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On-ramp Merging on Highway for Cooperative Automated Vehicles based on an Online Reconfigurable Formation Control Approach

Lyes Saidi¹, Reine Talj¹ and Lounis Adouane¹

Abstract—On-ramp merging scenarios remain among the most complex challenges for Autonomous Vehicle (AV) technology despite the significant advancements. In this paper, instead of considering individually each AV during the merging, it is proposed to take advantage from the Cooperative Automated Vehicles (CAVs) to tackle the on-ramp merging on highway. The main contribution of this paper is an overall cooperation strategy and formation control approach based on the online cooperative formation reconfiguration strategy, called Formation Reconfiguration Approach based on an Online Control Strategy (FRA-OCS). The proposed strategy operates under the cooperative mode part of the Altruistic Formation Reconfiguration Strategy (AFRS) [2]. To overcome the limitations of both the Constrained Optimal Reconfiguration Matrix (CORM) [1], and the Extended Constrained Optimal Reconfiguration Matrix (E-CORM) [2], the proposed FRA-OCS extends its functionality to ensure both formation safety criteria and efficient formation reconfiguration during the merging maneuvers, allowing thus even more reliable and flexible CAVs coordination. Several simulations are performed to evaluate the safety and reliability of the proposed approach.

I. INTRODUCTION

The development of autonomous vehicles (AVs) technology has made significant progress over the last decade. However, there remain challenging scenarios that require further mastery, such as the on-ramp merging on highways. On-ramp merging is a complex task for AVs as it requires cooperation between the vehicles participating in the merging maneuver to ensure safe and efficient merging. The individual decision-making of AVs during the merging process may lead to traffic congestion, accidents, and inefficiencies in the merging maneuver.

Cooperative Automated Vehicles (CAVs) is one auspicious concept that is employed in addition to the AVs technology motion coordination. According to the authors in [3], urban intersections, highway fleet navigation and merging on on-ramp are among the scenarios where cooperation between the AVs can, in addition to avoiding accidents, decrease road congestion and improve CAVs energy efficiency. CAVs motion coordination and synchronization ability permit to establish efficient collision avoidance strategy, what improves the road safety. The CAVs technology can provide shorter gaps between the AVs and shorter responses time while improving the road capacity, what enhances the traffic flow [4]. CAVs make use of the information offered by the connectivity and road preview, which can lead to auspicious energy potential.

On-ramp merging maneuvers correspond to a complex task for AVs due to the need for cooperation among the participating vehicles to ensure safe and efficient merging. Inappropriate individual decision-making by AVs during the merging process can result in traffic congestion, accidents, and low energy efficiency.

To address these challenges, the use of appropriate coordination of CAVs, based on the formulation of the problem as a formation reconfiguration has emerged, which leverages motion coordination and synchronization capabilities in addition to AV technology. The authors in [3] highlight the potential of CAVs in various scenarios such as urban intersections, highway fleet navigation, and on-ramp merging. By promoting formation cooperation among AVs, these scenarios can not only prevent accidents but also reduce road congestion and enhance energy efficiency. The motion coordination and synchronization abilities of CAVs enable the establishment of collision avoidance strategies, thereby improving road safety. Furthermore, CAVs' utilization of connectivity and road preview information allows for shorter gaps between vehicles and faster response times, ultimately enhancing traffic flow [4][5]. The integration of CAVs paradigm into the transportation system has the potential to unlock significant energy-saving opportunities, while guaranteeing the safety of the CAVs [6][7].

This paper proposes an online cooperative formation strategy for on-ramp merging on highway on a based complet analytic formulation. The main objective of the proposed strategy is to guarantee the safety criterion during the merging, and the CAVs dynamics smoothness. To this aim, the Formation Reconfiguration Approach based on an Online Control Strategy (FRA-OCS) is proposed (cf. Section IV). The FRA-OCS uses a formal approach for formation modeling [2][8] and an online control strategy for formation reconfiguration.

The remainder of the paper is organized as follows. In Section II, the related work to the on-ramp merging scenario is discussed, in addition to the objectives of the proposed online cooperative formation strategy. In Section III, it is introduce the nomenclature used in the paper and the problem statement. The proposed Formation Reconfiguration Approach based on an Online Control Strategy (FRA-OCS), along with a brief summary on the Altruistic Formation Reconfiguration Strategy (AFRS) [2] are discussed in Section IV. The Section V presents the conducted simulations. We draw conclusions and set perspectives in Section VI.

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II. RELATED WORK AND OBJECTIVES

Cooperative on-ramp merging on highway for CAVs requires addressing two key aspects: (a) the formalism used to model the formation composed by the participating CAVs, (b) and the formation reconfiguration approach used to coordinate the motion of the CAVs to perform the merging maneuver.

