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Altruistic Coordination Strategy for On-Ramp Merging on Highway of a Formation of Cooperative Automated Vehicles

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Context:

On-ramp merging on highway performed by Autonomous Vehicles (AVs)

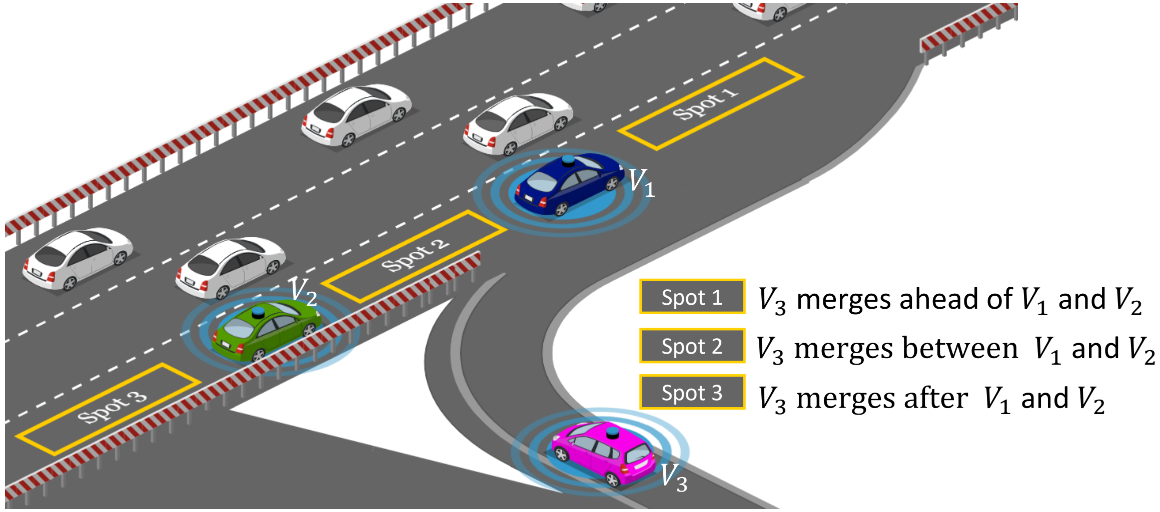


Fig 1. On-ramp merging on highway performed by AVs

- **Ego-centered** resulting merging maneuver,
- Lake of **anticipation** and **synchronization**,
- Not **efficient** in terms of **energy consumption**.

On-ramp merging on highway performed by Cooperative and Automated Vehicles (CAVs)

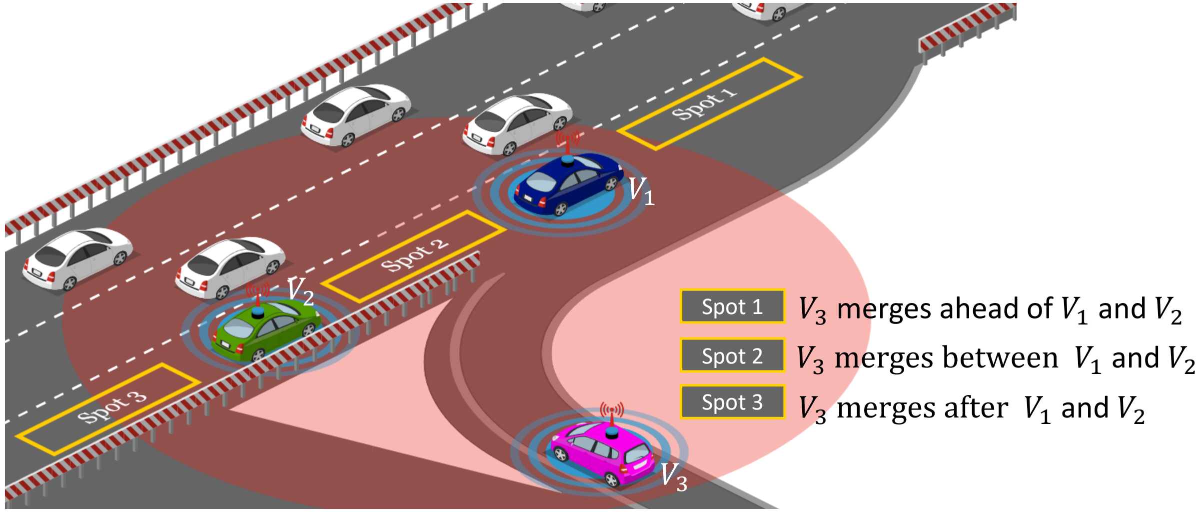


Fig 2. On-ramp merging on highway performed by CAVs

- **Cooperative** on-ramp merging maneuver,
- **Anticipation** is improved using surrounding CAVs information shared using communication,
- Synchronization permits to improve the energy **efficiency.**

Goals:

- Adapt the **inter-target distance matrix** proposed in [1] [2] for open world to on-road constrained environment,
- Ensure **safe and smooth on-ramp merging on highway maneuver** for CAVs.

[1] L. Saidi, L. Adouane and R. Talj, CORM: Constrained Optimal Reconfiguration Matrix for Same On-Ramp Cooperative Merging of Automated Vehicles, IEEE International Conference on Intelligent Transportation Systems, Macau, China, pp. 2783-2790, 2022.
[2] J. Vilca, L. Adouane and M. Youcef, Stable and Flexible Multi-Vehicle Navigation Based on Dynamic Inter-Target Distance Matrix, IEEE Transactions on Intelligent Transportation Systems, vol 20, pp. 1416- 1431, 2019.

The control architecture skeleton

E-CORM: **E**xtended **C**onstrained **O**ptimal **R**econfiguration **M**atrix algorithm

