Disturbance observer-based control of longitudinal vehicle platoon

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MOTIVATION

Intelligent and Automatic Transportation

- Intelligent vehicles is considered as a promising solution to improve traffic flow and reduce the risk of accidents (FENG *et al*., 2019).

- In the context of platooning, the inter-vehicular distances are controlled using automatic speed and distance controllers (MAHFOUZ et al., 2023)

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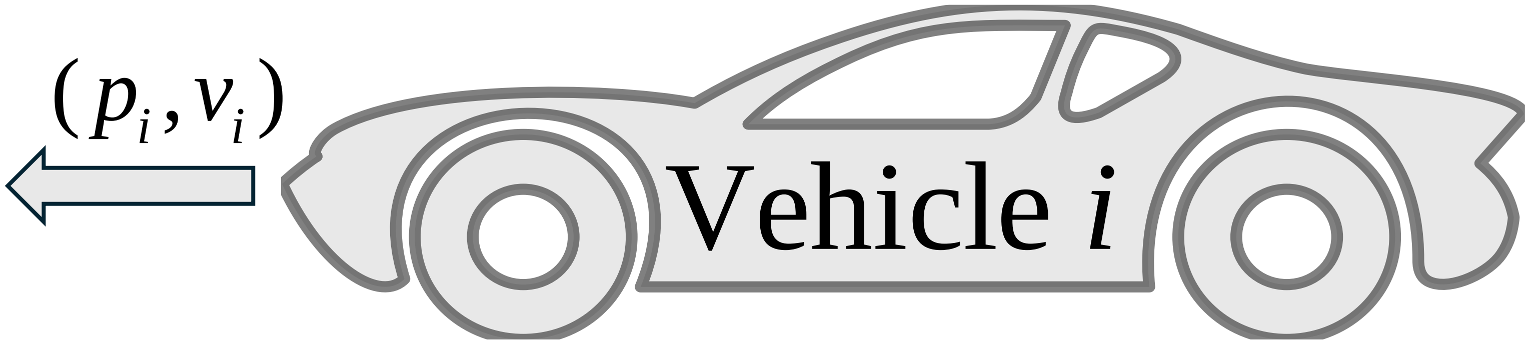
Ploeg et all., 2011,

A group of self-driving cars successfully formed a platoon during a recent field test at Aberdeen Proving Ground, 2017, https://www.volpe.dot.gov/sites/volpe.dot.gov/files/pictures/Cadillacs_platooning_dry-FHWA-500px.jpg

LONGITUDINAL VEHICLE PLATOONING

General problem

Vehicle dynamics And Measures



$\mathcal{V}_i$

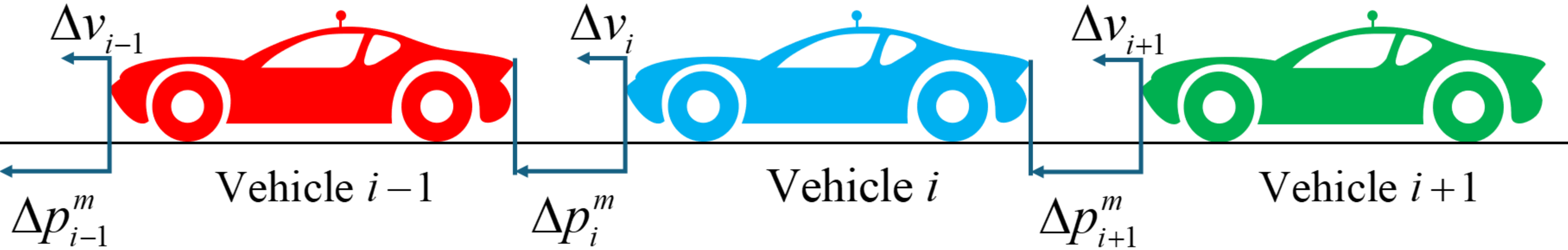
Vehicle Longitudinal dynamics

$$\begin{aligned}
\dot{p}_i &= v_i \\
\dot{v}_i &= \frac{1}{\mathbf{W}_i}\left(\mathbf{R}_{h,i}T_i - \mathbf{m}_i\mathbf{g}F_{r,i} - \mathbf{B}_i v_i - \mathbf{C}_i v_i^2\right) \\
\dot{T}_i &= -\frac{1}{\rho_i}T_i + \frac{1}{\rho_i}u_{e,i}
\end{aligned}$$

$$\begin{aligned}
\mathbf{W}_i &= \frac{(\mathbf{m}_i\mathbf{h}_{w,i}^2 + \mathbf{J}_{r,i} + \mathbf{J}_{f,i})\mathbf{R}_{g,i}^2 + \mathbf{J}_{e,i}}{\mathbf{h}_{w,i}^2\mathbf{R}_{g,i}^2} \\
\mathbf{R}_{h,i} &= (\mathbf{h}_{w,i}\mathbf{R}_{g,i})^{-1}.
\end{aligned}$$

Adaptive Cruise Control (ACC)

- ❑ Vehicles are equipped with sensor to provide measurements about distance, velocity and acceleration



Adaptive Cruise Control (ACC)

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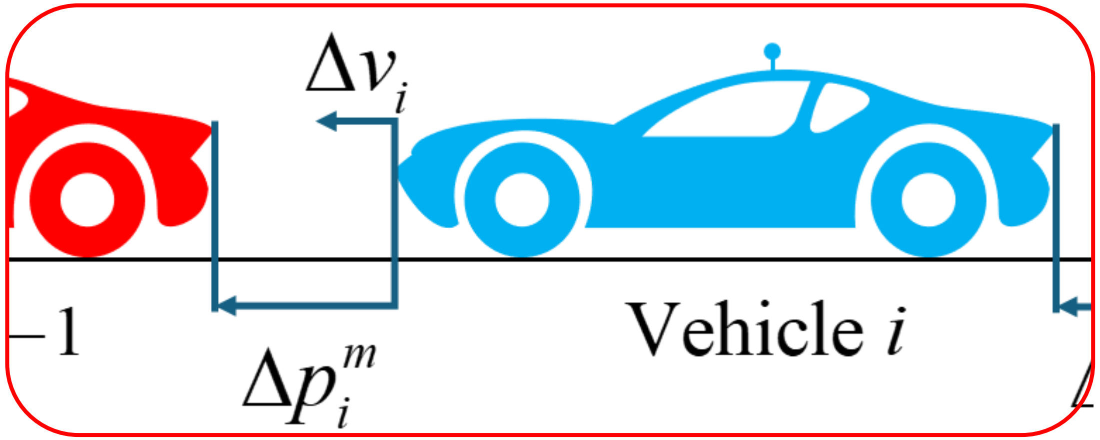
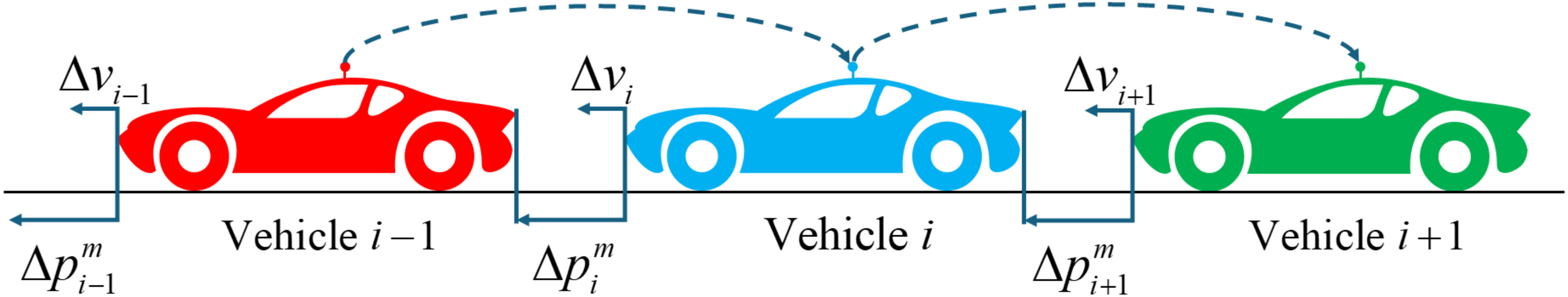


- Inter vehicular distance: $\Delta p_i^m = p_{i-1} - p_i - L_{c,i}$
- Velocity difference: $\Delta v_i = v_{i-1} - v_i$
- Acceleration and velocity: (a_i, v_i)

Cooperative ACC

- Cooperative ACC introduces communication devices for vehicles to share information
  - Improves platoon performance (DARBHA *et al*., 2019, GUANETTI et al., 2018)



