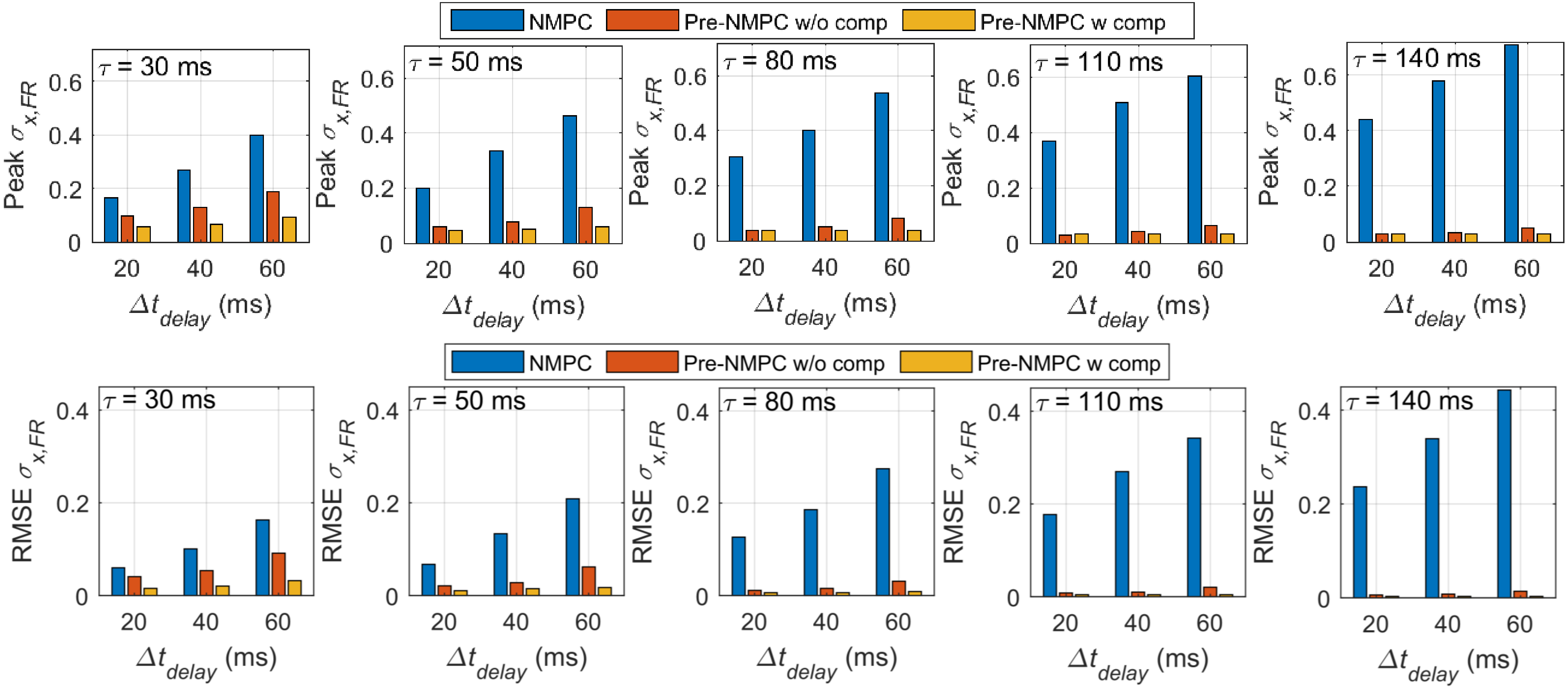


- Effect of the pure time delay ($\tau = 140$ ms)



Simulation analysis

- Overall trends



Conclusion

The main conclusions are:

- The NMPC can run in real-time on the EV prototype
- The traction controller can pre-emptively reduce wheel torque
- The preview NMPC can compensate for a wide range of dynamic characteristics of the electric powertrains

THANK YOU

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