X_T, v: targets and velocity of the CAV,

Γ, δ: torque and steering wheel

X_M: vehicle state

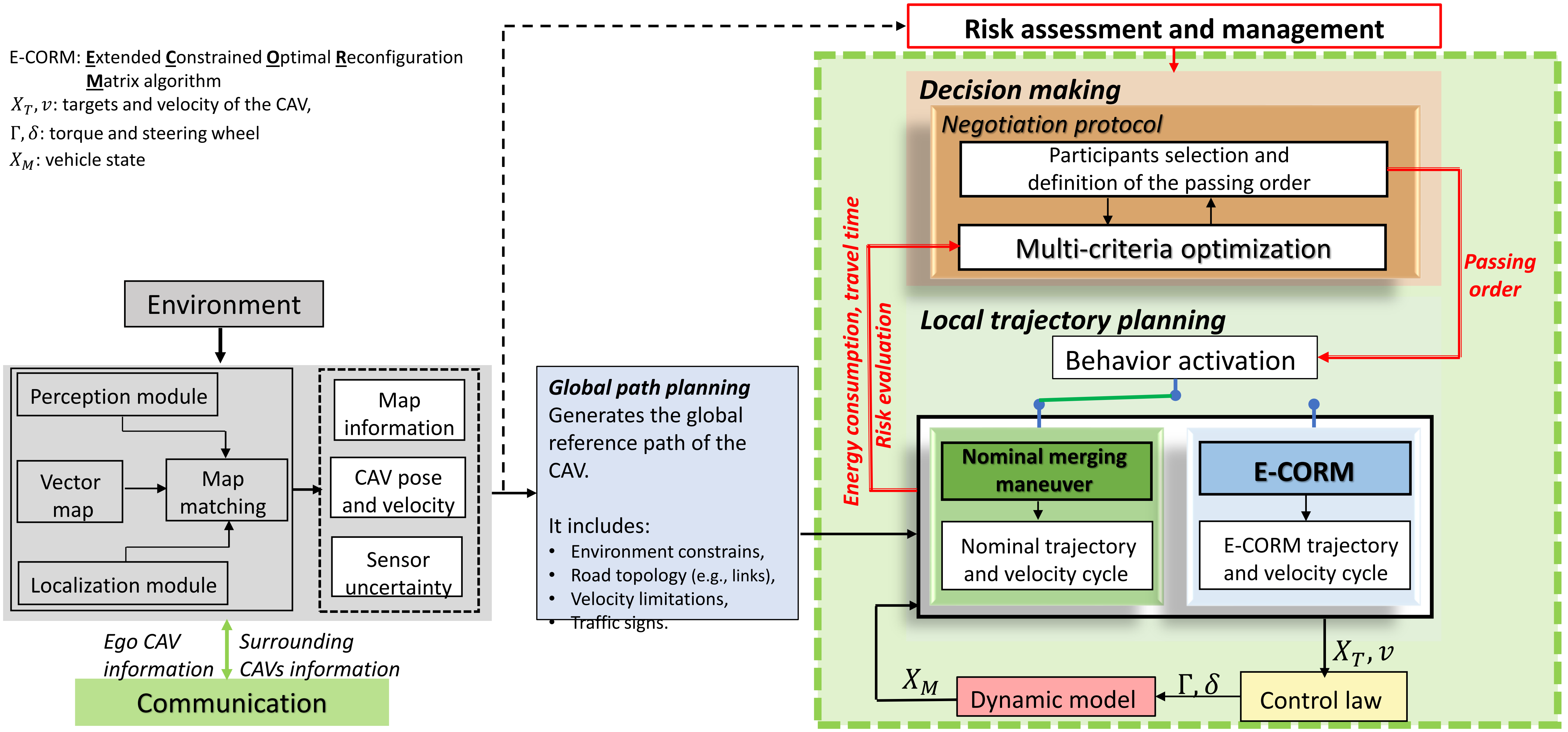


Fig 3. The control architecture skeleton

Plan

- Multi-level architecture for the Altruistic Formation Reconfiguration Strategy (AFRS)
- Multi-mode safe and efficient decision-making level
- Extended Dynamic Reconfiguration matrix (E-CORM)
- Simulation results
- Conclusion and perspectives

Multi-level architecture for the Altruistic Formation Reconfiguration Strategy (AFRS)

Multi-level architecture for the Altruistic Formation Reconfiguration Strategy (AFRS)

① Decision making level:

- Based on the scenario, it selects the CAVs part of formation appropriate behavior.

Its goal:

- Using safety metrics, it select the CAVs behavior w.r.t. the scenario data.

② Behavior selection level:

- Switch between the CAVs ' **nominal mode** and **cooperation mode**, according to the decision making level.

Its goal:

- Nominal mode: perform the merging scenario from the merging CAV perspective.
- Cooperation mode: perform the merging scenario from the formation perspective.

③ Local planning level:

- Based on the selected mode, it has the responsibility of providing the CAVs local trajectory and the corresponding velocity cycles, thus, for both the nominal and cooperation mode.

Its goals:

- Ensure the respect of the *passing order*,
- Track the *global reference path* and respect *the road geometry*,
- Take advantage from the CAVs interactions to perform *safe and smooth merging maneuver*.

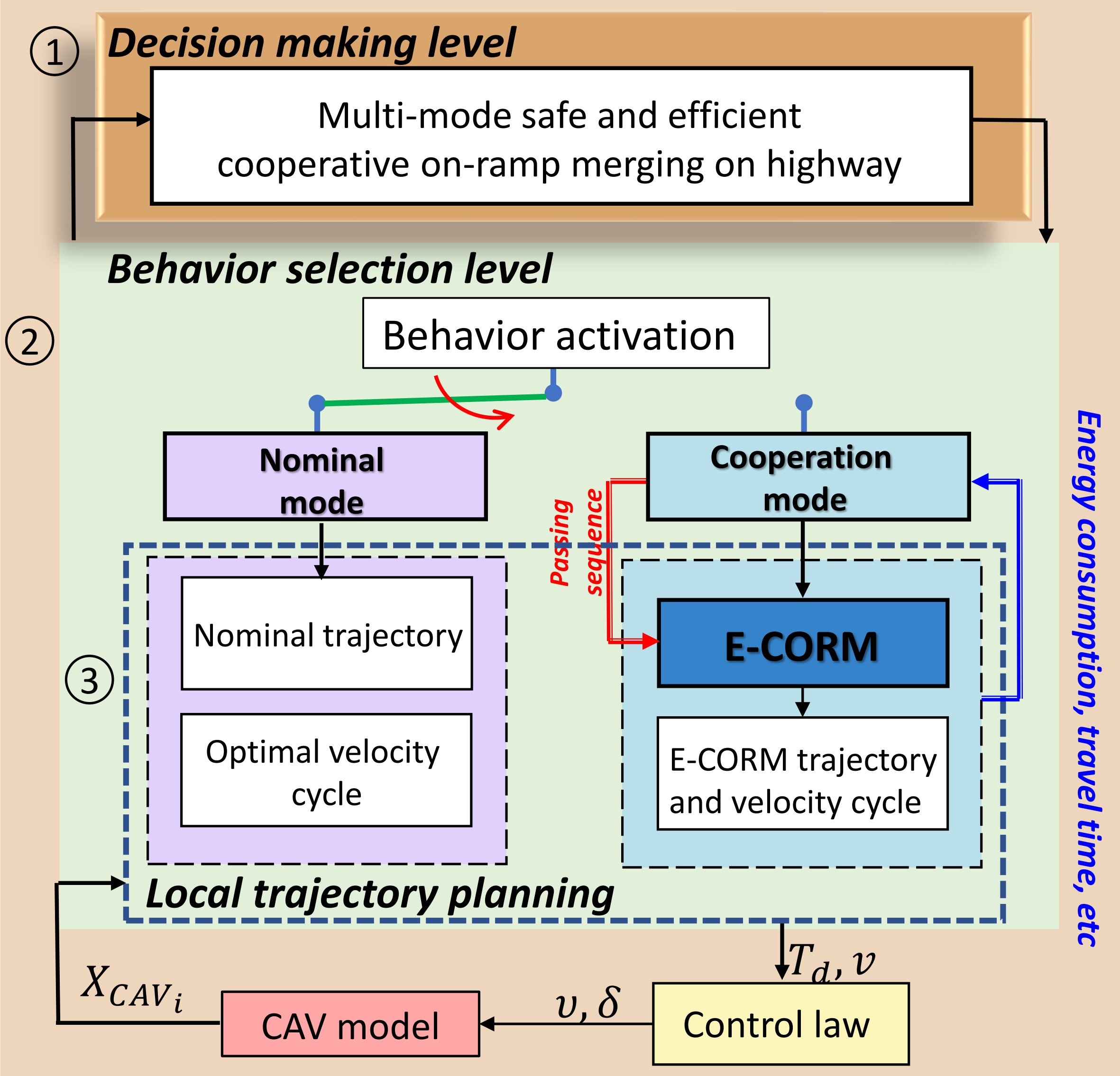


Fig 4. Altruistic Formation Reconfiguration Strategy (AFRS)

Multi-mode safe and efficient decision-making level

Multi-mode safe and efficient decision-making level

Nominal mode:

- The goal of the nominal mode is to perform the merging maneuver from ***the point of view of the merging CAV***.
- The nominal mode is built based on a ***free merging zone at the merging moment***.