Problem of Interest

- ❑ Designing a control law for vehicles platoons equipped with Cooperative ACC to:

Individual stability

Achieve vehicle formation ensuring a safe distance

String stability

Ensure that perturbations will no be amplified in the platoon

- ❑ Designing an ETC to achieve efficient communication

CONTROL AND DOB DESIGN

Vehicle Dynamics

- Through classical feedback linearization procedure, we can write the vehicle dynamics as

$$
\begin{aligned}
\dot{p}_i &= v_i \\
\dot{v}_i &= \frac{1}{\mathbf{W}_i}\left(\mathbf{R}_{h,i}T_i - \mathbf{m}_i\mathbf{g}F_{r,i} - \mathbf{B}_i v_i - \mathbf{C}_i v_i^2\right) \\
\dot{T}_i &= -\frac{1}{\rho_d}T_i + \frac{1}{\rho_i}u_{e,i}
\end{aligned}
\quad \Leftrightarrow \quad
\begin{aligned}
\dot{p}_i &= v_i \\
\dot{v}_i &= a_i \\
\dot{a}_i &= f_i(v_i, a_i) + b_i u_i
\end{aligned}
\quad \mathcal{V}_i
$$

Vehicle Dynamics

- We can rewrite the vehicle dynamics as

$\mathcal{V}_i$

$$\dot{a}_i = f_i^n(v_i, a_i) + b_i^n u_{e,i} - d_i$$

$$d_i = \underbrace{f_i(v_i, a_i) - f_i^n(v_i, a_i)}_{\Delta f_i} + \underbrace{\left(b_i - b_i^n\right)}_{\Delta b_i} u_{e,i}$$

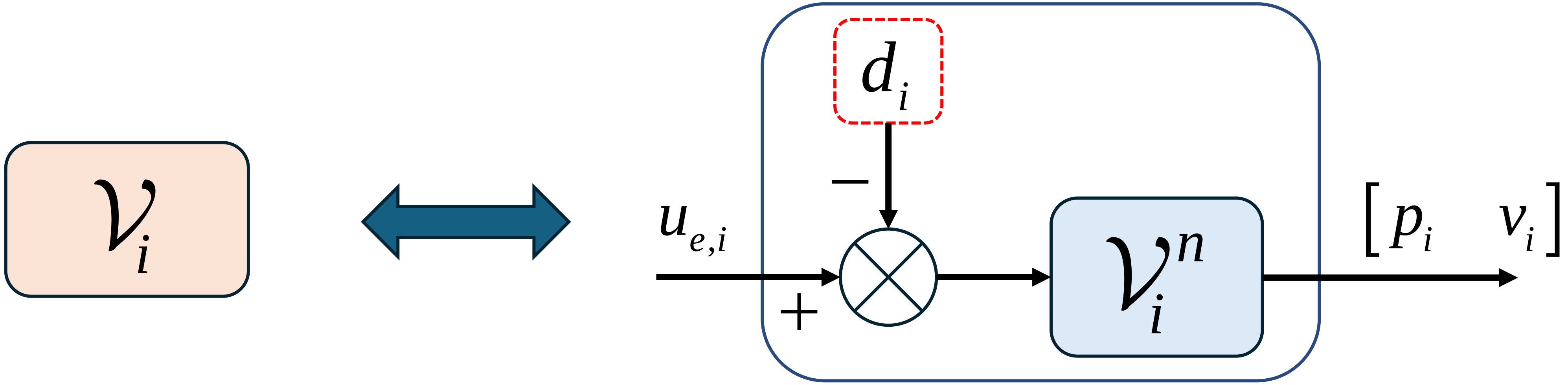
- Uncertain: $\{ f_i(v_i, a_i), \quad b_i \}$
- Known (nominal): $\{ f_i^n(v_i, a_i), \quad b_i^n \}$

Vehicle Dynamics

- We can rewrite the vehicle dynamics as

$\mathcal{V}_i$

$$\dot{a}_i = f_i^n(v_i, a_i) + b_i^n u_{e,i} - d_i$$



Feedback linearization

- Based on the vehicle dynamics

$\mathcal{V}_i$

$$\dot{a}_i = f_i^n(v_i, a_i) + b_i^n u_{e,i} - d_i$$

We consider a feedback linearizing control law

$$u_{e,i} = \frac{1}{b_i^n}\left(-f_i^n(v_i, a_i) - \frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + \hat{d}_i\right)$$

$\hat{d}_i$ Is an estimation of d_i

u_i Is a new control input

Feedback linearization

- Based on the vehicle dynamics

v_i

$$\dot{a}_i = f_i^n(v_i, a_i) + b_i^n u_{e,i} - d_i$$

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$\hat{d}_i$ Is an estimation of d_i

u_i Is a new control input

Vehicle Dynamics

- Linearized dynamics

$\mathcal{V}_i$

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

$$\dot{v}_i = a_i$$

$$\dot{a}_i = -\frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + \hat{d}_i - d_i$$

Estimation error:

$$e_{d,i} = \hat{d}_i - d_i$$

Vehicle Dynamics

- Linearized dynamics

$\mathcal{V}_i$

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

$$\dot{v}_i = a_i$$

$$\dot{a}_i = -\frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + \hat{d}_i - d_i$$

- Vehicles parameters without uncertainties

$$e_{d,i} = \hat{d}_i - d_i = 0$$

Homogeneity

- All vehicles have the same ρ_d

Vehicle Dynamics

- Linearized dynamics

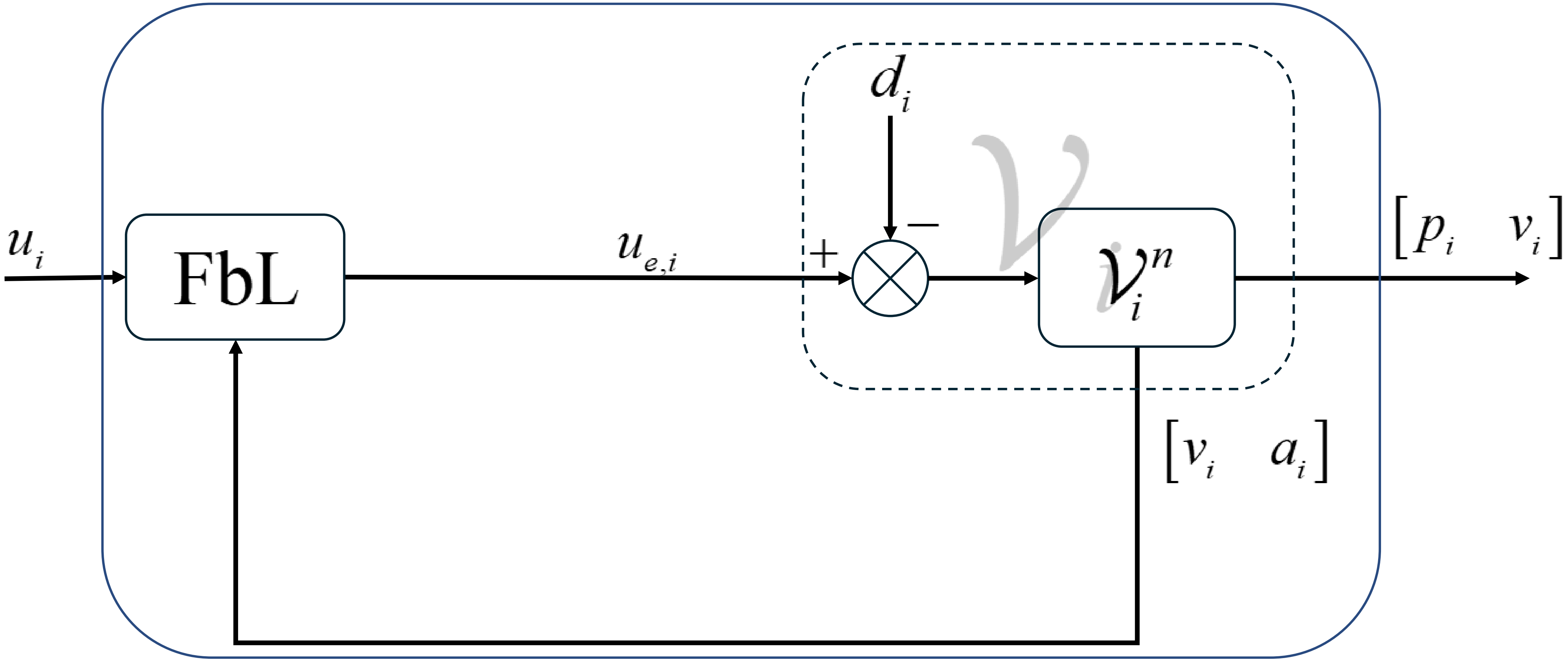
$\mathcal{V}_i$

$$\dot{p}_i = v_i$$
$$\dot{v}_i = a_i$$
$$\dot{a}_i = -\frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + \hat{d}_i - d_i$$

