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Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

Università degli Studi di Palermo

Project FORESEEN

Proposed Vehicle Models and Controllers

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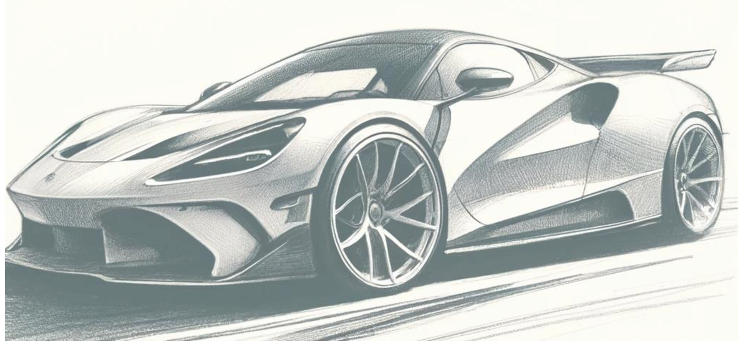
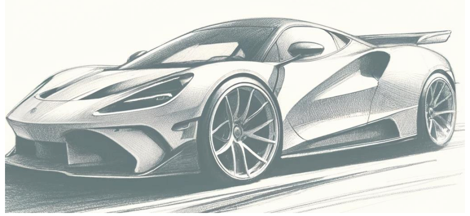
Meeting of 15th April 2024





MIRPALAB

MOBILE & INTELLIGENT ROBOTS @ PANORMOUS LABORATORY

1. *Longitudinal Dynamics*
2. *Distributed Controller*
3. *Lateral Dynamics*

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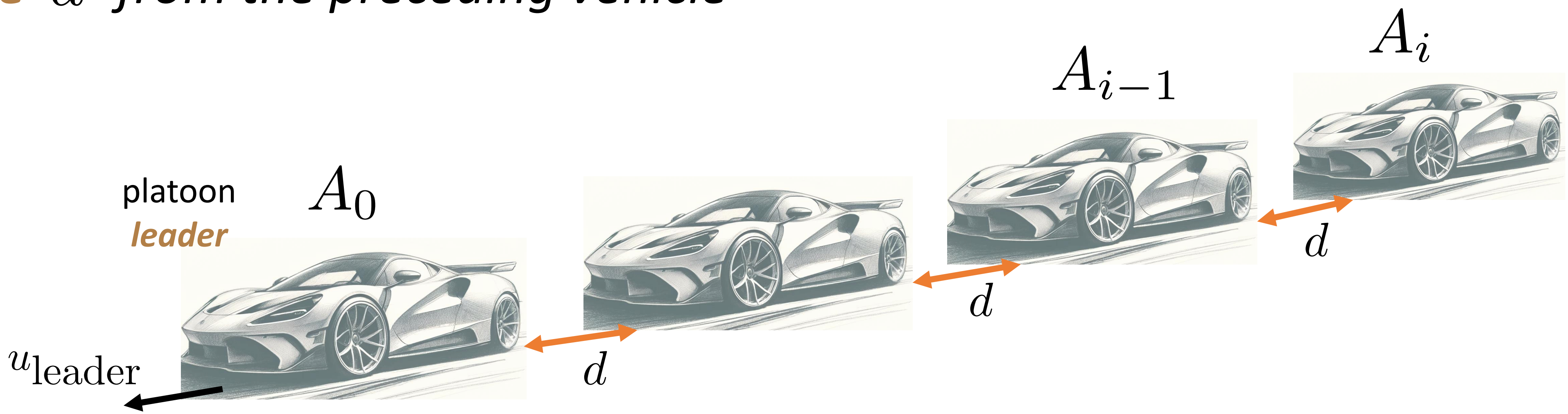
The Platoon Scenario

- N+1 vehicles moving along a road in ***platoon*** configuration:

  *"travelling as a string of vehicles while copying the speed of a **leader** and maintaining a **safety distance** d from the preceding vehicle"*