Cooperation mode:

- The cooperation mode has the responsibility of setting a ***conflict-free passing Sequence*** sq of the CAVs in the merging zone.
- It is activated when ***a collision may occur*** in the merging zone ***following the nominal mode***.

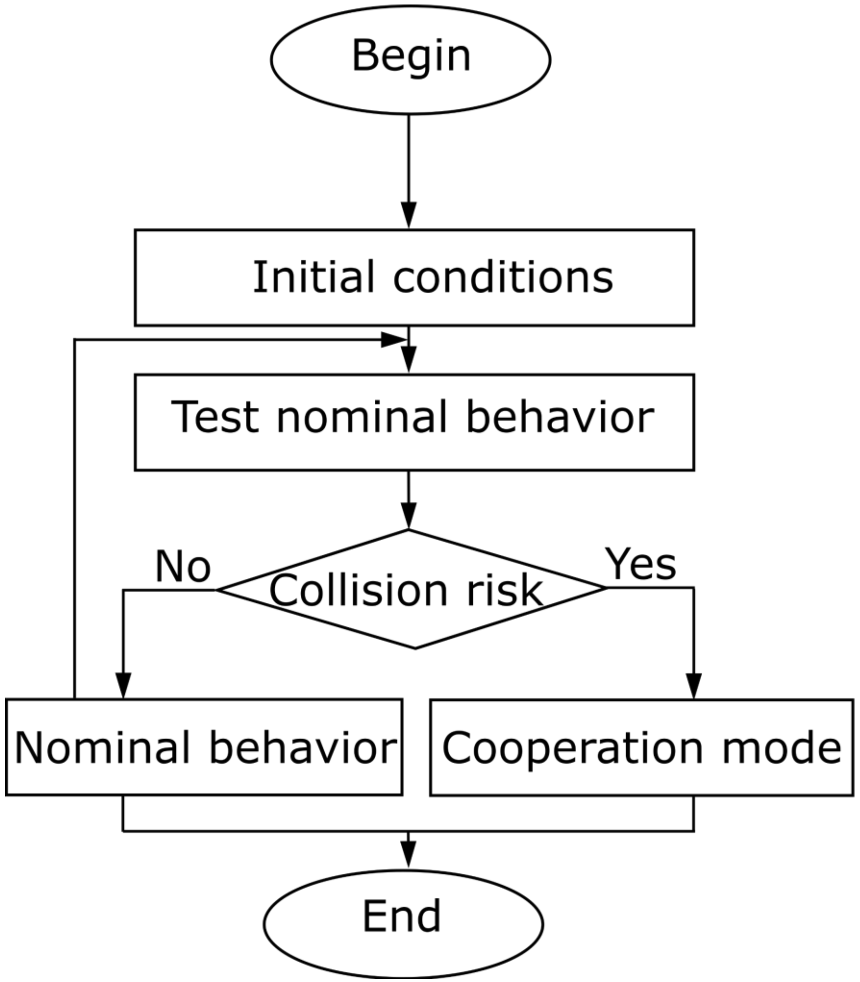


Fig 5. The proposed multi-mode decision-making system

The nominal mode

Nominal mode:

Generate merging CAV velocity cycle $V_m(k)$ based on a sigmoid function:

$$V_m(k) = V_m^{init} + \frac{V_m^{desired} - V_m^{init}}{1 - e^{-\alpha^*(k-\beta^*)}} \quad \ldots (1)$$

with

$V_m^{desired}$ the desired velocity of the merging CAV

V_m^{init} the initial velocity of the merging CAV

The terms α^* and β^* are obtained using an optimization process, which follows the objective function, given below:

$$\min_{\alpha,\beta} \ \omega_1 \frac{TravelTime}{\bar{t}} + \omega_2 \sum_{k=1}^{I_N} \left(\frac{a(k)}{\bar{a}}\right)^2 \quad \ldots (2)$$

with

ω_1 and ω_2: the two sub-criteria weights

$TravelTime$: the required time to perform the merging

$a(k)$: the acceleration profile

$\bar{t}$ and $\bar{a}$: the normalization terms. The maximum time and the maximum acceleration, respectively.

So that:

$$-4\left[\frac{m}{s^2}\right] \leq a(k) \leq 4\left[\frac{m}{s^2}\right], k \in \{1, I_N\}$$
$$V(k) \leq V_{max}, \quad k \in \{1, I_N\}$$

The cooperation mode

Cooperation mode:

The cooperative mode uses the nominal data as an input (cf. Figure) to define the optimal passing sequence sq of the CAVs in the merging zone P_{sq} is selected based on a multi-criteria optimization function.