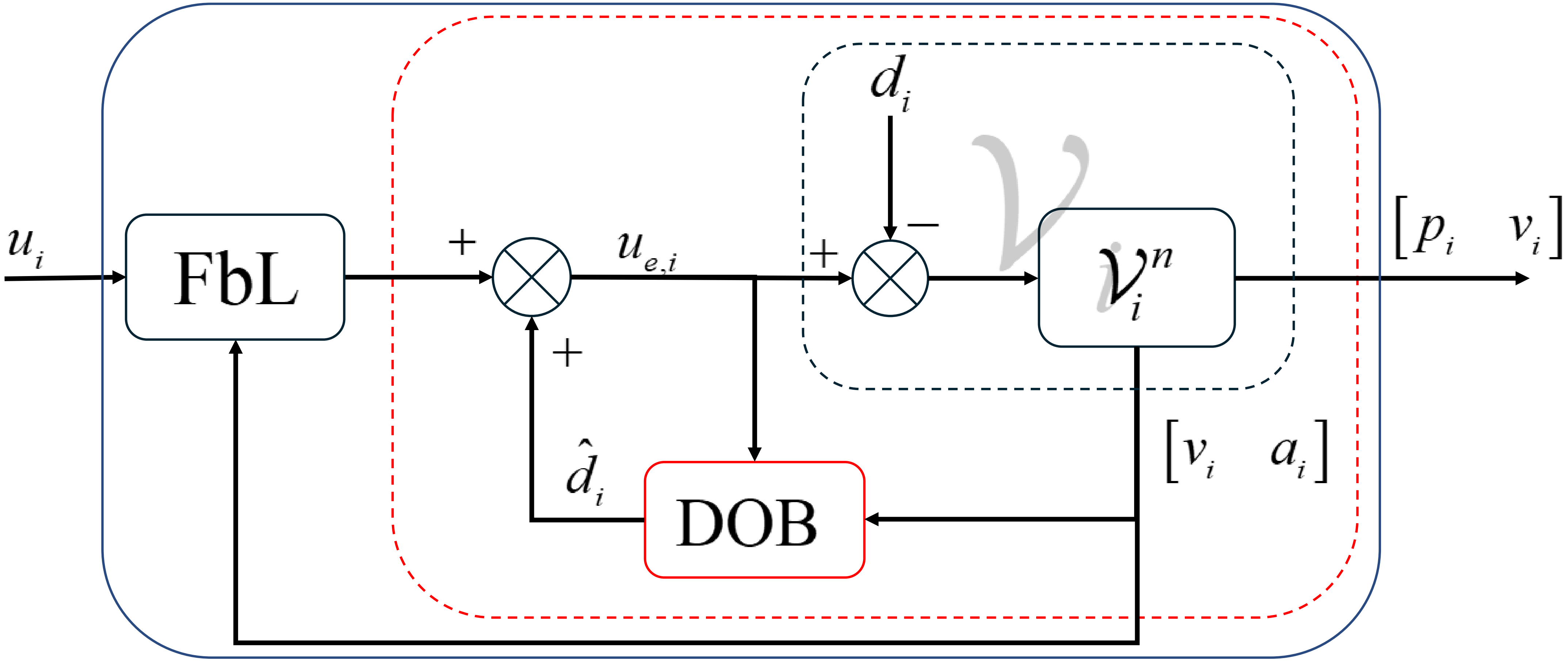
- All vehicles have the same ρ_d

- Due to uncertainties the platoon is not fully homogenous

Feedback linearization and DOB



Feedback linearization and DOB



DOB Dynamics

- Disturbance observer dynamics

$$\dot{\omega}_i = L_i(f_i^n(v_i, a_i) + b_i^n u_i - \hat{d}_i)$$

$$\hat{d}_i = \omega_i - L_i a_i$$

- Considering the estimation error: $e_{d,i} = \hat{d}_i - d_i$
- Disturbance estimation error dynamics

$$\dot{e}_{d,i} = -L_i e_{d,i} + \dot{d}_i$$

$\dot{d}_i \approx 0$ **Slow dynamics**

$e_{d,i} \to 0$

Literature Review

1

Some works in the literature assume that the system without disturbances or uncertainties (DOLK *et al*., 2017, Ploeg *et al*., 2011)

$$\dot{a}_i = -\frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + \hat{a}_i - d_i$$

2

Another work as (HUANG. KARIMI, 2021) assumes uncertainties or exogenous inputs but do not introduce any compensation

$$\dot{a}_i = -\frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + \hat{a}_i - d_i$$

Literature Review

3

The works of (WANG *et al.*, 2022a, LUO *et al.*, 2021) propose compensation, but the conditions do not ensure scalability

$$\dot{a}_i = -\frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + \hat{d}_i - d_i$$

Scalability

Stability conditions are independent of the number of vehicles

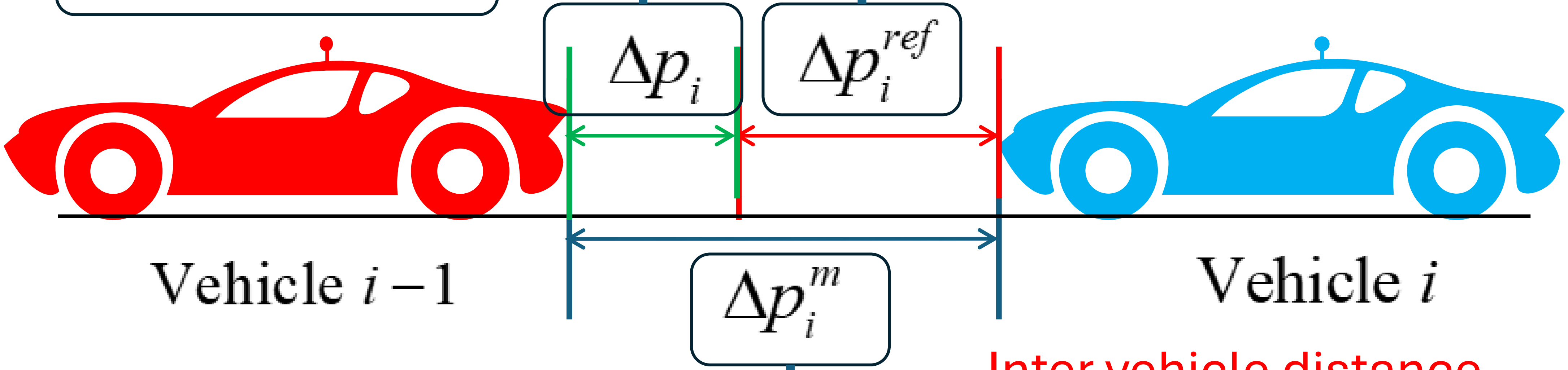
Distance policy and Individual stability