The topic of formation modeling addresses first, approaches used to identify the CAVs that participate into the formation. In this paper, it is proposed to use the communication range of the Road Side Unit (RSU) (cf. Figure 2), to identify the CAVs present in the merging environment to be part of the considered formation. They are identified and attributed a personal ID. The details related to the communication level are out of the scope of this paper. Second, the formalism used to model the formation is based on the virtual structure approach. Further details about the formation modeling literature can be found in [1].

Motion coordination through the formation reconfiguration aims to synchronize the CAVs' motion to respect a specific passing order in the merging zone. Approaches based on consensus algorithms can be used to coordinate the CAVs motion [9][10][11]. The main drawback of the consensus approaches considering the dynamic nature of the highway merging is its dependency on the strongly connected graph assumption. Approaches based on the virtual mapping of the vehicles from the merging road to the main highway [12][13] can also be considered for the motion coordination. Considering the use of a formation-based approach to tackle the merging scenario, it is usually considered that the virtual mapping focuses on the merging CAV, which is opponent with the proposed contribution in this paper. In [14], the leader followers approach is proposed to tackle the on-ramp scenario. The CORM algorithm [1] uses the virtual structure formalism [8] to propose a restricted motion convergence approach for motion coordination. The formation reconfiguration approach in [1] is based on the reconfiguration matrix designed with the help of an optimization algorithm to reshape the formation from the initial shape to the desired one, while ensuring the respect of the safety criterion and the efficiency of the reconfiguration. The E-CORM algorithm [2] uses an extended reconfiguration matrix that overcomes the CORM flexibility limitations, however, the motion convergence matrix is still computed using an optimization algorithm.

The main objective behind the FRA-OCS presented in this paper is to overcome the limitations of the CORM in terms of flexibility and the E-CORM in terms of optimization dependency. First, this paper proposes to extend the virtual structure modeling formalism to offer the formation an improved flexibility during the reconfiguration. Second, an online control strategy under the FRA-OCS is proposed to identify the reconfiguration matrix needed to perform the merging, as well as, the needed CAVs dynamic behavior.

III. PRELIMINARIES AND PROBLEM STATEMENT

The main focus of this section is to introduce the primary terminology employed in this paper, In addition to this section, please confer to Figure 2. For the knowledge of the reader, the vehicle model and the control law used in this paper are given in [1].

- $N \in \mathbb{N}$ is the number of the considered CAVs that are in the communication range, referred to individually by i , and $\mathcal{N} = \{1, \dots, N\}$ is the set representing all the CAVs indices.
- The subset \mathcal{M} with $\mathcal{M} \in \mathcal{N}$ contains only the m -indexes of the merging CAVs (CAV_m), \mathcal{H} with $\mathcal{H} \in \mathcal{N}$ contains only the hw -indexes of the highway CAVs (CAV_{hw}). Consequently, $\mathcal{N} \equiv \mathcal{M} \cup \mathcal{H}$.
- The pose in the global frame $\{X_G, Y_G\}$ of CAV_i is defined by $X = [x, y, \theta]^T$ and its dynamic is referred to by $[\mathcal{V}, \delta]^T$ for linear velocity and steering angle, respectively.
- The coordinates of CAV_i w.r.t. the mobile reference frame centered on CAV_R are h_i and l_i for longitudinal and lateral coordinates respectively.
- $f_i = [h_i, l_i]^T$ is CAV_i coordinates in the formation, $F = [f_1^T, \dots, f_N^T]^T$ is the vector of coordinates of the formation composed of $N, N \in \mathcal{N}$ CAVs.
- T_{d_i} is the CAV_i dynamic target used by the virtual structure to control the shape of the formation.
- The operator $Eucl_{ij}$ is the Euclidean distance between the CAVs i and j .
- d_{safe} is the minimum Euclidean distance between two vehicles on the same lane.
- sq is the passing sequence of the CAVs in the merging zone.
- The collision time is known as CT , and CP is the collision partner.

IV. ONLINE COOPERATIVE FORMATION RECONFIGURATION STRATEGY

The main objective of the proposed Formation Reconfiguration Approach based on an Online Control Strategy (FRA-OCS) is to ensure the formation safety, the feasibility and efficiency of the CAVs driving behavior during the merging scenario, utilizing cooperation between the CAVs. Consequently, the proposed FRA-OCS operates under the cooperative mode part the Altruistic Formation Reconfiguration Strategy (AFRS) (cf. Figure 1). Thus, for the clarity of the paper, this section presents a concise overview of the AFRS before delving into the specific details of the proposed FRA-OCS.

