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

Lyes Saidi [1], Reine Talj [1] and Lounis Adouane [1]

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

In the past decade, AV technology has made remarkable progress. However, challenging scenarios like on-ramp merging on highways still need improvement. On-ramp merging requires vehicle cooperation to achieve safe and efficient merging, presenting complexities for AVs. Individual decision-making during merging can result in traffic congestion, accidents, and inefficiencies.

Cooperative Automated Vehicles (CAVs) offer a promising solution for motion coordination alongside AV technology. Cooperation between CAVs can enhance safety, reduce road congestion, and improve energy efficiency, as demonstrated in scenarios like urban intersections, highway fleet navigation, and on-ramp merging [3]. CAVs' motion coordination and synchronization enable efficient collision avoidance strategies, contributing to road safety. Utilizing connectivity and road preview information, CAVs can achieve shorter gaps between vehicles and faster response times, leading to improved traffic flow and increased road capacity [4]. Moreover, CAVs can leverage this information for advantageous energy savings.

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 tackle these challenges, coordinating Cooperative Automated Vehicles (CAVs) through formation reconfiguration has emerged as a solution, harnessing both AV technology and motion coordination. CAVs show great potential in various scenarios, such as urban intersections, highway fleet navigation, and on-ramp merging [3]. Through formation cooperation, these scenarios can enhance safety, reduce road congestion, and improve energy efficiency. CAVs' motion coordination enables effective collision avoidance strategies, enhancing road safety. Leveraging connectivity and road preview information allows CAVs to achieve shorter gaps between vehicles and quicker response times, leading to improved traffic flow [4][5]. Integrating the CAV paradigm into the transportation system presents significant energy-saving opportunities while ensuring CAV safety [6][7].

This paper proposes an online cooperative formation strategy for on-ramp merging on highway on a based complete 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. The proposed Formation Reconfiguration Approach based on an Online Control Strategy (FRA-OCS) is discussed in Section IV. The Section V presents the conducted simulations. We draw conclusions and set perspectives in Section VI.

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.

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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 in formation reconfiguration aims to synchronize CAVs' movement during highway merging. Consensus algorithms [9][10][11] are commonly used, but their dependency on strongly connected graph assumptions may not suit dynamic merging scenarios. Virtual mapping of vehicles from the merging road to the main highway [12][13] is another approach for motion coordination. However, existing methods often focus on the merging CAV, which differs from the proposed contribution in this paper. Various strategies address merging scenarios, including the leader-follower approach [14] and the CORM algorithm [1], which uses virtual structure formalism [8] for restricted motion convergence. In [1], formation reconfiguration relies on an optimization algorithm to design a reconfiguration matrix, ensuring safety and efficiency. The E-CORM algorithm [2] improves flexibility limitations but still uses an optimization algorithm for the motion convergence matrix computation. 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 $\mathcal{N} = \{1, ..., N\}$ 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, $\mathcal{N} \equiv \mathcal{M} \bigcup \mathcal{H}$.
- 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, $F = [f_1^T, ..., f_N^T]^T$ 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 is a cooperative approach [2] with two levels (cf. Figure 1): (1) The multi-mode decision-making level activates CAV behavior, transitioning between nominal and cooperative modes based on safety assessment of the merging scenario. (2) The planning level generates dynamic target T_d transitions, with the help of the decision-making level, between FRA-OCS for online formation reconfiguration during merging and the nominal planning mode.

In the cooperation mode, if the nominal mode fails to meet the safety criterion, the first task is to generate a list of passing sequences (sq) for the merging CAVs (cf. Figure 2). These sequences are then used as input for the FRA-OCS, which predicts the formation reconfiguration and dynamics. The second task in the coordination mode evaluates these sequences based on safety, acceleration, and kinetic energy criteria.

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. 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.

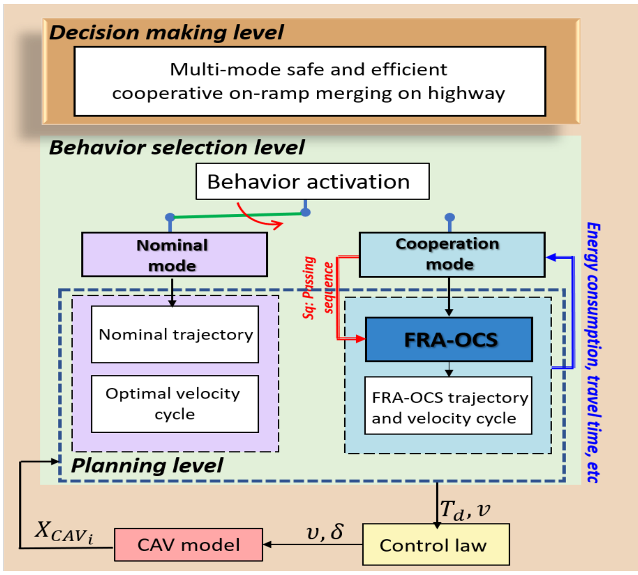


Fig. 1. Altruistic Formation Reconfiguration Strategy (AFRS) [2]

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.