- We want to ensure a safe distance:

$$\Delta p_i = \Delta p_i^m - \Delta p_i^{\text{ref}}$$

Distance policy

$$r_i + hv_i$$

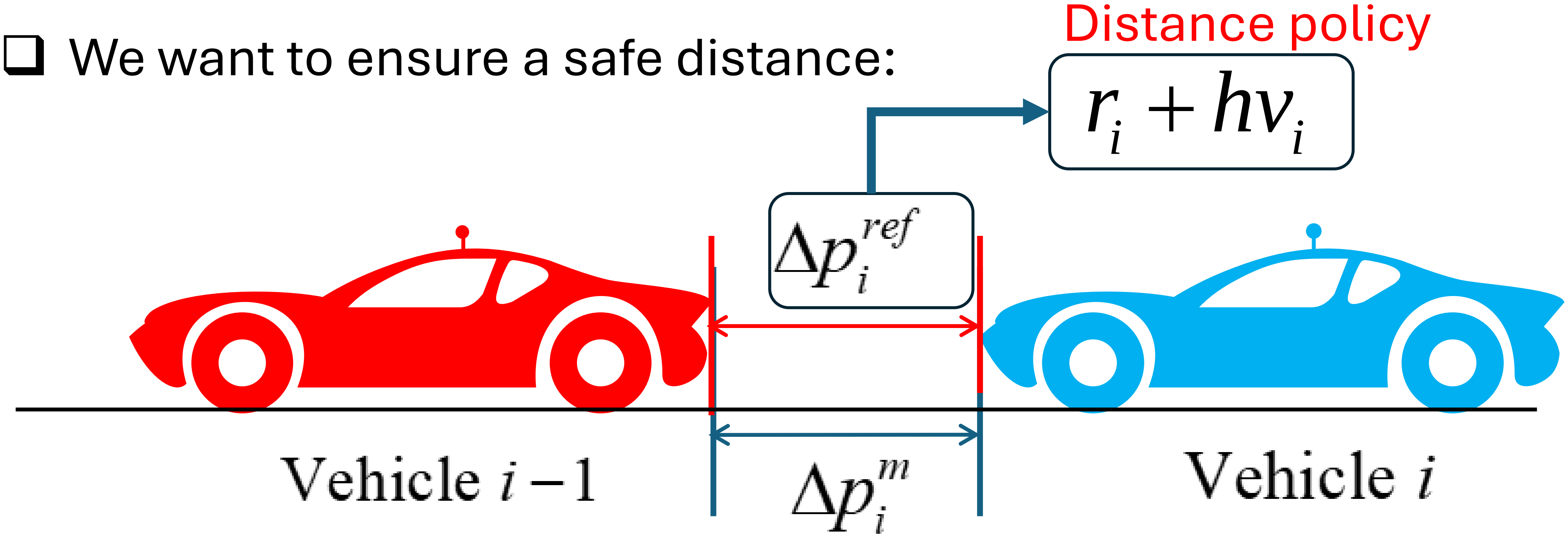


Inter vehicle distance

$$p_{i-1} - p_i - L_{c,i}$$

Distance policy and Individual stability

- We want to ensure a safe distance:



Individual stability

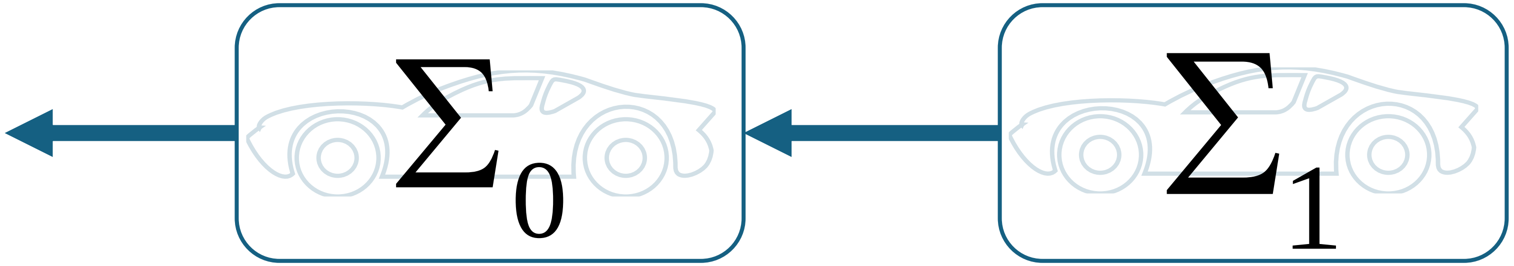
Ensure that $\Delta p_i = \Delta p_i^m - \Delta p_i^{\mathrm{ref}} \to 0 \quad \Delta v_i = v_{i-1} - v_i \to 0$

DOB compensation simulations

Main results assuming continuous communication

DOB COMPENSATION SIMULATION

- To evaluate the DOB performance, we consider a platoon of one leader and one follower:



- Distance policy

$$\Delta p_i^{\text{ref}} = 2.5 + 0.6 v_i$$

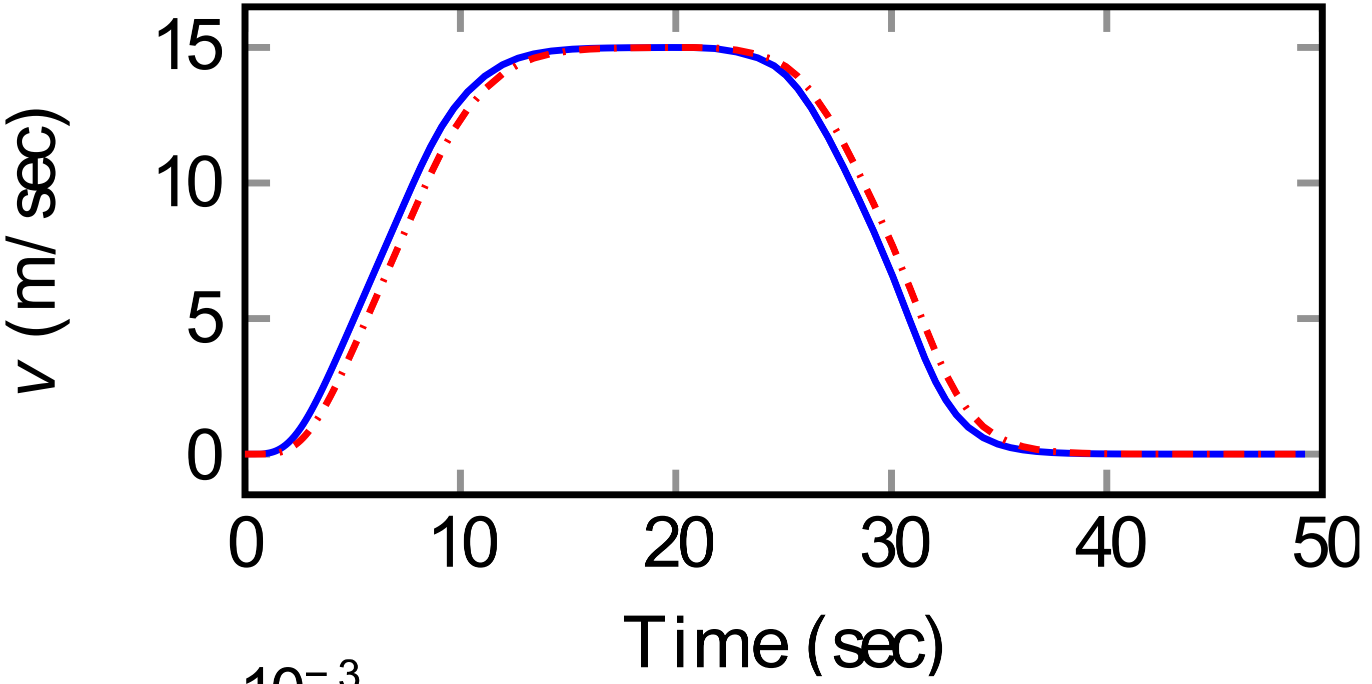
- Vehicle parameters

	Vehicle	r	m	h_w	J_r	J_e	R_g	B	C	ρ
	Σ_0		1724	0.28	0.75	0.14	0.10	7.35	0.05	0.05
	$\tilde{\Sigma}_0$		1724	0.25	1.05	0.14	0.13	8.09	0.06	0.08
Compute the feedback linearization and DOB	Σ_1	2.5	2241	0.63	0.97	0.35	0.18	13.96	0.11	0.10
Simulation	$\tilde{\Sigma}_1$		2017	0.51	0.68	0.46	0.18	11.17	0.16	0.09