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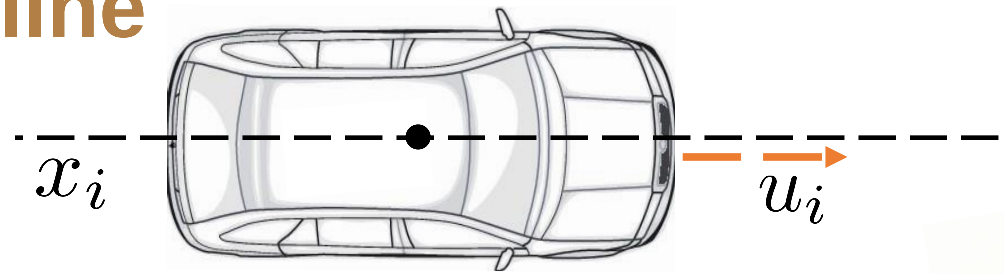
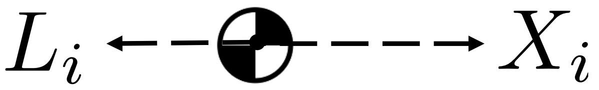
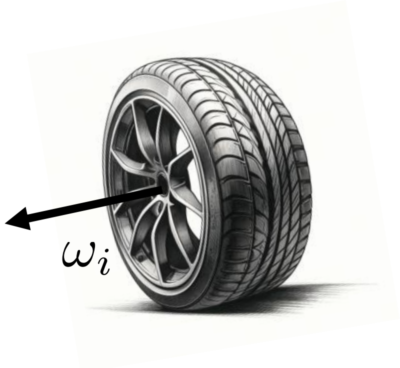
Longitudinal dynamics on straight line







x_i	position along line/curve	m
u_i	longitudinal speed	m/s
ω_i	wheel rotation speed	rad/s
m_i	total mass	kg
J_i	wheel inertia	Kg m2
R_i	wheel radius	m
X_i	longitudinal force	N
L_i	(loss) resistance force	N
T_i	driving torque	Nm

$$\dot{x}_i = u_i$$

$$\dot{u}_i = \frac{1}{m_i}\left(X_i(u_i, \omega_i, t) - L_i(u_i)\right)$$

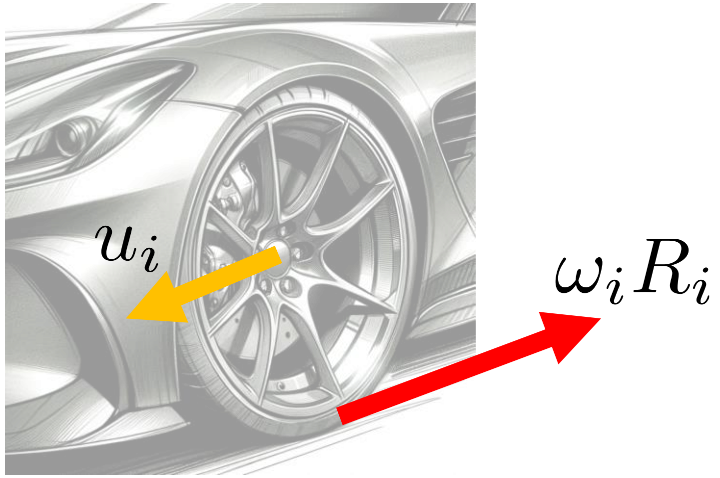
$$\dot{\omega}_i = \frac{1}{J_i}\left(T_i - R_i\, X_i(u_i, \omega_i, t)\right)$$

- $X_i(u_i, \omega_i, t)$ complex, almost unknown, depends on friction between road and (virtual) wheel tire
- *Li* includes aerodynamic drag, wind, bank angle effect

$$L_i(u_i) = 1/2\,\rho\, C_{xi}\, S_{xi}\, u_i^2 + W_i + \cdots$$

Longitudinal Slip ratio & Force

$$\sigma_i = \begin{cases} \dfrac{\omega_i R_i - u_i}{\omega_i R_i} = 1 - \dfrac{u_i}{\omega_i R_i} & \text{if } \omega_i R_i > u_i \quad \text{(acceleration)} \\[2ex] \dfrac{\omega_i R_i - u_i}{u_i} = \dfrac{\omega_i R_i}{u_i} - 1 & \text{if } \omega_i R_i < u_i \quad \text{(braking)} \end{cases}$$