A. The Altruistic Formation Reconfiguration Strategy (AFRS)

The AFRS [2] is an overall cooperative approach composed of two levels (cf. Figure 1): (1) The multi-mode decision-making level responsible for the activation of the appropriate behavior of the CAVs, transitioning between the nominal mode and the cooperative mode, depending on the safety assessment of the merging scenario. (2) The planning

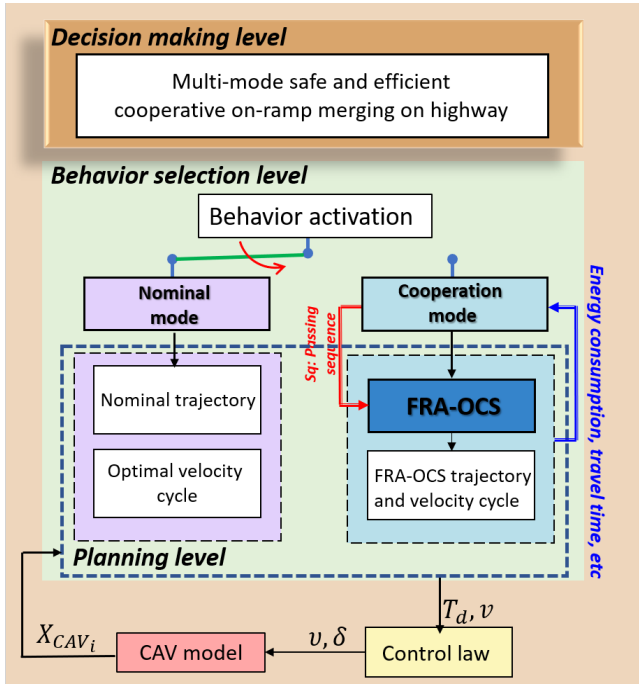


Fig. 1. Altruistic Formation Reconfiguration Strategy (AFRS) [2]

level responsible for the generation of the dynamic targets T_d transitions, with the help of the decision-making level, between the FRA-OCS responsible for the online formation reconfiguration during the merging, and the nominal planning mode.

The cooperation mode is selected when the nominal mode fails to respect the safety criterion. The first task of the cooperative is to create a list of different passing sequences sq of the CAVs in the merging sequence (cf. Figure 2). The latter constitute the entry of the FRA-OCS. Based on sq the FRA-OCS predict the formation reconfiguration and the dynamics related to the later. The second task of the coordination mode is the evaluation of the sq according to the safety, acceleration and kinetic energy criterion.

B. FRA-OCS: Formation Reconfiguration Approach based on an Online Control Strategy

Prior to delving into the specifics of the proposed Formation Reconfiguration Approach based on an Online Control Strategy (FRA-OCS), this section first provides an overview of the fundamentals related to the virtual structure formalization used to represent the formation of CAVs. The stability analysis of the used formation reconfiguration approach is studied in Section IV-B.1. Further details on the adopted formation modeling formalism can be found in [1] [8]. The online procedure used to identify the reconfiguration gains and consequently, generate the CAVs velocity profiles needed for the reconfiguration is described in Section IV-B.2.

1) *Formation Reconfiguration Modeling*: To establish the coordinates of the N CAVs part of the formation, the virtual structure formalism employs a coordinate system based on the Frenet reference frame, w.r.t. the reference vehicle CAV_R pose, in which the longitudinal and lateral Frenet coordinates

h and l , respectively, are used. These coordinates, when transformed to the global reference frame $\{X_G, Y_G\}$, enable the generation of the dynamic target T_{d_i} followed by the CAV_i . For further details about the used coordinate system and the virtual structure formalism, please refer to [1] [8].

As stated previously, in this paper it is proposed to consider the on-ramp merging maneuver as a formation reconfiguration. In other terms, the initial coordinates of the formation F^{init} are reshaped to match the desired coordinates F^{end} , corresponding to the formation coordinates at the end of the merging maneuver (cf. Figure 2). $F(t)$ are the intermediate coordinates used to reshape the formation. Consequently, based on $F(t)$, the dynamic targets $T_d(t)$ are generated for each CAV part of the formation.

$$\begin{cases} F^{init} = [f_1^{init^T}, \dots, f_N^{init^T}]^T, \\ F^{end} = [f_1^{end^T}, \dots, f_N^{end^T}]^T, \\ F(t) = [f_1(t)^T, \dots, f_N(t)^T]^T, \end{cases} \quad (1)$$

$f_i^{init}, f_i^{end} \parallel i \in \mathcal{N}$ are the coordinates of the CAV_i in the initial and final formation, respectively. $f_i(t) \parallel i \in \mathcal{N}$ are its instantaneous coordinates in the formation.

The convergence error between the desired coordinates of CAV_i in the formation and the actual ones is $e_{f_i} = [e_{h_i}, e_{l_i}]^T$, it can be defined as:

$$\begin{cases} e_{f_i} = f_i^{end} - f_i(t), \\ f_i(t) = [h_i(t), l_i(t)]^T, \\ f_i^{end} = [h_i^{end}, l_i^{end}]^T, \end{cases} \quad (2)$$

with $e = [e_{f_1}^T, \dots, e_{f_N}^T]^T$ the convergence error vector.