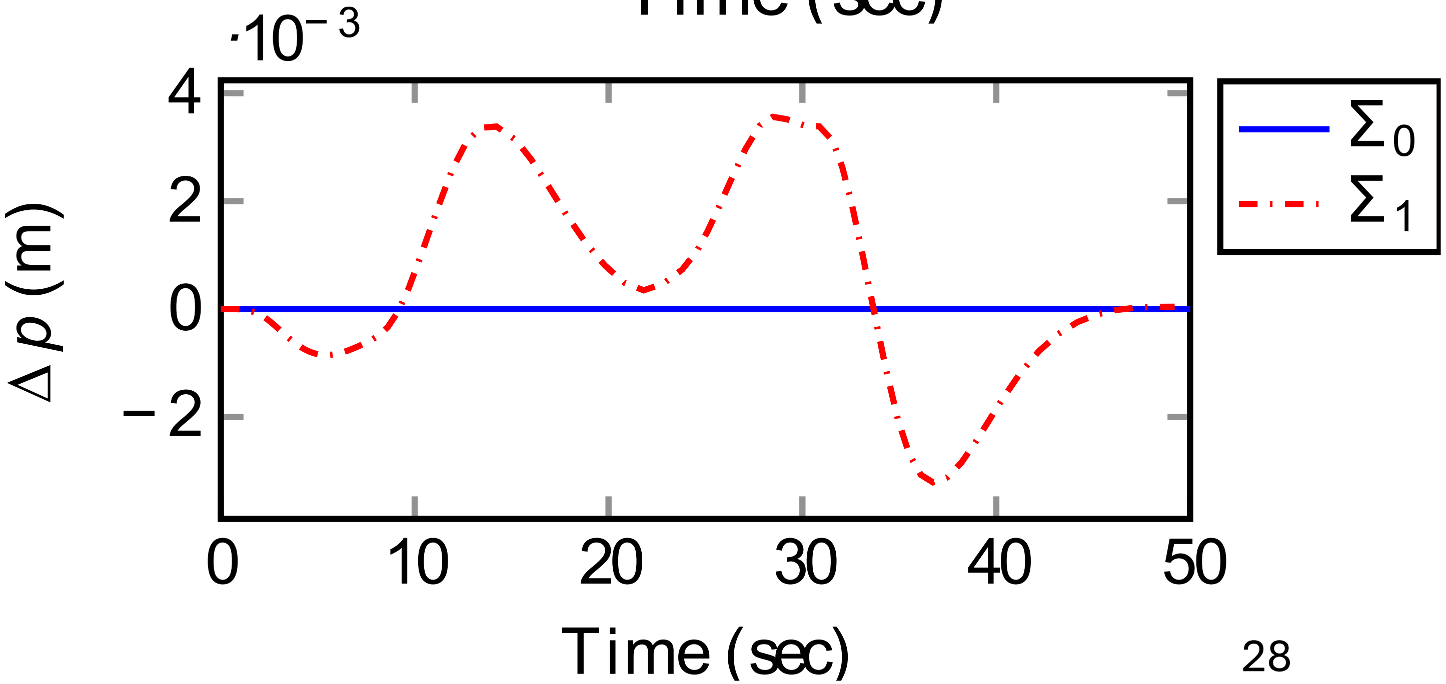
Velocity profile and tracking

No mismatch $d_1 = 0$

$$\Sigma_1 = \tilde{\Sigma}_1$$



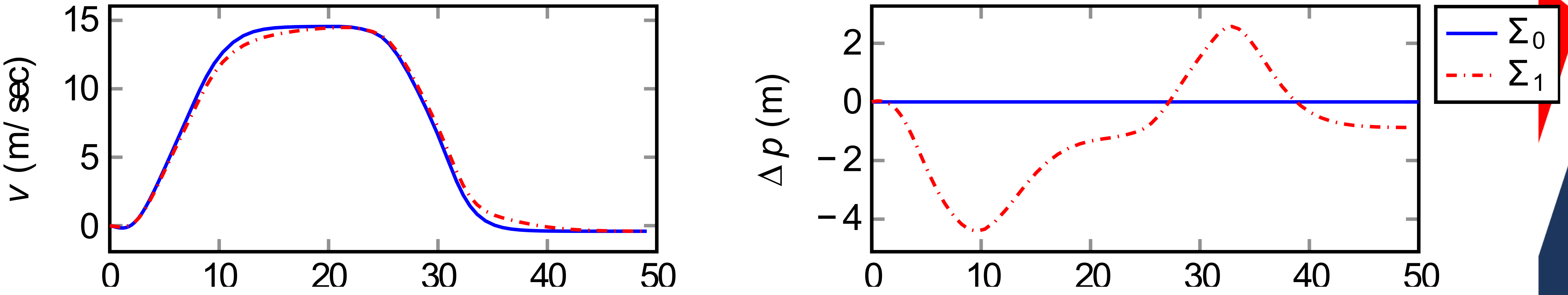
Distance policy error



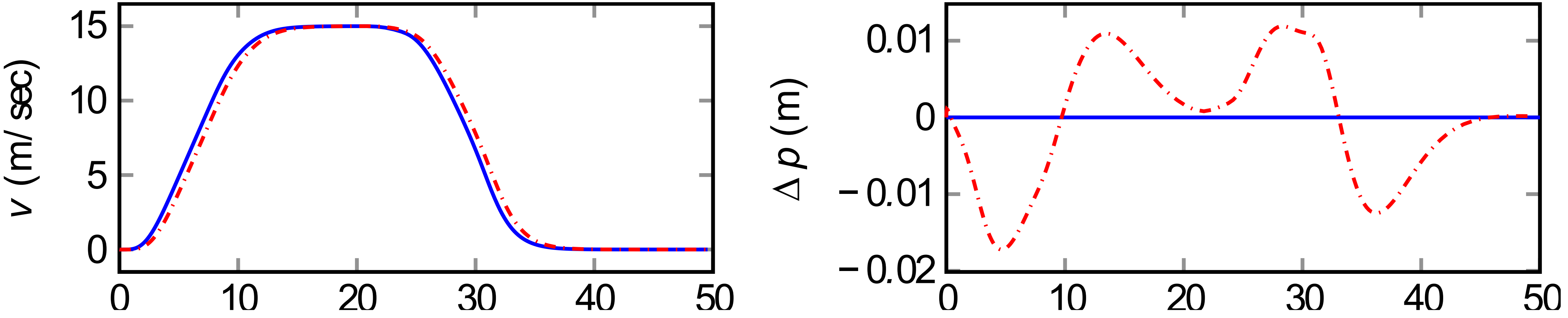
Uncertain dynamics

$$d_1 \neq 0 \quad \Sigma_1 \neq \tilde{\Sigma}_1$$

Without DOB compensation



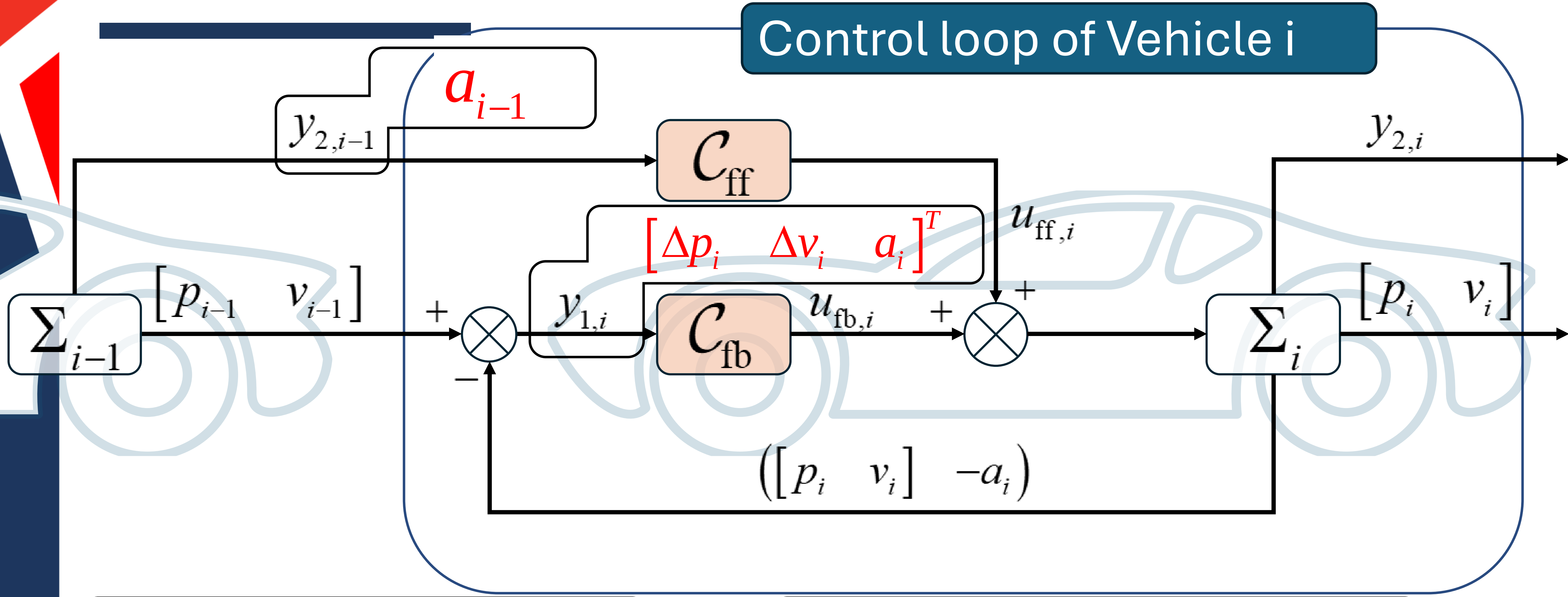
DOB compensation



Vehicles interactions

Modeling vehicles interactions (communication)