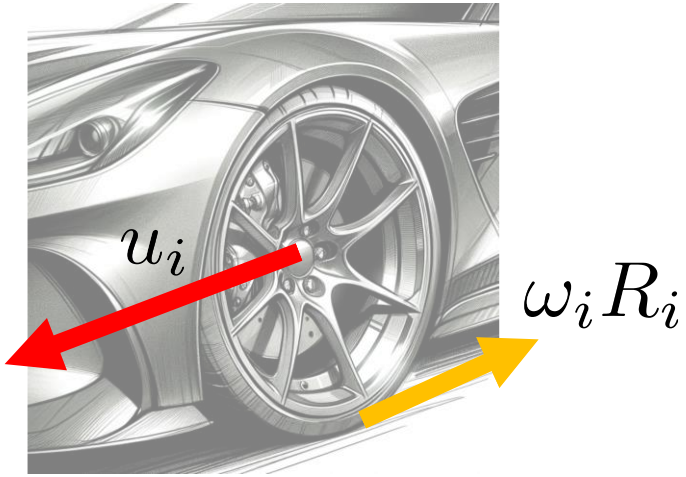
Longitudinal Force Models

$$X_i = \mu_i Z_i$$

friction coeff.

$$Z_i \simeq m_i\, g \frac{a_{i,1}}{l_i}$$

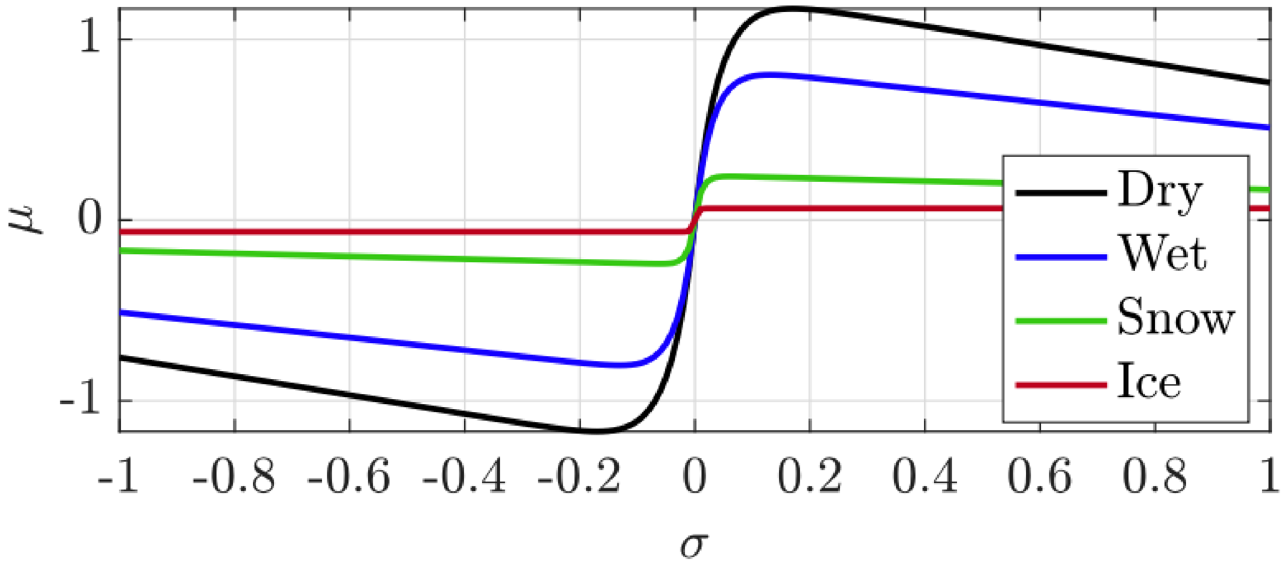
vertical force



long. force $$X_i(u_i, \omega_i, t) = \mu_i(\sigma_i, t)\, m_i\, g \frac{a_{i,1}}{l_i}$$

Heuristics Friction Models

- Friction is a nonlinear function of *slip ratio* (state variable) and *Tire-Surface Interaction (TSI)* (external variable)
- TSI depends on the tire and road surface (e.g., dry, wet, snowy, icy)



- Pacejka's Magic Formula

$$\mu_i(\sigma_i,t) = \mu_{i1}(t)\sin\left(\mu_{i2}(t)\arctan\left(\mu_{i3}(t)\,\sigma_i + \right.\right.$$
$$\left.\left. - \mu_{i4}(t)(\mu_{i3}(t)\,\sigma_i - \arctan(\mu_{i3}(t)\sigma_i))\right)\right)$$