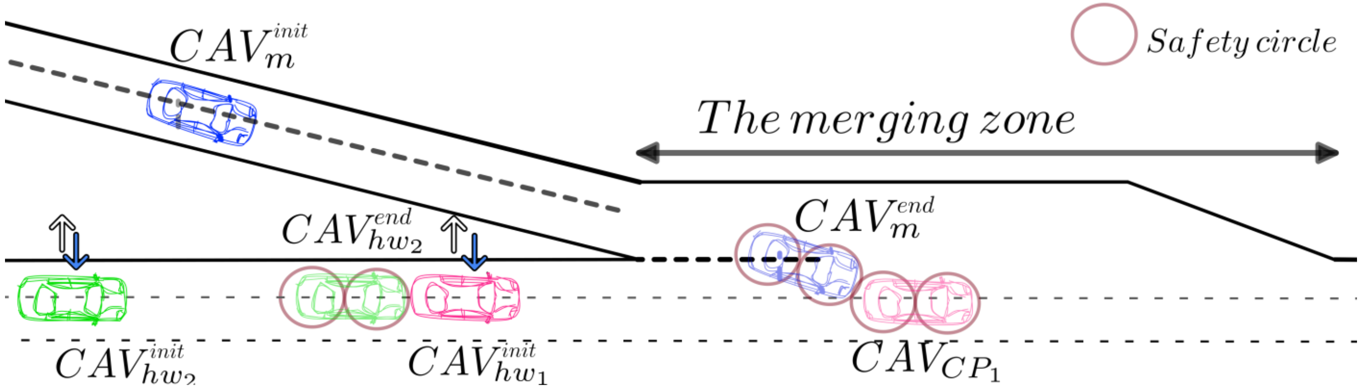


Fig 6. Image of the merging scenario at $t = CT$

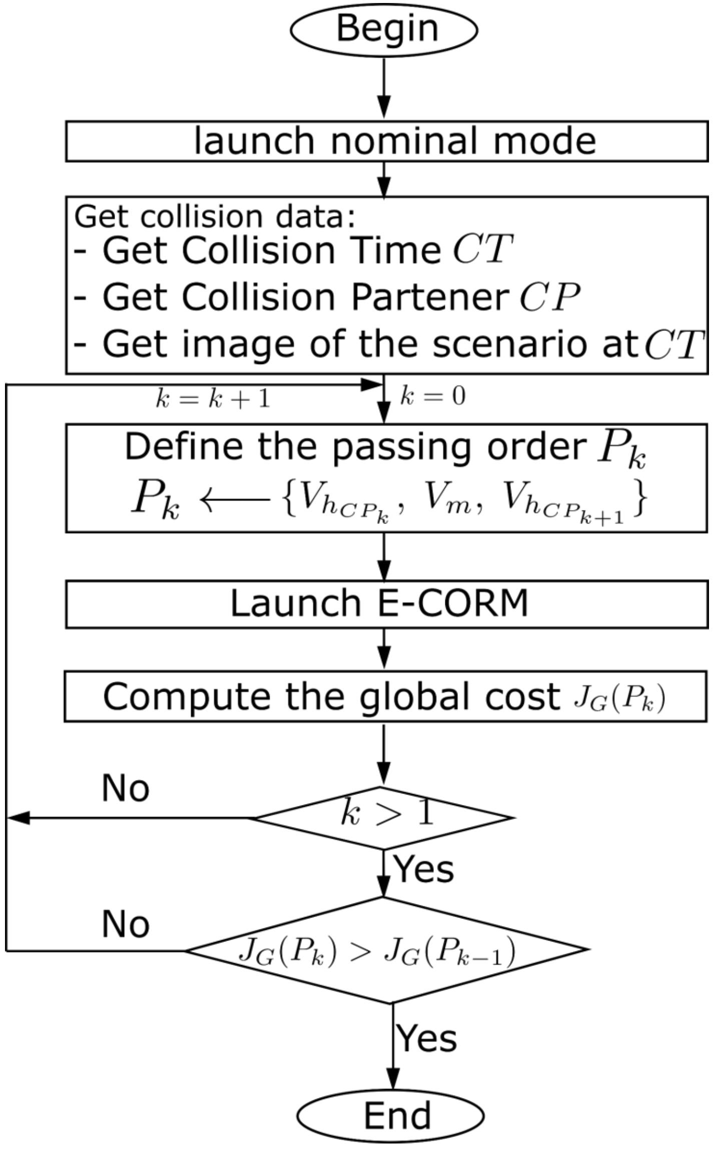


Fig 6. Flowchart representing the step sequence of the cooperation mode

The global objective function:

The global objective function J_G in eq. (3) is used to evaluate the level of cooperation related to the different passing sequencesP_{sq}.

$$J_G(P_{sq}) = \sum_{i=1}^{N} \omega_i \, J_i \quad \dots (3)$$

J_i the CAV_i individual cost w.r.t. the merging maneuver.

With $$\sum_{i=1}^{N} \omega_i = 1 \quad \dots (4)$$

ω_i the weight given to the CAV_i.

The individual cost function:

$$\underset{\forall i \epsilon N}{{}^{i}J} = \omega_{safe} \, J_i^{safe} + \omega_{Acc} \, J_i^{Acc} + \omega_{KE} \, J_i^{KE} + \omega_{NC} \, J_i^{NC}$$

and $$\omega_{safe} + \omega_{ACC} + \omega_{KE} = 1 \qquad \omega = \{\omega_{safe}, \omega_{ACC}, \omega_{KE}, \omega_{NC}\}$$

With J_i^{safe} and ω_{safe} the safety cost and weight, respectively.

J_i^{ACC} and ω_{ACC} the acceleration cost and weight, respectively.

J_i^{KE} and ω_{KE} the kinetic energy cost and weight, respectively.

J_i^{NC} and ω_{NC} the non-collaborative cost and weight, respectively.

Altruistic passing sequence:

The term $\omega_{NC} J_i^{NC}$ is the non-collaborative term. Its objective is to ensure the avoidance of extensive cooperation efforts from the perspective of the highway CAVs.

E-CORM: Extended Dynamic Reconfiguration Matrix

Virtual structure formation modeling

- The **communication range C_R** is used to define the CAVs part of the formation.
- $N \in \mathbb{N}$ is the number of the CAVs under $\mathbf{C_R}$
- i is the *indices* of the considered CAV.
- $\mathcal{N} = \{1, \ldots, N\}$ the *set representing all the CAVs indices*.
- The initial pose $[X, Y, \theta]^T$ and velocity $\mathcal{V}$ of each CAV are known.
- A **Frenet reference** frame based on V_R is used to compute the coordinates of the CAVs part of the formation.