To address the limited flexibility of the CORM algorithm [1], the FRA-OCS introduces an intermediate state, S , as an essential component for characterizing the evolution of the reconfiguration process from the initial shape of the formation to its desired shape. By employing this intermediate state vector, the FRA-OCS enables a smooth and controlled transition of the formation towards its desired shape. Eq. (3) provides the explicit expression of the intermediate state vector, S .

$$S = \dot{e} + \lambda e \quad (3)$$

The FRA-OCS utilizes in addition to the convergence error vector e , the convergence rate \dot{e} . By introducing the gain $\lambda \in \mathbf{R}^+$, the FRA-OCS offers greater flexibility in achieving the desired formation reconfiguration.

The use of an optimization approach allows the computation of reconfiguration gains within the CORM algorithm [1]. By combining the longitudinal and lateral motion, the computation time required for optimization is reduced. However, one drawback of this motion coupling is its limited flexibility. As a result, in addition to the state vector S used by the FRA-OCS, the proposed approach suggests decoupling the longitudinal convergence from the lateral convergence. Figure 2 illustrates the segmentation approach based on the road geometry used to define the available

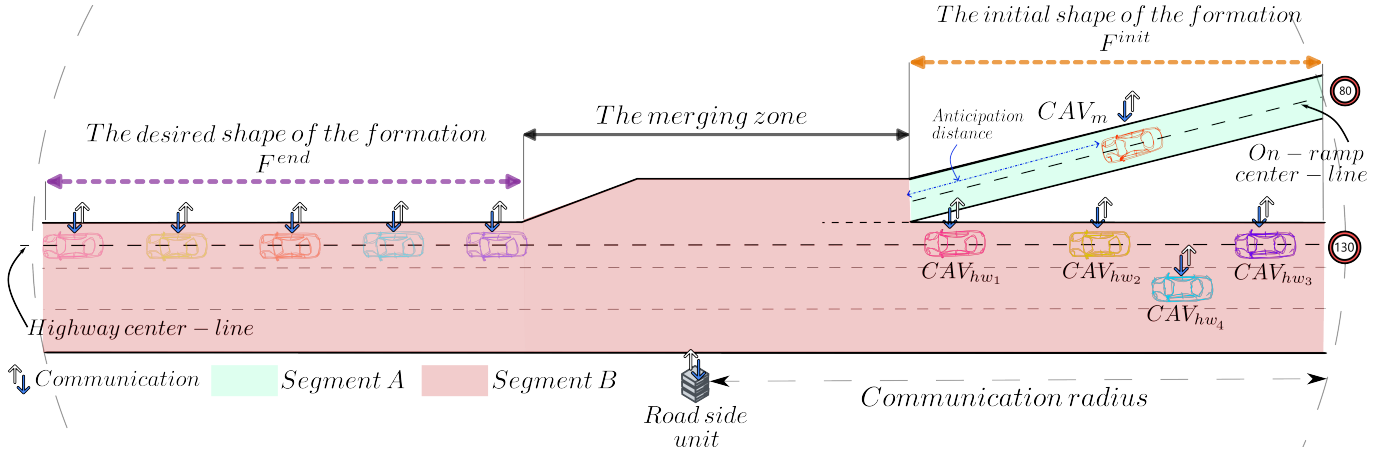


Fig. 2. Illustration of the on-ramp merging on highway scene. The initial shape of the formation of the CAVs under the communication range of the RSU is represented, along with the final desired shape. The Segment A representing the zone where the CAV behaves according to the longitudinal motion. In Segment B the CAV behaves according to both the longitudinal and the lateral motion.

CAVs motion according to its motion. Considering a CAV located on the segment B (cf. Figure 2, Segment B), its reconfiguration w.r.t. the formation can be done according to both the longitudinal and the lateral motion. In contrast, a CAV located in the segment A (cf. Figure 2, Segment A) can only activate its longitudinal reconfiguration since its lateral motion is constrained by the merging road borders.

The convergence of S follows a first order convergence model detailed in eq. (4).

$$\dot{S} = A \times S = A\dot{e} + A\lambda e \quad (4)$$

where $A^{2N \times 2N}$ is a negative-definite convergence matrix.

Using eq. (2) in eq. (4) permits to write the extended system of equations representing the studied formation re-configuration studied system.

$$\begin{aligned} \dot{S}_{h_1} &= a_{h_1} \dot{e}_{h_1} + a_{h_1} \lambda_{h_1} e_{h_1} \\ \dot{S}_{l_1} &= a_{l_1} \dot{e}_{l_1} + a_{l_1} \lambda_{l_1} e_{l_1} \\ &\vdots \\ \dot{S}_{h_N} &= a_{h_N} \dot{e}_{h_N} + a_{h_N} \lambda_{h_N} e_{h_N} \\ \dot{S}_{l_N} &= a_{l_N} \dot{e}_{l_N} + a_{l_N} \lambda_{l_N} e_{l_N} \end{aligned} \quad (5)$$

where h_i and l_i , representing the longitudinal and the lateral coordinates of the formation, converge toward the target with different convergence rates a_{h_i} and a_{l_i} .