- Burckhardt's Model

$$\mu_i(\sigma_i,t) = \mu_{i1}(t)\left(1 - e^{\mu_{i2}(t)|\sigma_i|}\right) - \mu_{i3}(t)|\sigma_i|$$

max value

curve shape

value at full slip $|\sigma_i| = 1$

Approximated Model for "small" slip ratio

$$\sigma_i = 0 \quad \rightarrow \quad \omega_i R_i = u_i \quad \rightarrow \quad \dot{\omega}_i R_i + \cancel{\omega_i \dot{R}_i} = \dot{u}_i$$

$$\dot{u}_i = \frac{1}{m_i}\left(X_i(u_i, \omega_i, t) - L_i(u_i)\right)$$

$$R_i \dot{u}_i = \frac{1}{J_i}\left(T_i - R_i X_i(u_i, \omega_i, t)\right)$$

$$\boxed{\begin{aligned}\dot{u}_i &= \frac{1}{m_i^*}\left(\frac{T_i}{R_i} - L_i(u_i)\right)\\ m_i^* &= m_i + J_i/R_i^2\end{aligned}}$$

equivalent total mass

- *eliminates one equation*
- *independent of Xi*
- driving torque appears in the speed equation

Decentralized i*th* controller (step 1: introduce a desired speed)

$$u_{id}(t) = u_{id}(u_{i-1}, u_i, t) \longleftarrow$$

i*th* ***desired*** speed

$$\delta u_i = u_i - u_{id} \longleftarrow$$

i*th* speed ***tracking*** error

$$\delta \dot{u}_i = \dot{u}_i - \dot{u}_{id} = \frac{1}{m_i^*}\left(\frac{T_i}{R_i} - L_i(u_i)\right) - \dot{u}_{id}$$

reference model

$$\delta \dot{u}_i + k\,\delta u_i = 0 \qquad k > 0$$

$$\delta u_i(t) = e^{-\alpha t}\delta u_i(0)$$

$$T_i = m_i^* R_i\,(\dot{u}_{id} - k\,\delta u_i) + R_i\,L_i(u_i)$$

i*th* ***control input***

- *independent of Xi*

Decentralized *ith* controller (step 2: design the desired speed to maintain the safety distance)

$$\delta d_i = d_i - d$$

*i*th ***distance*** error

$$\delta \dot{d}_i = \dot{x}_{i-1} - \dot{x}_i - \dot{d} =$$

$$= u_{i-1} - u_i = u_{i-1} - u_{id}$$

reference model

$$\delta \dot{d}_i + \alpha\, \delta d_i = 0$$
$$k > 0$$

$$u_{id}(t) = u_{i-1} + \alpha\, \delta d_i = u_{i-1} + \alpha\,(x_{i-1} - x_i - d)$$

*i*th ***desired*** speed

…it is extended to stabilize also slip ratio $\delta\sigma_i = \sigma_i - \sigma_{id}$