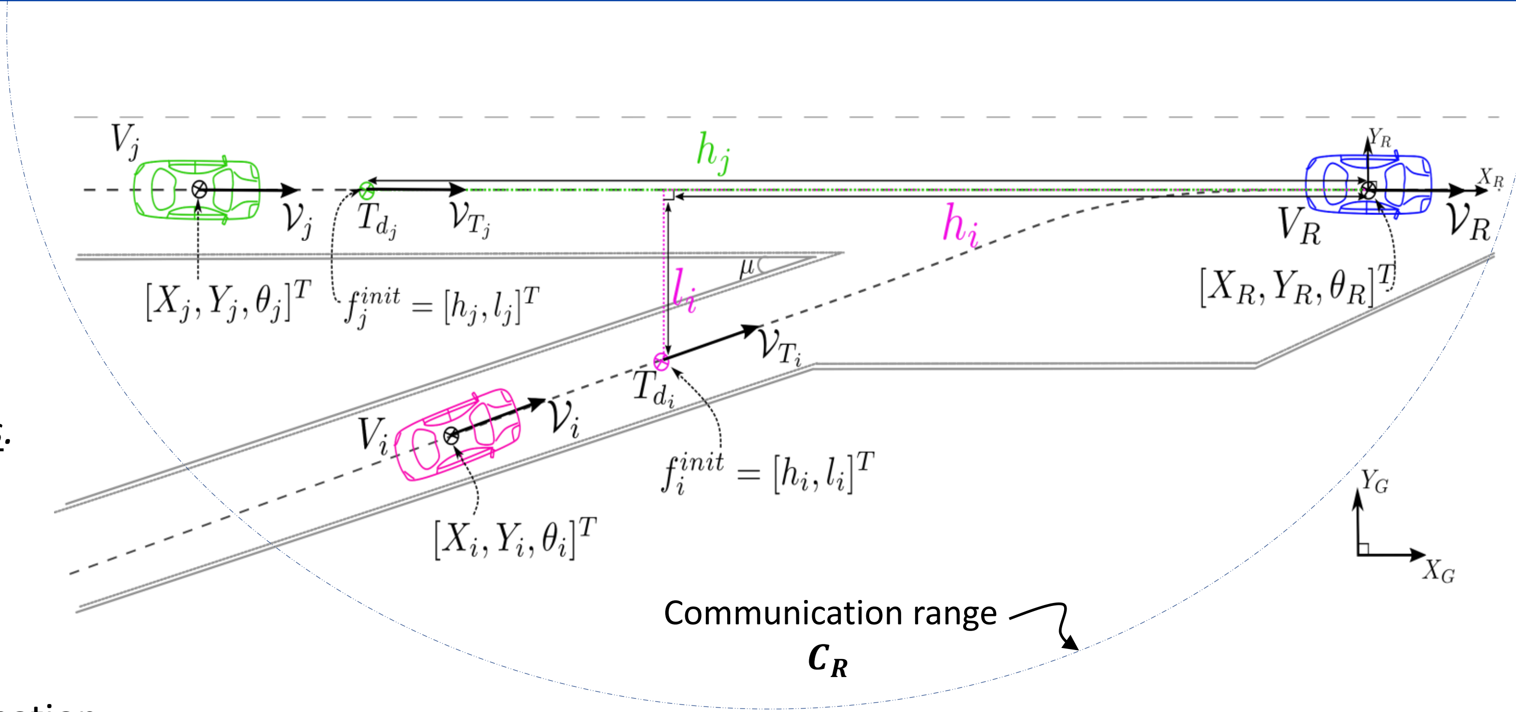
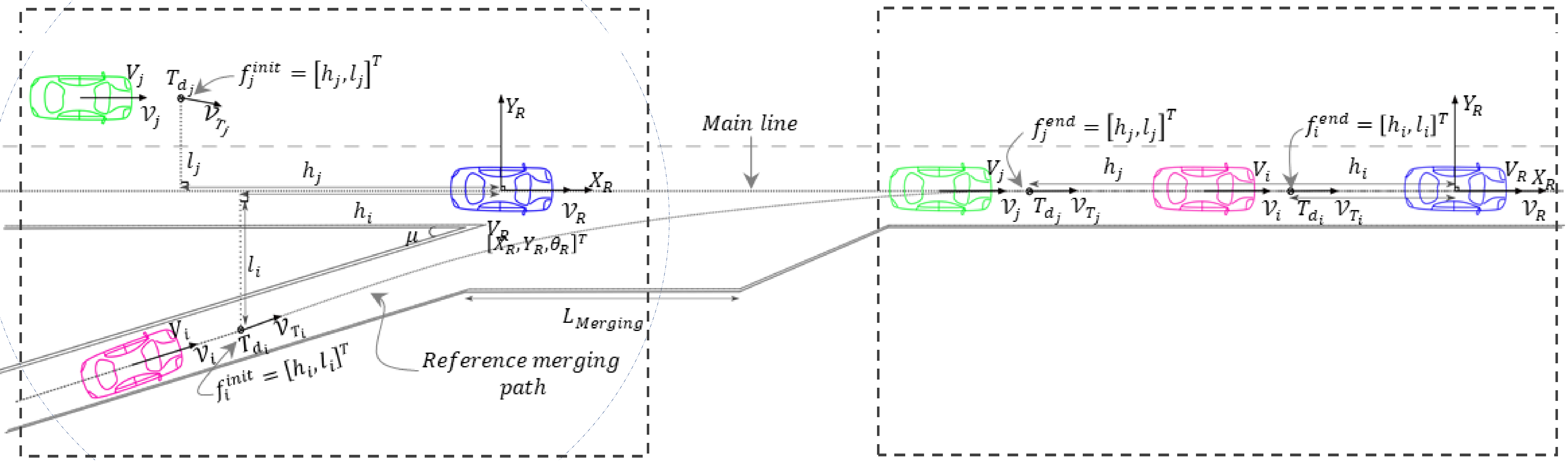


Fig 4. Virtual structure formation modeling framework

- h and l are respectively, *the longitudinal and lateral coordinates* w.r.t. V_R's pose.
- The shape of the **virtual structure** is defined by *the virtual targets T_d*.
- The transformation from the mobile reference to the global reference is obtained with:

$$\begin{bmatrix} x_{T\,i} \\ y_{T\,i} \end{bmatrix} = \begin{bmatrix} x_R(h_i) \\ y_R(l_i) \end{bmatrix} + \begin{bmatrix} -l_i \sin(\theta_R(h_i)) \\ l_i \cos(\theta_R(h_i)) \end{bmatrix} \qquad (1)$$



(a) Initial coordinates of the formation (b) Final coordinates of the formation

Fig 5. The virtual structure approach used to model the formation and its reconfiguration to perform the merging maneuver. (a) The initial shape of the formation and its coordinates. (b) The final shape of the formation after the merging maneuver and its desired coordinates.

The initial coordinates of the formation

$$F^{init} = \begin{bmatrix} h_i & h_j & \cdots & h_N \\ l_i & l_j & \cdots & l_N \end{bmatrix}$$

The intermediary coordinates of the formation

$$\boldsymbol{F(t)} = \begin{bmatrix} \boldsymbol{h_i} & \boldsymbol{h_j} & \cdots & \boldsymbol{h_N} \\ \boldsymbol{l_i} & \boldsymbol{l_j} & \cdots & \boldsymbol{l_N} \end{bmatrix}$$

The final coordinates of the formation

$$F^{end} = \begin{bmatrix} h_i & h_j & \cdots & h_N \\ l_i & l_j & \cdots & l_N \end{bmatrix}$$

With $N \epsilon \mathbb{N}$ | $\mathcal{N} = \{1, \cdots, N\}$ | $i, j \in \mathcal{N}$ where N is the number of the CAVs part of the formation.

Inter-target distance matrix formalization

The **convergence error e_{f_i}** between *the initial* and *the final coordinate* of the CAV_i part of the formation:

$$e_{f_i} = f_i^{end} - f_i(t) \qquad (2)$$

The **global convergence error e_F** for a formation composed of N CAVs can be written as:

$$e_F = F^{end} - F(t) \qquad (3)$$

With $F^{end} = \begin{bmatrix} h_i & h_j & \cdots & h_N \\ l_i & l_j & \cdots & l_N \end{bmatrix}$ And $F(t) = \begin{bmatrix} h_i & h_j & \cdots & h_N \\ l_i & l_j & \cdots & l_N \end{bmatrix}$

The **convergence error rate** is known as: $\dot{e}_F = g\left(e_{f_i}, e_{f_j}, \dots, e_{f_N}\right) \qquad (4)$

The **vector state S** is introduced to control the error convergence: $S = \dot{e}_F + \lambda\, e_F + \gamma \int e_F\, dt \;, \qquad \lambda, \gamma \in \mathbb{R}^+$

$$\begin{bmatrix} \dot{S}_{h_1} \\ \dot{S}_{l_1} \\ \dot{S}_{h_2} \\ \dot{S}_{l_2} \\ \vdots \\ \dot{S}_{h_N} \\ \dot{S}_{l_N} \end{bmatrix} = \Omega_1 \begin{bmatrix} \dot{e}_{h_1} \\ \dot{e}_{l_1} \\ \dot{e}_{h_2} \\ \dot{e}_{l_2} \\ \vdots \\ \dot{e}_{h_N} \\ \dot{e}_{l_N} \end{bmatrix} + \Omega_2 \begin{bmatrix} e_{h_1} \\ e_{l_1} \\ e_{h_2} \\ e_{l_2} \\ \vdots \\ e_{h_N} \\ e_{l_N} \end{bmatrix} + \Omega_3 \begin{bmatrix} \int e_{h_2} dt \\ \int e_{l_1} dt \\ \int e_{h_2} dt \\ \int e_{l_2} dt \\ \vdots \\ \int e_{h_N} dt \\ \int e_{l_N} dt \end{bmatrix}$$

$\Omega_1^{2N\times 2N}, \Omega_2^{2N\times 2N}, \Omega_3^{2N\times 2N}$ are the extended reconfiguration matrix.