The system in eq. (6) presents the matrix form of the studied system.

$$\begin{bmatrix} \dot{S}_{h_1} \\ \dot{S}_{l_1} \\ \vdots \\ \dot{S}_{h_N} \\ \dot{S}_{l_N} \end{bmatrix} = \Omega_1 \begin{bmatrix} \dot{e}_{h_1} \\ \dot{e}_{l_1} \\ \vdots \\ \dot{e}_{h_N} \\ \dot{e}_{l_N} \end{bmatrix} + \Omega_2 \begin{bmatrix} e_{h_1} \\ e_{l_1} \\ \vdots \\ e_{h_N} \\ e_{l_N} \end{bmatrix} \quad (6)$$

with $\Omega_1 = \text{diag}[a_{h_1}, a_{l_1}, \dots, a_{h_N}, a_{l_N}]$ and $\Omega_2 = \text{diag}[a_{h_1} \lambda_{h_1}, a_{l_1} \lambda_{l_1}, \dots, a_{h_N} \lambda_{h_N}, a_{l_N} \lambda_{l_N}]$.

Stability analysis w.r.t. the convergence error: The fundamental stability analysis ensured under the FRA-OCS is given in this section. The stability of the system given in eq. (6) is proved in two steps; 1) the stability analysis of the state S in the system in eq. (4) using a Lyapunov analysis and; 2) the stability of the convergence error e using the system given in eq. (5).

First, the Lyapunov candidate function is defined:

$$V = \frac{1}{2} S^T S \quad (7)$$

V is a positive-definite function. To guarantee the stability of the system, \dot{V} must be negative-definite. By taking the derivative of eq. (7) and using eq. (4), \dot{V} can be written:

$$\dot{V} = \dot{S}^T S = S^T A^T S \quad (8)$$

Since A^T is a diagonal negative-definite matrix, then $\dot{V} < 0$ and the state S converges asymptotically to zero.

The second step of the stability analysis is to prove the convergence of the formation error system given in (3). The stability analysis of eq. (8) permits to write around the equilibrium point of the state S :

$$\begin{cases} \dot{S} = 0 \\ S = 0 \end{cases} \quad (9)$$

Considering eq. (9), the convergence of the error e in eq. (3) is studied according to the stability of a first order system, where the convergence of the system is ensured if and only if λ is positive.

2) *Online reconfiguration gains identification and velocity profile generation:* One limitation of the formation re-configuration based on the CORM is its dependency on an optimization process. In fact, reconfiguration gains computation based on optimization can lack of online computation, especially, when N CAVs are part of the formation and $2 \times N$ gains (decoupled longitudinal and lateral motion are considered) need to be computed. Considering an on-road environment, in one hand, the approach ability to compute and recompute when necessary the reconfiguration gains is mandatory to guarantee the respect of the safety criterion, explicitly in a highly dynamic environment. In the other

hand, due to the dynamic nature of the considered scenario, the approach needs to guarantee the continuity of the CAVs dynamic during the switch from one configuration to another.

Consequently, the FRA-OCS proposed in this paper is designed to overcome the CORM limitation in terms of its real-time computation, with an optimization free procedure to compute the reconfiguration gains. As for the FRA-OCS ability to recompute the convergence gains when necessary, under the FRA-OCS formalism the continuity during the switch from one configuration to another is formally ensured. This section presents the procedure employed to write the system of equation that needs to be solved to reconfigure the formation from the initial shape to the final, while taking into account the initial and the desired dynamics of the CAVs part of the formation.

Using eq. (3) in eq. (4), the convergence model of the formation reconfiguration error is a system of second order linear differential equations, given in eq. (10).

$$\begin{aligned} \ddot{e}_{h_1} + (\lambda_{h_1} - a_{h_1})\dot{e}_{h_1} - a_{h_1}\lambda_{h_1}e_{h_1} &= 0 \\ \ddot{e}_{l_1} + (\lambda_{l_1} - a_{l_1})\dot{e}_{l_1} - a_{l_1}\lambda_{l_1}e_{l_1} &= 0 \\ &\vdots \\ \ddot{e}_{h_N} + (\lambda_{h_N} - a_{h_N})\dot{e}_{h_N} - a_{h_N}\lambda_{h_N}e_{h_N} &= 0 \\ \ddot{e}_{l_N} + (\lambda_{l_N} - a_{l_N})\dot{e}_{l_N} - a_{l_N}\lambda_{l_N}e_{l_N} &= 0 \end{aligned} \quad (10)$$

The general solution $x(t)$ (representing the general form of e_i and its derivatives) of the system in eq. (10) can be written as:

$$x(t) = \alpha_1 e^{\beta_1 t} + \alpha_2 e^{\beta_2 t} \quad (11)$$

with β_1 and β_2 are the roots of the second order linear differential equation related to $x(t)$, and α_1 and α_2 are the gains related to the initial and final conditions of the solution.