Vehicles interactions



$y_{2,i-1} = a_{i-1}$ Transmitted

$y_{1,i} = [\Delta p_i \quad \Delta v_i \quad a_i]^T$ Measured

Vehicle Linearized Dynamics

- Vehicle linearized dynamics with the distance policy error

$$\Sigma_i \quad \begin{aligned} \Delta \dot{p}_i &= v_i \\ \Delta \dot{v}_i &= a_{i-1} - a_i \\ \dot{a}_i &= -\frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + e_{d,i} \end{aligned}$$

$$y_{1,i} = \begin{bmatrix} \Delta p_i & \Delta v_i & a_i \end{bmatrix}^T$$

$$y_{2,i-1} = a_{i-1}$$

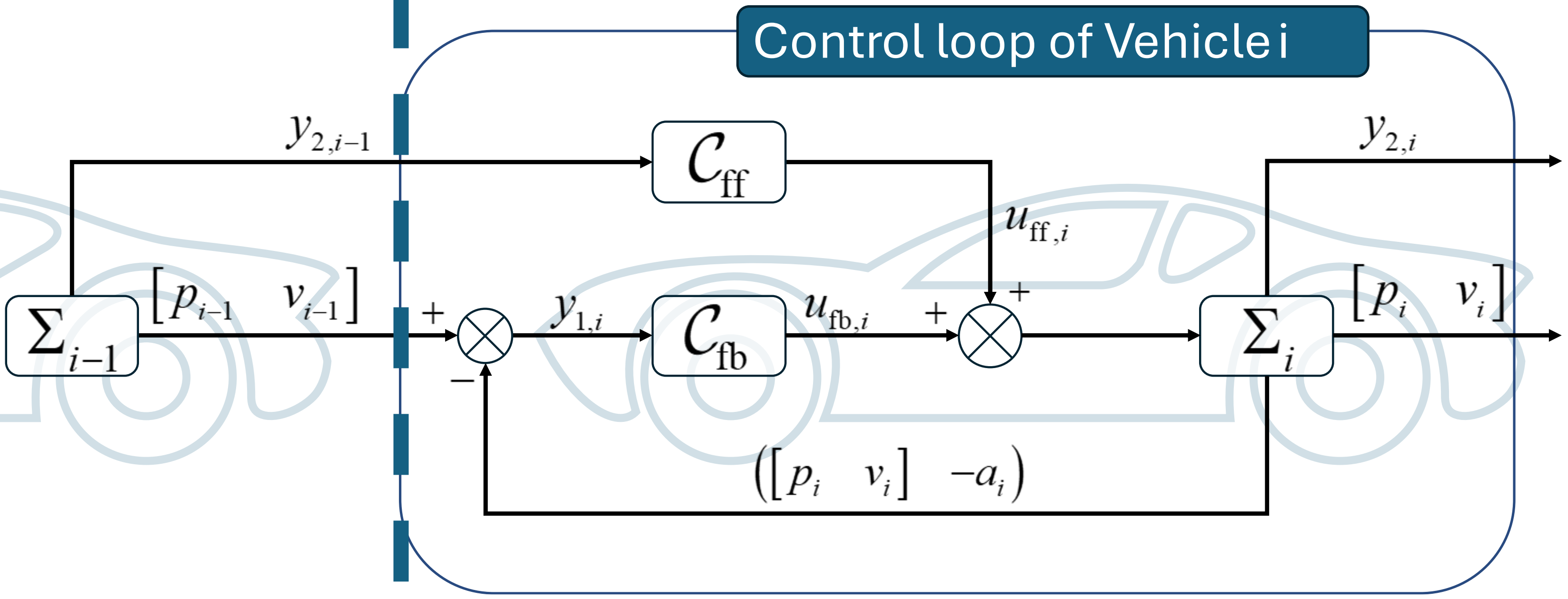
- Vehicle control with feedback and feedforward components

$$u_i = u_{\text{fb},i} + u_{\text{ff},i}$$

$$u_{\text{fb},i} = K_1 y_{1,i}$$ Feedback

$$u_{\text{ff},i} = K_2 y_{2,i-1}$$ Feedforward

Vehicles interactions



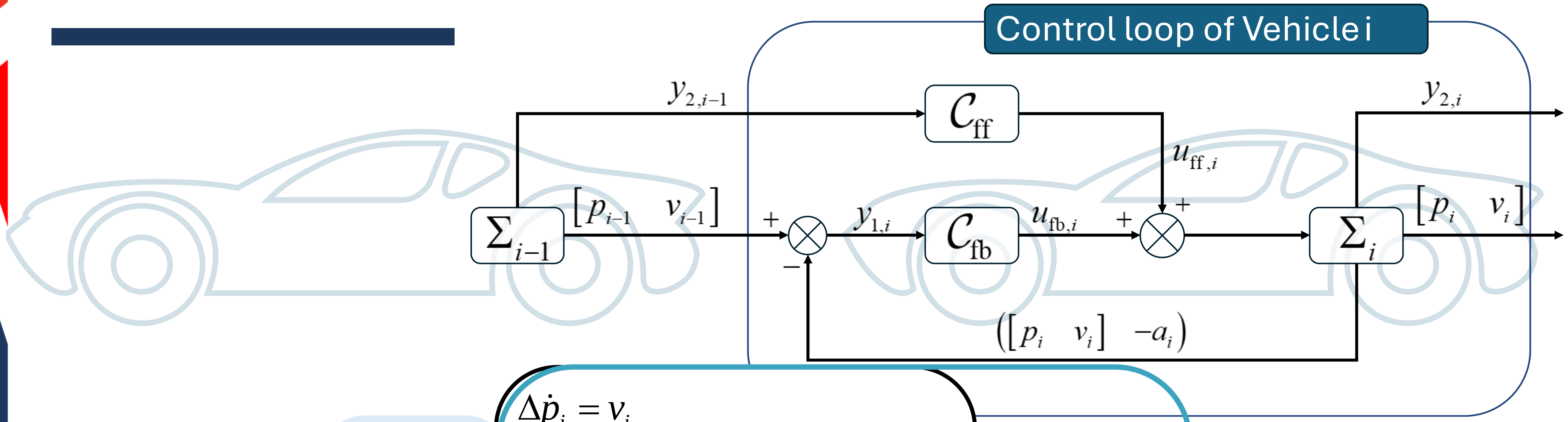
Σ_{i-1}

$$\Delta\dot{p}_{i-1} = v_{i-1}$$
$$\Delta\dot{v}_{i-1} = a_{i-2} - a_{i-1}$$
$$\dot{a}_{i-1} = -\frac{1}{\rho_d} a_{i-1} + \frac{1}{\rho_d} u_{i-1} + e_{d,i-1}$$

Σ_i

$$\Delta\dot{p}_i = v_i$$
$$\Delta\dot{v}_i = a_{i-1} - a_i$$
$$\dot{a}_i = -\frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + e_{d,i}$$

Vehicles interactions



$\Sigma_{i,i-1}$

$$\Delta\dot{p}_i = v_i$$

$$\Delta\dot{v}_i = a_{i-1} - a_i$$

$$\dot{a}_i = -\frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + e_{d,i}$$

Σ_i

Σ_{i-1}

$$\dot{a}_{i-1} = -\frac{1}{\rho_d} a_{i-1} + \frac{1}{\rho_d} u_{i-1} + e_{d,i-1}$$

Vehicle Linearized Dynamics

- Augmented dynamics model for vehicle interactions

$\Sigma_{i,i-1}$

$$\Delta \dot{p}_i = v_i$$

$$\Delta \dot{v}_i = a_{i-1} - a_i$$

$$\dot{a}_i = -\frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + e_{d,i}$$

$$\dot{a}_{i-1} = -\frac{1}{\rho_d} a_{i-1} + \frac{1}{\rho_d} u_{i-1} + e_{d,i-1}$$