With

$$\Omega_1 = \mathrm{diag}\left(a_{h_1}, a_{l_1}, \dots, a_{h_N}, a_{l_N}\right)$$

$$\Omega_2 = \mathrm{diag}\left(a_{h_1}\lambda_{h_1}, a_{l_1}\lambda_{l_1}, \dots, a_{h_N}\lambda_{h_N}, a_{l_N}\lambda_{l_N}\right)$$

$$\Omega_3 = \mathrm{diag}\left(a_{h_1}\gamma_{h_1}, a_{l_1}\gamma_{l_1}, \dots, a_{h_N}\gamma_{h_N}, a_{l_N}\gamma_{l_N}\right)$$

An optimization algorithm is used to compute the values of the **extended reconfiguration matrix**. Further details can be found in [1].

[1] L. Saidi, L. Adouane and R. Talj, CORM: Constrained Optimal Reconfiguration Matrix for Same On-Ramp Cooperative Merging of Automated Vehicles, IEEE International Conference on Intelligent Transportation Systems, Macau, China, pp. 2783-2790, 2022.

Simulation results

Simulation scenario:

Context:

Four vehicles participate into the on-ramp merging on highway maneuver:

- **CAV hw_1** considered as the **reference CAV**,
- **CAV hw_2** and **CAV hw_3** already in the **main line** and behind **CAV hw_1**,
- **CAV_m the merging CAV**, behind both**CAV hw_1**and **CAV hw_2**.

The goal:

Under the communication range of the road side unit, **the merging of CAV_m is operated using the nominal mode** part if the proposed AFRS.

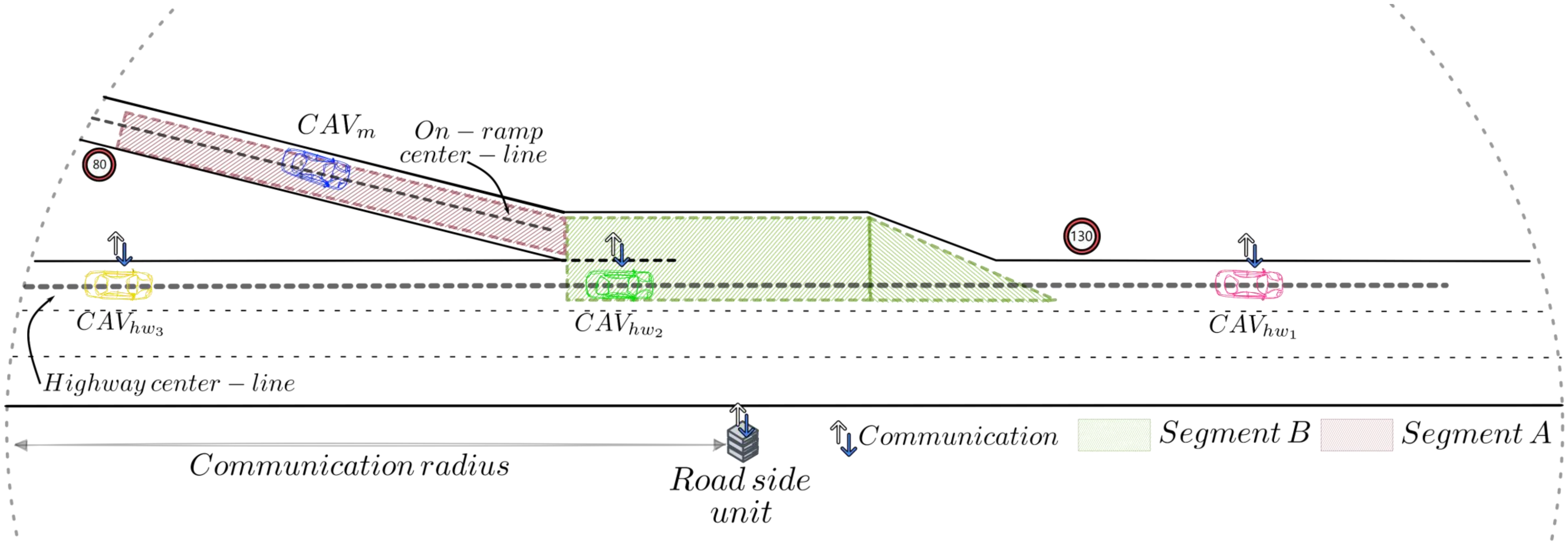
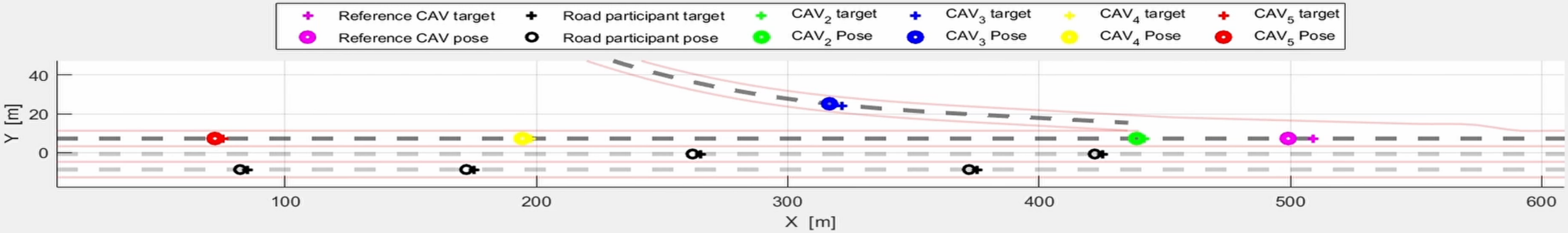


Fig 10. Illustration of the on-ramp merging on highway scene

Nominal mode:

The merging scenario is performed with the help of the nominal mode part of the AFRS.