The system in eq. (12) is the proposed velocity profile generator model used to compute the needed CAV velocity to reconfigure the formation from the initial shape toward its desired one. The generator model is inspired from eq. (11). The latter is used to control the convergence rate of the coordinates h and l with the help of five degrees of freedom (DOFs) K_1 , K_2 , a , λ and c .

$$\mathcal{V}(t) = K_1 e^{at} + K_2 e^{-\lambda t} + c \quad (12)$$

with a and λ being the roots of the differential equation in eq. (10). K_1 , K_2 and c are the gains used to take into account the initial and final conditions imposed to the velocity generator. The procedure used to solve the system in eq. (10) by the identification of the five DOFs of the velocity profile generator is described above:

(a) In order to generate a velocity profile that takes into account explicitly the anticipation distance available to perform the merging, it is proposed to introduce the time t_{max} . The latter permits to set the moment where \mathcal{V} reaches its maximum, hence the acceleration $\dot{\mathcal{V}}$ is zero as expressed in eq. (13). Consequently, t_{max} permits to dynamically adapt

the acceleration dynamic of the CAVs w.r.t. the length of the anticipation zone.

$$\dot{\mathcal{V}}(t_{max}) = aK_1 e^{at_{max}} - \lambda K_2 e^{-\lambda t_{max}} = 0 \quad (13)$$

(b) The velocity profile generator in eq. (12) needs to take into account the initial velocity of the CAVs and the desired one at the end of the reconfiguration.

Thus $c = \mathcal{V}^{init} - K_1 - K_2$ is computed to impose the initial velocity.

In order to impose the final velocity $\mathcal{V}(t = t_f) = \mathcal{V}^{end}$, with \mathcal{V}^{end} is the velocity of the reference CAV, the eq. (14) is introduced.

$$K_1 e^{at_f} + K_2 e^{-\lambda t_f} - K_1 - K_2 + \mathcal{V}^{init} - \mathcal{V}^{end} = 0 \quad (14)$$

(c) Based on eq. (12), the expression of the position $P(t)$ of the CAV can be written as in eq. (15).

$$P(t) = \frac{K_1}{a} e^{at} - \frac{K_2}{\lambda} e^{-\lambda t} + (\mathcal{V}^{init} - K_1 - K_2)t + d \quad (15)$$

The term $d = P_0 - \frac{K_1}{a} + \frac{K_2}{\lambda}$ is used to impose the initial position P_0 of the CAV at $t = 0$.

(d) Let us define $M(t)$ as the coordinate of the CAV in the formation and M^{end} is its desired final coordinate. M can be either a longitudinal coordinate or a lateral one. In order to link the proposed convergence model to the coordinates used in the virtual structure formalism, eq. (16) is proposed.

$$M(t) = P_{ref} - P(t) \quad (16)$$

with $P_{ref} = \mathcal{V}_{ref} * t + P_{ref_0}$ is the pose of the reference CAV and \mathcal{V}_{ref} is the reference CAV velocity, said to be constant according to the Frenet based coordinates system used by the virtual structure approach.

To guarantee that the desired final coordinate is reached by the CAV at $t = t_f$ (i.e., $M(t_f) = M_f$), eq. (17) is used.

$$\begin{aligned} (\mathcal{V}_{ref} t_f + P_{ref_0}) - \left[\frac{K_1}{a} e^{at_f} - \frac{K_2}{a} e^{-\lambda t_f} + \right. \\ \left. (\mathcal{V}_{min} - K_1 - K_2)t_f + P_0 - \frac{K_1}{a} + \frac{K_2}{\lambda} \right] - M_f = 0 \end{aligned} \quad (17)$$

To solve equations (13), (14) and (17), a numerical solver is employed. Following this, a prediction step is initiated using the generated velocity profiles and the initial conditions of the formation. Subsequently, the numerical solution is evaluated based on the satisfaction of the safety criterion and the dynamic feasibility (e.g., respect of the acceleration limits, the maximum authorized velocity, etc.).

As an example, when the formation reconfiguration takes into account both longitudinal and lateral motions, a longitudinal velocity profile is generated based on the initial and final conditions and dynamics (cf. Section V, Segment A in green), and similarly, a lateral velocity profile is generated for the lateral motion cf. Section V, Segment B in red).

V. SIMULATION RESULTS

To assess the effectiveness of the proposed FRA-OCS in ensuring the safety criterion and the dynamics smoothness of the formation reconfiguration during the on-ramp

merging on highway, the evaluation focuses on analyzing the simulation results of two specific scenarios. The simulation videos of both the two scenarios can be found in: <https://shorturl.at/EIV89>

A. Scenario 1: Evaluation of the FRA-OCS performance w.r.t. a selected passing sequence sq

The following simulation aims to perform the reconfiguration of a formation composed of five CAVs (cf. Figure 2). The initial position of CAV_m is configured to trigger the safety criterion during the merging maneuver under the nominal mode. With the help of the FRA-OCS, four potential passing sequences sq were evaluated by the cooperative mode. Table I presents the numerical results of the two best sq w.r.t. the cooperative mode evaluation.