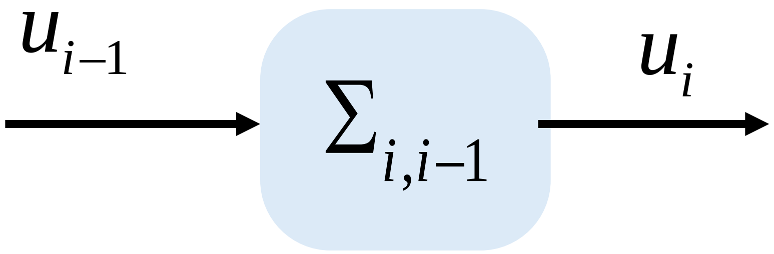
Vehicles interactions

- Augmented dynamics model for vehicle interactions

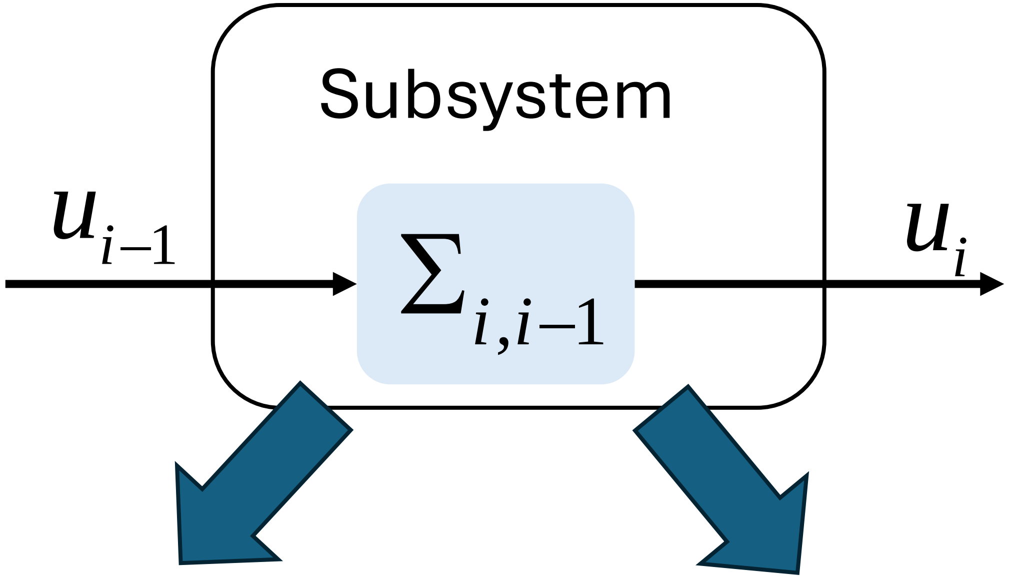
$\Sigma_{i,i-1}$

$$
\begin{aligned}
\Delta\dot{p}_i &= v_i \\
\Delta\dot{v}_i &= a_{i-1} - a_i \\
\dot{a}_i &= -\frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + e_{d,i} \\
\dot{a}_{i-1} &= -\frac{1}{\rho_d} a_{i-1} + \frac{1}{\rho_d} u_{i-1} + e_{d,i-1}
\end{aligned}
$$

- Input: u_{i-1}
- Performance output: u_i



Vehicles interactions



Individual stability

String stability

Scalability

Stability conditions are independent of the number of vehicles

Augmented dynamics

- From the augmented dynamics and the control law

$$\Sigma_{i,i-1}:\quad \begin{aligned} \Delta\dot{p}_i &= v_i \\ \Delta\dot{v}_i &= a_{i-1} - a_i \\ \dot{a}_i &= -\frac{1}{\rho_d} a_i + \frac{1}{\rho_d} u_i + e_{d,i} \\ \dot{a}_{i-1} &= -\frac{1}{\rho_d} a_{i-1} + \frac{1}{\rho_d} u_{i-1} + e_{d,i-1} \end{aligned}$$

- Control input

$$u_i = K_1 \begin{bmatrix} \Delta p_i \\ \Delta v_i \\ a_i \end{bmatrix} + K_2 a_{i-1}$$

Augmented dynamics

❑ Considering the closed-loop augmented system:

$$\Sigma_{i,i-1}$$

$$\dot{x}_i = \left(A + B\begin{bmatrix} K_1 & K_2 \end{bmatrix}\right) x_i + D u_{i-1} + E \begin{bmatrix} e_{d,i} \\ e_{d,i-1} \end{bmatrix}$$

$$z_i = \begin{bmatrix} K_1 & K_2 \end{bmatrix} x_i$$

$$y_{1,i} = C_1 x_i$$

$$y_{2,i-1} = C_2 x_i$$

- System states: $x_i = \begin{bmatrix} \Delta p_i \\ \Delta v_i \\ a_i \\ a_{i-1} \end{bmatrix}$
- Input: u_{i-i}
- Performance output: $z_i = u_i$

Designing conditions (Interconnected)

- Considering the closed-loop augmented system:

$$\Sigma_{i,i-1} \quad \dot{x}_i = \left(A + B\begin{bmatrix} K_1 & K_2 \end{bmatrix}\right) x_i + D u_{i-1} + E \begin{bmatrix} e_{d,i} \\ e_{d,i-1} \end{bmatrix}$$

$$z_i = \begin{bmatrix} K_1 & K_2 \end{bmatrix} x_i$$

$$y_{1,i} = C_1 x_i$$

$$y_{2,i-1} = C_2 x_i$$

- Design a control law such that:

The platoon is string stable

String stability analysis

- To account for uncertainties and ensure scalability, we propose

Considering the system $\Sigma_{i,i-1}$. Assuming that the uncertainties are bounded with $\|w_{d,i}\| \leq w_{\max}$ and there exist positive scalars $\gamma \leq 1$ and β such that :

$$\| z_i \| \leq \gamma \| z_{i-1} \| + \beta \| w_{d,i} \| \quad w_{d,i} = \left(e_{d,i}, e_{d,i-1}\right)$$

then,

$$\| z_i \| \leq \| u_0 \| + i\beta w_{\max}$$

Designing conditions

- Lyapunov based stability conditions:

$$V(x_i) > 0, \quad \forall x_i \neq 0, \quad V(0) = 0,$$
$$\dot{V}(x_i) \leq -z_i^T z_i + \gamma u_{i-1}^T u_{i-1} + \beta w_{d,i}^T w_{d,i}$$

- LMI conditions: Determine $\{P \quad L \quad \alpha \quad \beta\}$ such that:

$$\begin{bmatrix} \mathrm{He}\{AP + BL\} + \alpha P & D & E & L \\ * & -\gamma^2 I & 0 & 0 \\ * & * & -\beta^2 I & 0 \\ * & * & * & -I \end{bmatrix} \prec 0$$

$$K = LP^{-1}$$ Control gain

$$\gamma \leq 1$$

PLATOON SIMULATION

Main results assuming continuous communication

PLATOON SIMULATION

❑Vehicle base parameters values

Vehicle	r	$\boldsymbol{m}$	$\boldsymbol{h}_w$	$\boldsymbol{J}_r$	$\boldsymbol{J}_e$	$\boldsymbol{R}_g$	$\boldsymbol{B}$	$\boldsymbol{C}$	ρ
Σ_0^b		1724	0.28	0.75	0.14	0.10	7.35	0.05	0.05
$\tilde{\Sigma}_0^b$		1724	0.25	1.05	0.14	0.13	8.09	0.06	0.08
Σ_1^b	2.5	2241	0.63	0.97	0.35	0.18	13.96	0.11	0.10
$\tilde{\Sigma}_1^b$		2017	0.51	0.68	0.46	0.18	11.17	0.16	0.09
Σ_2^b	2.5	2930	0.41	1.57	0.27	0.20	11.02	0.08	0.08
$\tilde{\Sigma}_2^b$		2637	0.33	1.26	0.40	0.30	8.82	0.05	0.06
Σ_3^b	2.5	3620	0.63	0.82	0.27	0.11	13.96	0.11	0.12
$\tilde{\Sigma}_3^b$		3258	0.89	1.15	0.40	0.08	15.36	0.16	0.12
Σ_4^b	2.5	3965	0.52	1.72	0.24	0.11	8.09	0.06	0.08
$\tilde{\Sigma}_4^b$		5947	0.63	2.41	0.29	0.14	11.32	0.08	0.11