Nominal mode: simulation results

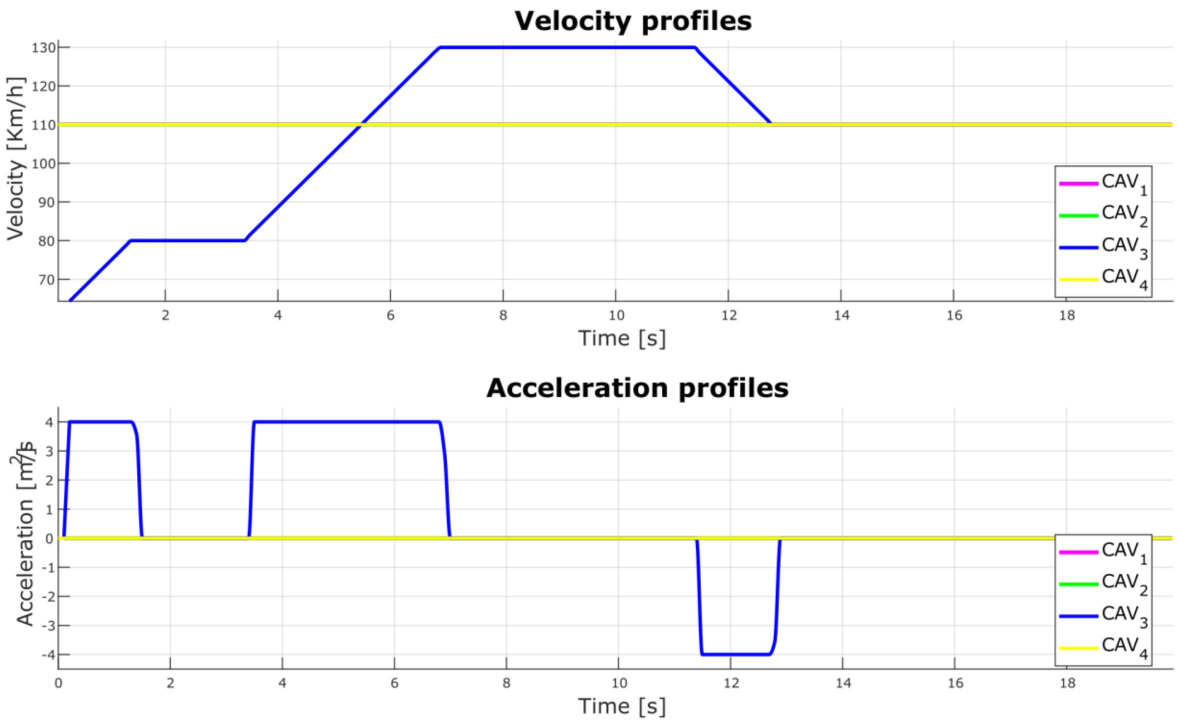


Fig 12. Velocity and acceleration profiles

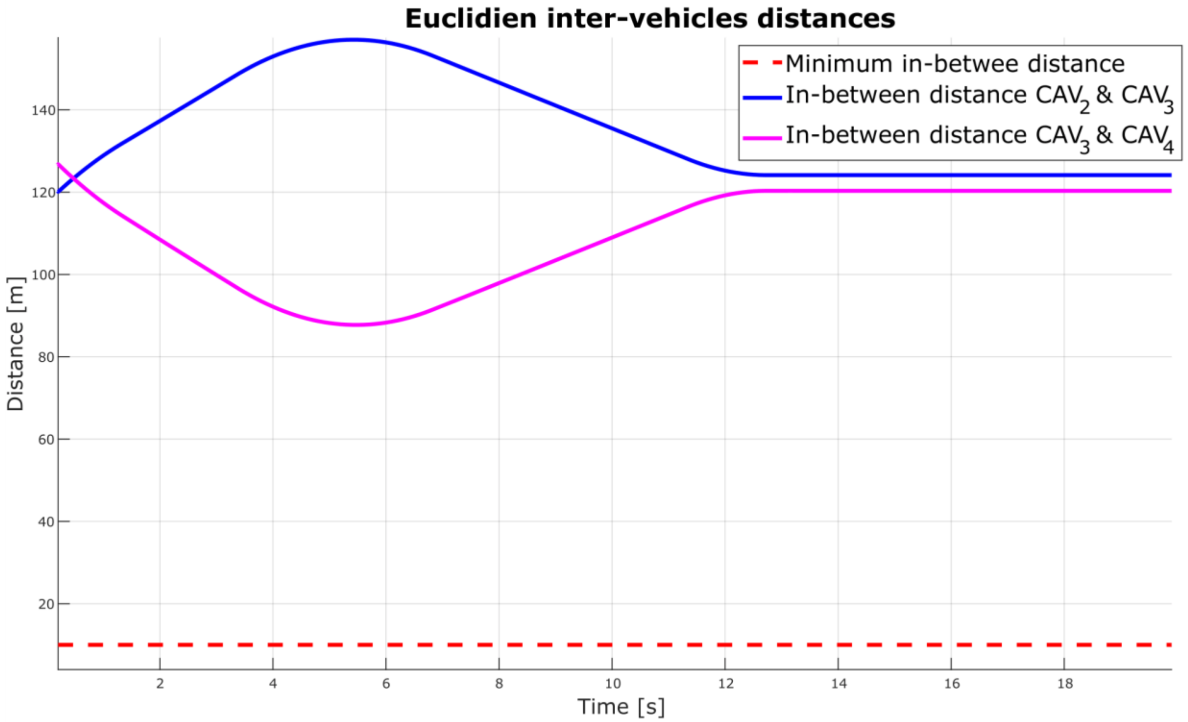


Fig 11. Formation in-between distances evolution

In summary:

- The virtual structure shape convergences from its initial toward its desired final one as shown in the simulation video.
- The in-between distances are safe, as they are always greater than the minimum safety distance $\underline{D_T}$.
- The merging maneuver is smoothly performed according the velocity and acceleration plots.

Simulation scenario:

Context:

Four vehicles participate into the on-ramp merging on highway maneuver:

- **CAV hw_1** considered as the **reference CAV**,
- **CAV hw_2** and **CAV hw_3** already in the **main line** and behind **CAV hw_1**,
- **CAV_m the merging CAV**, behind both**CAV hw_1**and **CAV hw_2**.

The goal:

Without cooperation between the CAVs under the communication rang of the road side unit, **according to the prediction of the nominal mode, a collision is detected**. Consequently, **the motions of the CAVs in the formation are coordinated by the cooperative mode** part of the AFRS.

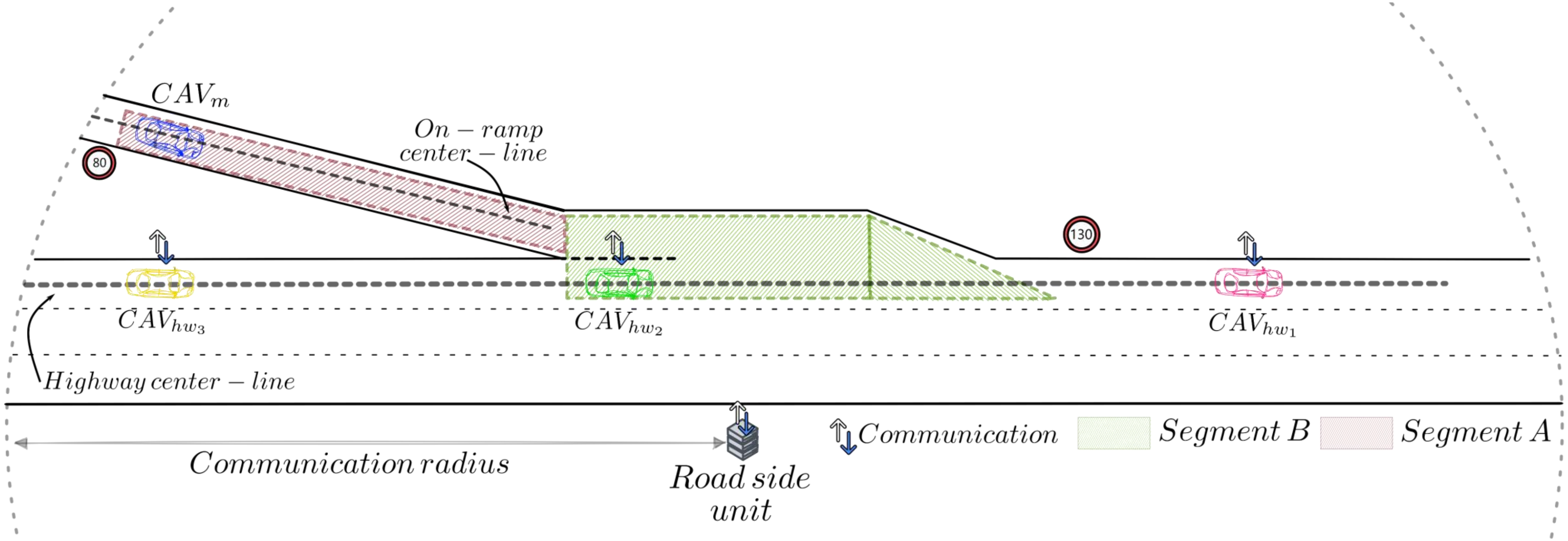


Fig 10. Illustration of the on-ramp merging on highway scene

Cooperation mode: simulation results

Passing sequence	V_1,V_2,V_4,V_3					V_1,V_2,V_3,V_4				
J_G	**0.1262**					0.1845				
CAV	V1	V2	V3	V4	V5	V1	V2	V3	V4	V5
J_{safety}	0.0705	0.0884	0.1058	0.1031	0.1004	0.0871	0.0894	0.1451	0.1031	0.0204
$J_{acceleration}$	0	0	0.1290	0.0571	0	0	0	0.1188	0.0971	0
J_{Energy}	0	0	0.0574	0.1159	0	0	0	0.1405	0.1509	0