TABLE I

SCENARIO 1: NUMERICAL RESULTS OF THE COOPERATION MODE

sq	$V_{hw_1}, V_m, V_{hw_2}, V_{hw_3}$				$V_{hw_1}, V_{hw_2}, V_m, V_{hw_3}$			
J_G	0.196				0.181			
CAV_i	hw ₁	m	hw ₂	hw ₃	hw ₁	m	hw ₂	hw ₃
J_{safe}	0.125	0.15	0.103	0.066	0.109	0.25	0.227	0.063
J_{acc}	0	0.11	0.047	0.063	0	0.335	0.025	0.035
J_{KE}	0.127	0.586	0.292	0.292	0.127	0.102	0.11	0.147

The $sq = \{V_{hw_1}, V_{hw_2}, V_m, V_{hw_3}\}$ is the best passing sequence according to the coordination mode. The simulation results obtained following the selected sq are presented in Figure 3. The green shaded part of the figures represents the results when the merging CAVs is located in the segment A (cf. Figure 2, Segment A in green), while the red shaded part represents the results for the segment B (cf. Figure 2, Segment B in red).

The longitudinal and lateral formation coordinates are displayed in Figure 3, (a) and (b), respectively. To maintain an appropriate longitudinal separation between the CAVs in the desired formation shape, an inter-vehicle distance corresponding to $\approx 2[s] \times \mathcal{V}[m/s]$ is employed. The formation inter-vehicular Euclidean distances are represented in Figure 3(c). Due to the positioning of CAV_{hw_2} before CAV_m as determined by the sq , their inter-vehicular Euclidean distance exceeds the safety threshold d_{safe} while the CAV_m is still within segment A, consequently, no risk of collision may occur. Figure 3(d) displays the CAVs velocity profiles. The latter respect the maximum authorized velocity in each segment (cf. Figure 2).

B. Scenario 2: Evaluation of the FRA-OCS reactivity performance and CAVs dynamics continuity

The objective of this second scenario is to evaluate the reactivity of the FRA-OCS w.r.t. the dynamics imposed by the on-road environment. Similar to the previous scenario, a formation reconfiguration involving five CAVs is initially considered. However, at $t = 8s$, a fifth CAV decides to join the formation. As a result, the initial sq (cf. Section V-A) no longer satisfies the safety criterion, prompting the coordination mode to recalculate a suitable sq to ensure safe reconfiguration. Four passing sequences were considered by

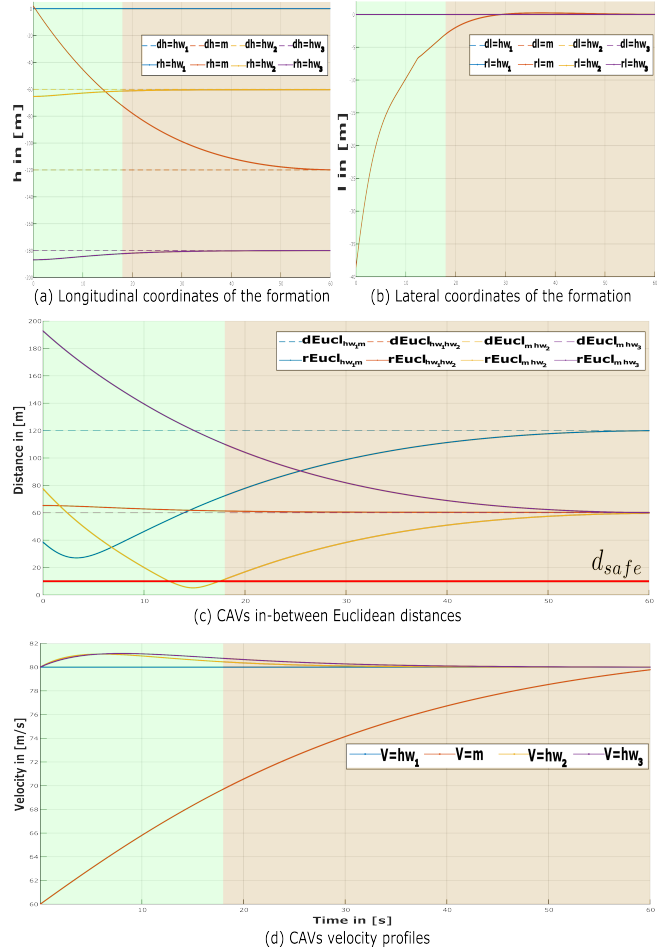


Fig. 3. Scenario 1: simulation results

TABLE II

SCENARIO 2: NUMERICAL RESULTS OF THE COOPERATION MODE

sq	$V_{hw_1}, V_{hw_2}, V_m, V_{hw_4}, V_{hw_3}$					$V_{hw_1}, V_{hw_2}, V_m, V_{hw_4}, V_{hw_3}$				
J_G	0.267					0.242				
CAV_i	hw ₁	m	hw ₂	hw ₃	hw ₄	hw ₁	m	hw ₂	hw ₃	hw ₄
J_{safe}	0.104	0.358	0.227	0.085	0.011	0.101	0.185	0.129	0.106	0.017
J_{acc}	0	0.11	0.135	0.035	0.041	0	0.156	0.089	0.031	0.152
J_{KE}	0.127	0.402	0.188	0.147	0.152	0.127	0.262	0.136	0.153	0.148

the coordination mode. In Table II the numerical results of the two best sq are presented.