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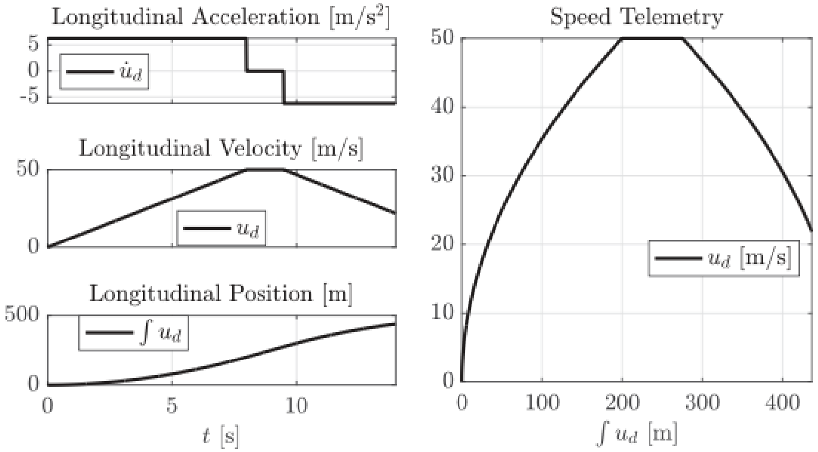
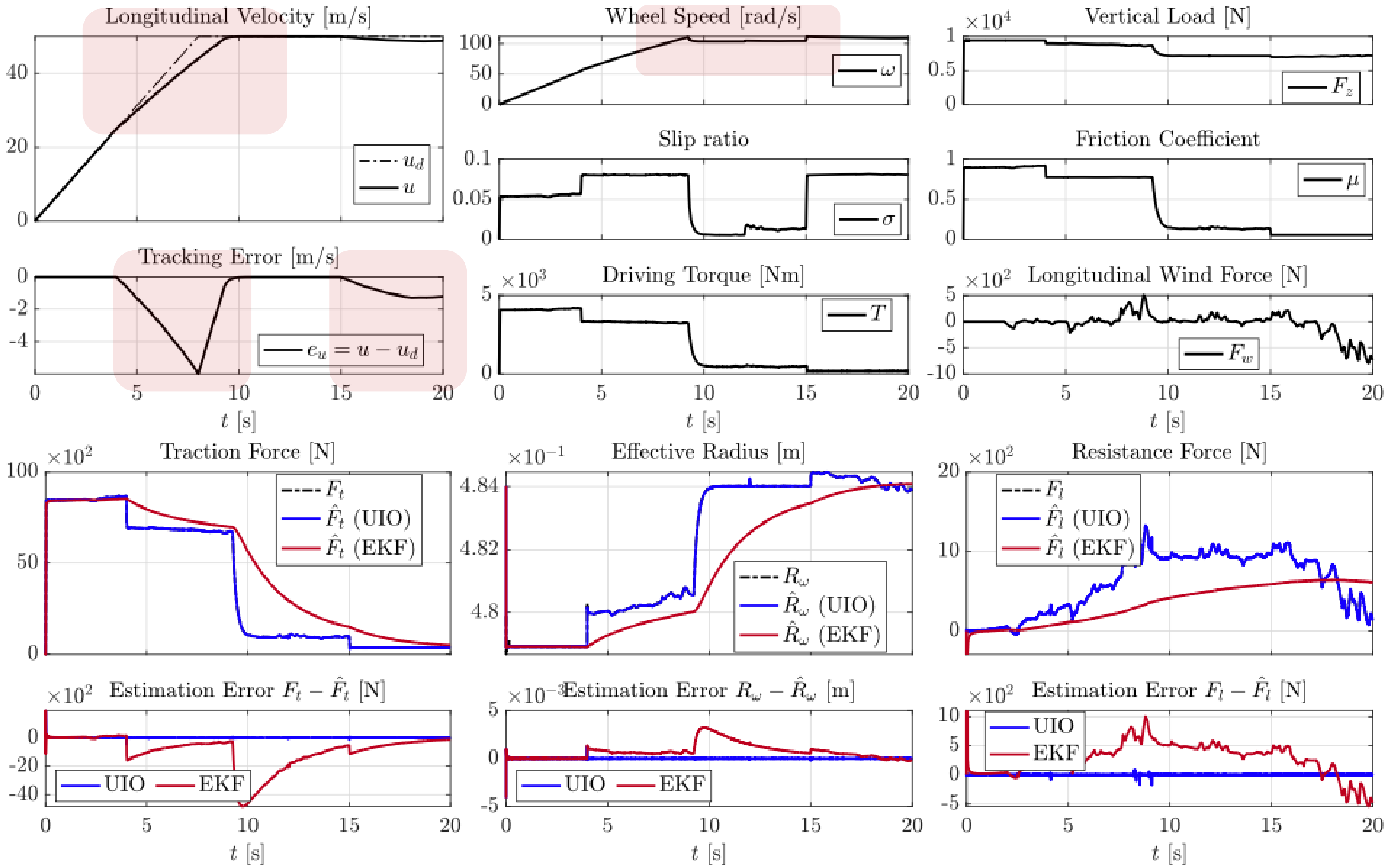
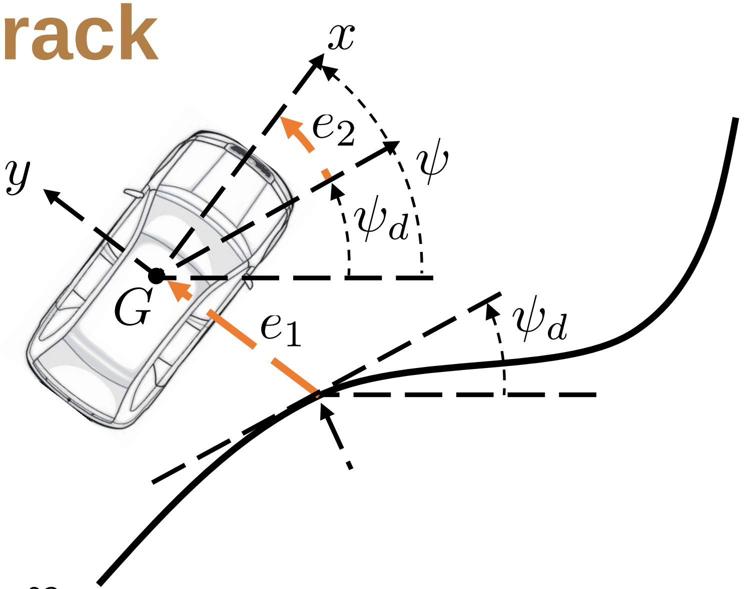
Simulation on a single vehicle scenario w/ wind disturbance