Tab 1. Numerical results of the cooperation mode

Sequence 1: Nominal Mode

Cooperation mode: simulation results

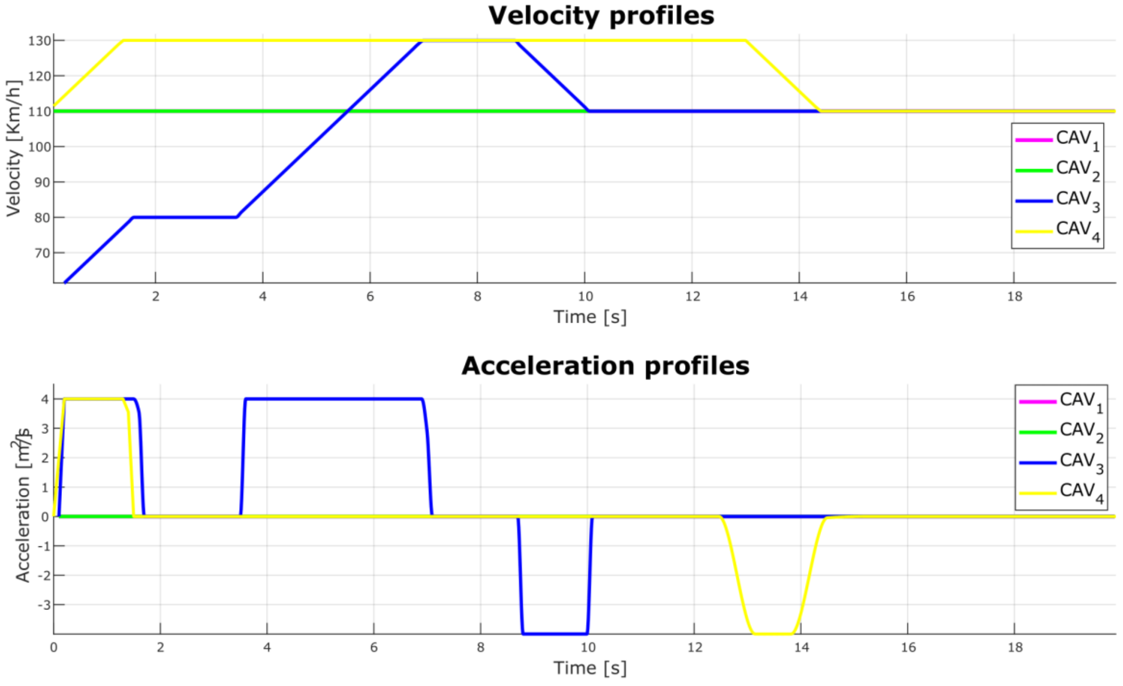


Fig 12. Velocity and acceleration profiles

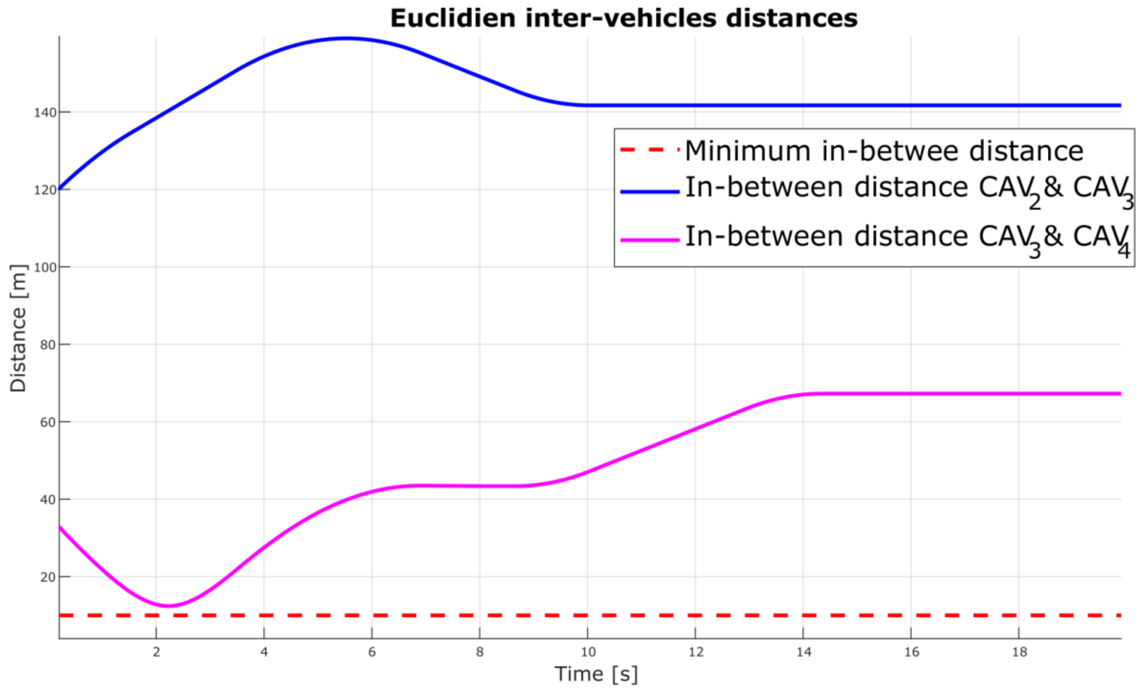


Fig 11. Formation in-between distances evolution

In summary:

- The collision is solved using the cooperation mode part of the proposed AFRS.
- The virtual structure shape convergences from its initial toward its desired final one as shown in the simulation video.
- The in-between distances are safe, as they are always greater than the minimum safety distance $\underline{D}_T$.
- The merging maneuver is smoothly performed according the velocity and acceleration plots.

Conclusion and perspectives

Conclusion and perspectives

- Safe and smooth on-ramp merging approach for Cooperative and Automated Vehicles (CAVs).
- A two steps strategy:
  1. Take the appropriate decision of the CAVs behavior using the Multi-mode safe and efficient decision-making level part of the proposed AFRS.
  2. Activate the selected behavior and generate the CAVs dynamics to control their motions through the merging.
- Several simulations were conducted in order to test the performance of the CORM algorithm.

Future work:

- Compare the performance of the proposed AFRS to other on-ramp merging approaches.
- Implementation of the proposed method into a real vehicle.

Thank you !
Questions ?

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