The $sq = V_{hw_1}, V_{hw_2}, V_m, V_{hw_4}, V_{hw_3}$ is the best passing sequence. The CAV_{hw_2} is asked to change the lane from *lane 1* to *lane 2*. The simulation results obtained following the selected sq are presented in Figure 4.

The inclusion of the fifth CAV at $t = 8s$ stimulated the reactivity of the FRA-OCS, leading to a switch in the configuration at $t = 8s$ (cf. Figure 4, (a) and (b)). The continuity of the reconfiguration is ensured formally by the FRA-OCS. The CAVs in-between Euclidean distances are displayed in Figure 4(c). The selected sq puts both CAV_{hw_2} and CAV_m at the same longitudinal coordinates but in two different lanes. Consequently, all the in-between distances are greater than d_{safe} in both the segments A and B. The velocity profiles of the CAVs are displayed in Figure 4(d). During the configuration switch at $t = 8s$, the continuity of

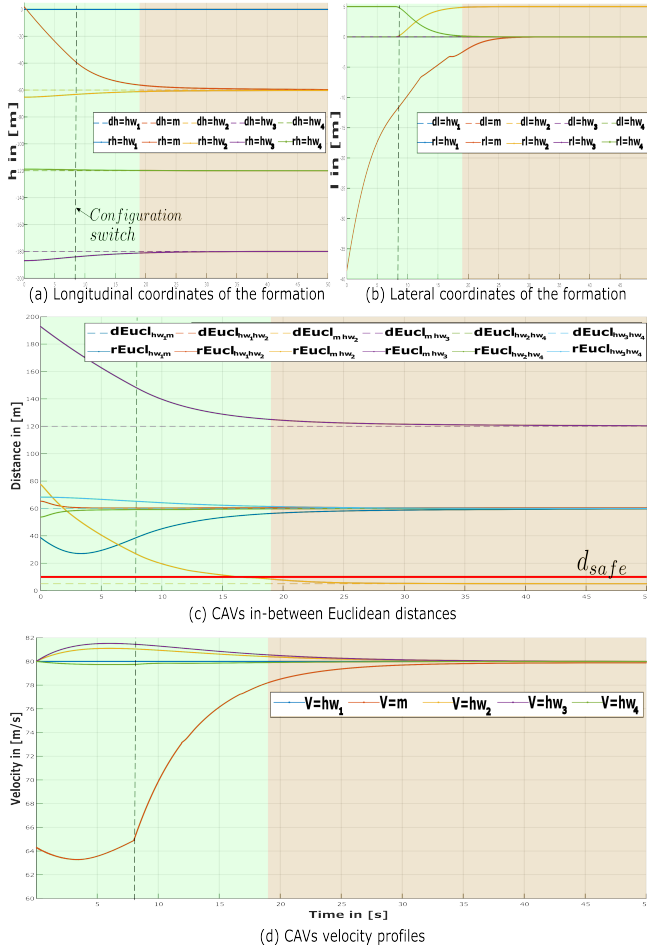


Fig. 4. Scenario 2: simulation results

the velocity profiles is ensured by the velocity generator part of the FRA-OCS.

VI. CONCLUSION AND PERSPECTIVES

This paper takes advantage of the Cooperative Automated Vehicles (CAVs) coordination ability to tackle on-ramp merging on highways, using the proposed Formation Reconfiguration Approach based on an Online Control Strategy (FRA-OCS). The FRA-OCS uses the virtual structure formalism of the formation of CAVs, and an extended reconfiguration matrix to reshape the formation from its initial shape toward its desired one, while ensuring the safety and smoothness of the CAVs motion. Based on the passing sequence selected by the coordination mode part of the Altruistic Formation Reconfiguration Strategy (AFRS), the CAVs dynamic needed to reconfigure the formation is computed with an online and optimization-free approach using the proposed online velocity generator. The FRA-OCS ability to ensure the reconfiguration continuity during the switch from one desired shape to another is formally ensured. The validation of the FRA-OCS was conducted in simulated environment, evaluating two main points: (1) the approach capability to guarantee the respect of the selected passing sequence while ensuring the safety criterion and the efficiency of the CAVs dynamics;

(2) ensuring the continuity of the generated dynamic targets of the FRA-OCS during the configuration switch. Future work will focus mainly on dealing with uncertainties in the considered scenario and implementing the proposed strategy on real vehicles.

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