Road conditions switch from dry (t < 4) to wet (4 < t < 12) to snow (12 < t < 15) and ice (t > 15). Sudden wind gust at t = 2.



Lateral dynamics single-track for small steering angles



y_i	lateral position w.r.t. path	m
v_i	lateral speed	m/s
ψ_i	c.c. orientation w.r.t. path	rad
r_i	angular speed about z	rad/s
I_i	vehicle inertia about z	Kg m2
δ_i	steering angle	rad

$$\dot{y}_i = v_i$$

$$\dot{v}_i = -u_i\, r_i - \gamma_{i1}\,\frac{v_i}{u_i} + \gamma_{i2}\,\frac{r_i}{u_i} + \gamma_{i3}\,\delta_i$$

$$\dot{\psi}_i = r_i$$

$$\dot{r}_i = \gamma_{i4}\,\frac{v_i}{u_i} - \gamma_{i5}\,\frac{r_i}{u_i} + \gamma_{i6}\,\delta_i$$

- γ_{ij} depend on ***cornering*** coefficients, vehicle mass and inertial
- non-null speed $v_i \neq 0$

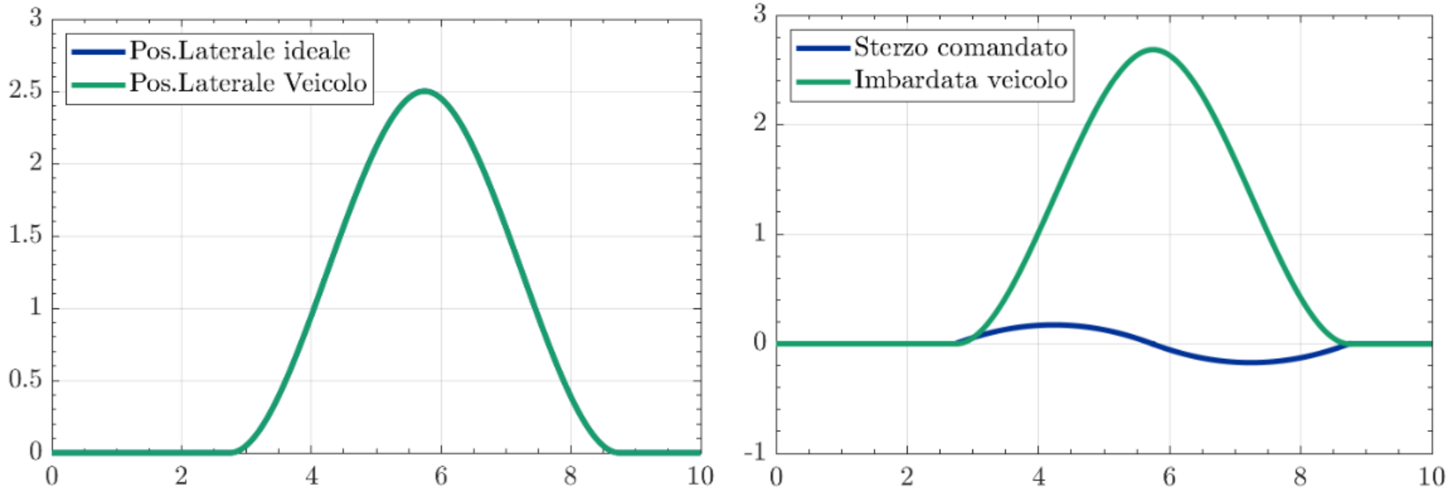
Objective of the Lateral Dynamics Control