PLATOON SIMULATION

- Vehicle base parameters values

Vehicle	r	$\boldsymbol{m}$	$\boldsymbol{h}_w$	$\boldsymbol{J}_r$	$\boldsymbol{J}_e$	$\boldsymbol{R}_g$	$\boldsymbol{B}$	$\boldsymbol{C}$	ρ
Σ_0^b		1724	0.28	0.75	0.14	0.10	7.35	0.05	0.05
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Σ_1^b	2.5	2241	0.63	0.97	0.35	0.18	13.96	0.11	0.10
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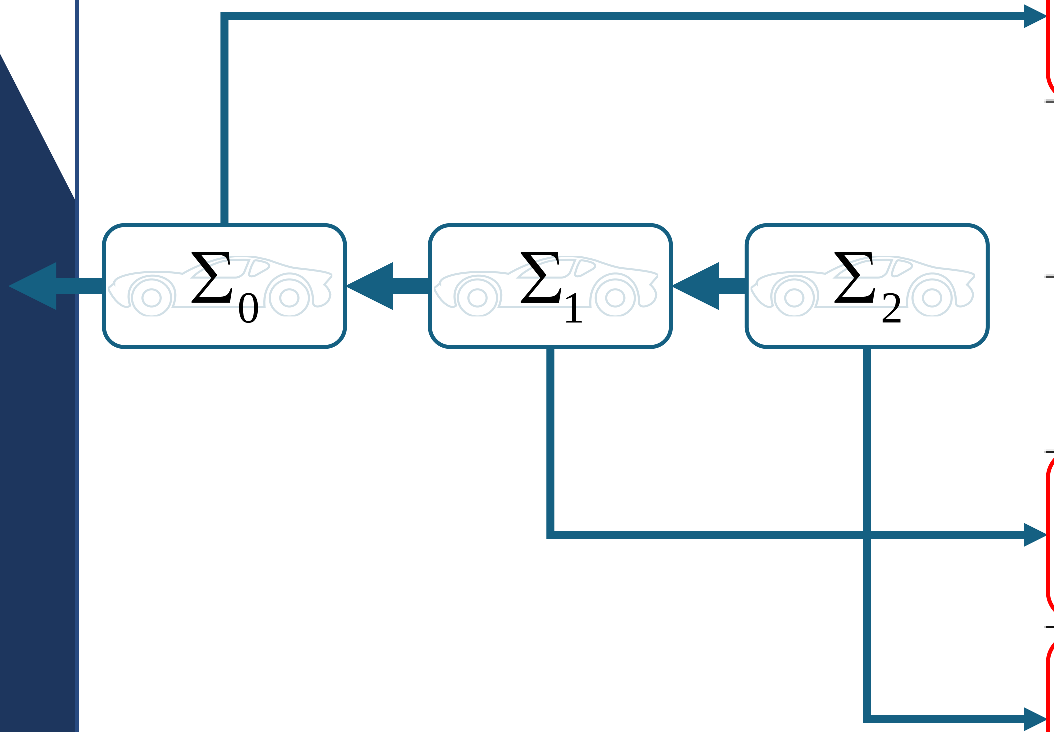
PLATOON SIMULATION

- Set of index:

$$\mathbb{J} = \{0, 3, 4\}$$



❑Vehicle base parameters values

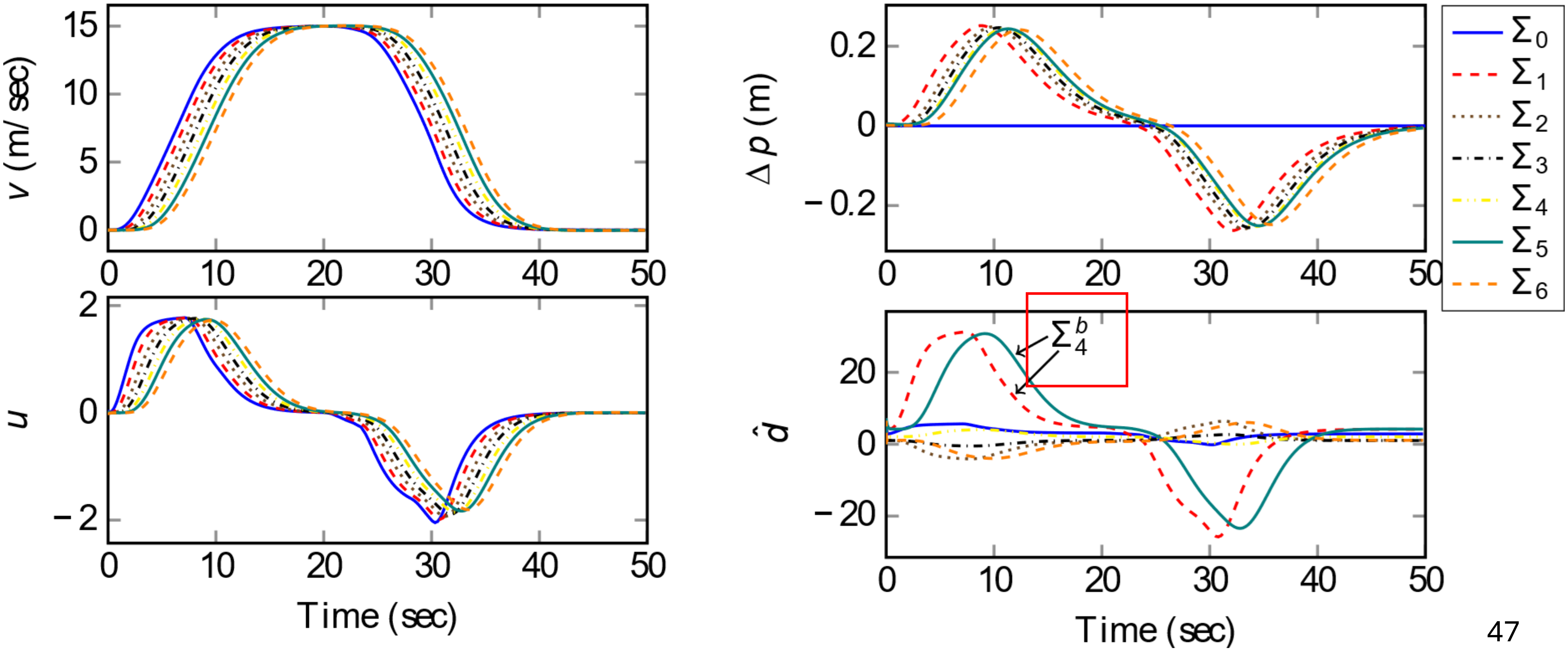
Vehicle	r	$\boldsymbol{m}$	$\boldsymbol{h_w}$	$\boldsymbol{J_r}$	$\boldsymbol{J_e}$	$\boldsymbol{R_g}$	$\boldsymbol{B}$	$\boldsymbol{C}$	ρ
Σ_0^b		1724	0.28	0.75	0.14	0.10	7.35	0.05	0.05
$\tilde{\Sigma}_0^b$		1724	0.25	1.05	0.14	0.13	8.09	0.06	0.08
Σ_1^b	2.5	2241	0.63	0.97	0.35	0.18	13.96	0.11	0.10
$\tilde{\Sigma}_1^b$		2017	0.51	0.68	0.46	0.18	11.17	0.16	0.09
Σ_2^b	2.5	2930	0.41	1.57	0.27	0.20	11.02	0.08	0.08
$\tilde{\Sigma}_2^b$		2637	0.33	1.26	0.40	0.30	8.82	0.05	0.06
Σ_3^b	2.5	3620	0.63	0.82	0.27	0.11	13.96	0.11	0.12
$\tilde{\Sigma}_3^b$		3258	0.89	1.15	0.40	0.08	15.36	0.16	0.12
Σ_4^b	2.5	3965	0.52	1.72	0.24	0.11	8.09	0.06	0.08
$\tilde{\Sigma}_4^b$		5947	0.63	2.41	0.29	0.14	11.32	0.08	0.11

❑ Interconnected system

$$\mathbb{J} = \{0, 4, 1, 3, 2, 4, 1\}$$

❑ Control law designed via the optimization problem

$$K = \begin{bmatrix} 0.462 & 1.5488 & -1.760 & 0.1667 \end{bmatrix}$$



Main point

1. Input output dynamics (block) that represents the interactions between vehicles.

Main point

2

Base on this augmented dynamics we can achieved scalable conditions accounting for:

- ETC:

SILVA, R.; NGUYEN, A.; GUERRA, T.-M.; SOUZA, F.; FREZZATTO, L. Switched dynamic event-triggered control for string stability of nonhomogeneous vehicle platoons with uncertainty compensation. *IEEE Transactions on Intelligent Vehicles*, p. 1–15, 2024.

- Time delays:

R. Nascimento Silva, "Event-triggered control for nonlinear systems : Application to vehicle platoons," Theses, Université Polytechnique Hauts-de-France ; Universidade Federal de Minas Gerais, Jul. 2024.

CONCLUSION

Conclusion

1

Conditions for longitudinal vehicle platoon were proposed such that:

- Individual and string stability can be ensured
- Uncertainties are compensated via DOB
- Design conditions are independent of the number of vehicles (scalability)

Acknowledgments

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THANK YOU ALL