Find $\delta_i(t) = \delta_i(u_i, v_i, \cdots)$
to ensure tracking of $y_{id}(t), \psi_d(t)$

$$\eta_i = \begin{pmatrix} y_i - y_{id} \\ \psi_i - \psi_{id} \end{pmatrix}$$

$$\xi_i = \begin{pmatrix} v_i - \dot{y}_{id} \\ r_i - \dot{\psi}_{id} \end{pmatrix}$$

*i*th position & speed
tracking errors



(a) Errore Posizione Laterale $[m]$ (b) Sterzo-Imabardata $[gradi]$

Complete bicycle model, single track for generic path and vehicle configuration

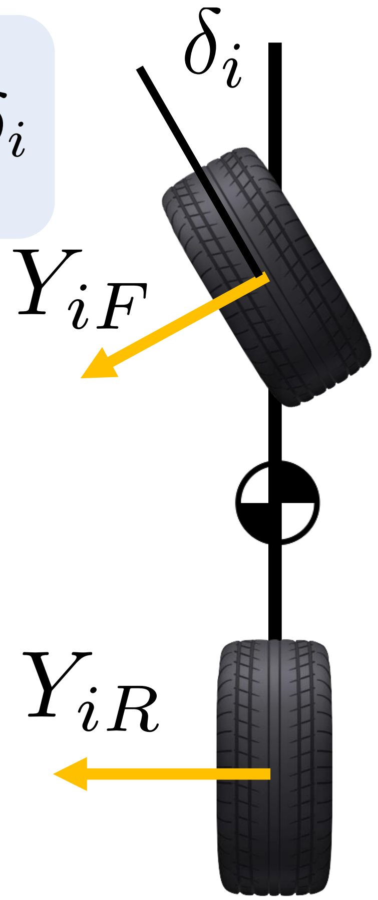
$$m_i\,(\dot{u}_i + v_i\,r_i) = X_i(u_i, \omega_i, t) - L_i(u_i) + C_{i1}\left(\frac{v_i + a_{iF}\,r_i}{u_i} - \delta_i\right)\delta_i$$

$$m_i\,(\dot{v}_i + u_i\,r_i) = Y_{iF}(\delta_i) + Y_{iR}(\delta_i)$$

$$I_i\,\dot{r}_i = a_{iF}Y_{iF}(\delta_i) - a_{1R}Y_{iR}(\delta_i)$$

$$Y_{ij}(\delta_i) = Y_{ij}\left(\tau_{ij}\delta_i - \frac{v_i + r_i a_{ij}}{u_i}\right)$$

$$j \in \{F, R\}$$



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In summary, the proposed model and controller

ith longitudinal dynamics

$$\dot{x}_i = u_i$$

$$\dot{u}_i = \frac{1}{m_i}\left(X_i(u_i, \omega_i, t) - L_i(u_i)\right)$$

$$\dot{\omega}_i = \frac{1}{J_i}\left(T_i - R_i\, X_i(u_i, \omega_i, t)\right)$$

ith lateral dynamics

$$\dot{y}_i = v_i$$

$$\dot{v}_i = -u_i\, r_i - \gamma_{i1}\,\frac{v_i}{u_i} + \gamma_{i2}\,\frac{r_i}{u_i} + \gamma_{i3}\,\delta_i$$

$$\dot{\psi}_i = r_i$$

$$\dot{r}_i = \gamma_{i4}\,\frac{v_i}{u_i} - \gamma_{i5}\,\frac{r_i}{v_i} + \gamma_{i6}\,\delta_i$$

ith driving torque

$$T_i = m_i^* R_i\left(\dot{u}_{id} - k\,\delta u_i\right) + R_i\, L_i(u_i)$$

estimated loss

ith steering angle

$$\delta_i = \delta_i(u_i, y_i, v_i, \psi_i, r_i, t)$$

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That's all for now, folks!

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*i*th vehicle and ***follower***

platoon ***leader***