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

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:

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

with $e = [e_{f_i}^T, ..., e_{f_N}^T]^T$ 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 $S = \dot{e} + \lambda e$, the FRA-OCS enables a smooth and controlled transition of the formation towards its desired shape.

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 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. (3).

$$\dot{S} = A \times S = A\dot{e} + A\lambda e \tag{3}$$

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

Using eq. (2) in eq. (3) permits to write the matrix form of the studied system in eq. (4)

$$\begin{bmatrix} \dot{S}_{h_1} \\ \dot{S}_{l_1} \\ \vdots \\ \dot{S}_{h_N} \\ \dot{S}_{l_N} \end{bmatrix} = \Omega_1 \begin{bmatrix} \dot{e}_{h_1} \\ \dot{e}_{l_1} \\ \vdots \\ \dot{e}_{h_N} \\ \dot{e}_{l_N} \end{bmatrix} + \Omega_2 \begin{bmatrix} e_{h_1} \\ e_{l_1} \\ \vdots \\ e_{h_N} \\ e_{l_N} \end{bmatrix} \tag{4}$$

with $\Omega_1 = diag[a_{h_1}, a_{l_1}, \cdots, a_{h_N}, a_{l_N}]$ and $\Omega_2 = diag[a_{h_1}\lambda_{h_1}, a_{l_1}\lambda_{l_1}, \cdots, a_{h_N}\lambda_{h_N}, a_{l_N}\lambda_{l_N}]$. 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' stability analysis is demonstrated in [2].

2) Online reconfiguration gains identification and velocity profile generation: One limitation of the formation reconfiguration based on the CORM is its dependence on an optimization process. Computation of reconfiguration gains through optimization can lack real-time capabilities, especially when dealing with a formation involving a large number of CAVs, which requires computing $2 \times N$ gains (considering decoupled longitudinal and lateral motion). In

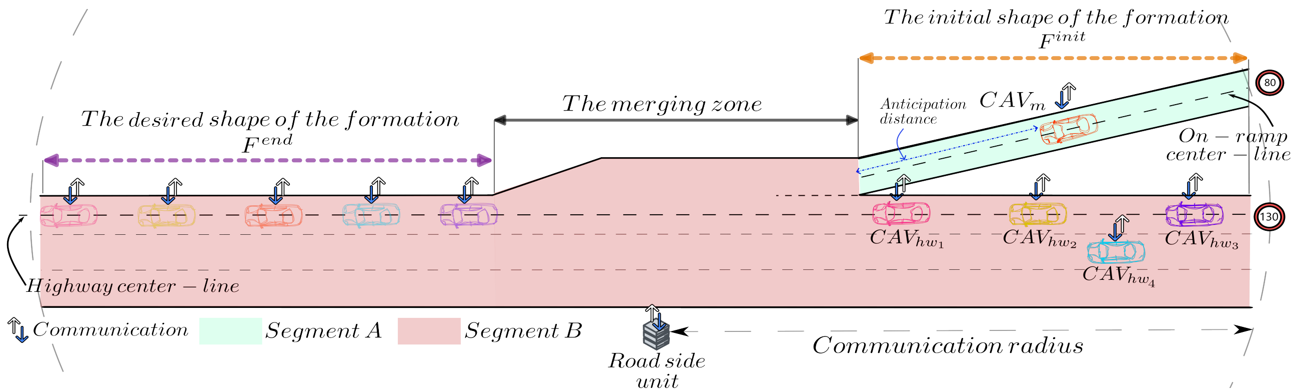


Fig. 2. Illustration of the on-ramp merging on highway scene. The initial shape of the formation of the CAVs under the communication range of the RSU is represented, along with the final desired shape. The Segment A representing the zone where the CAV behaves according to the longitudinal motion. In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

an on-road environment, it is crucial for the approach to have the ability to compute and recompute the reconfiguration gains as needed to ensure adherence to the safety criterion, particularly in a highly dynamic environment. Additionally, due to the dynamic nature of the considered scenario, the approach must guarantee the continuity of CAVs' dynamics during the transition from one configuration to another.

The proposed FRA-OCS in this paper addresses the limitations of the CORM, specifically in terms of real-time computation, by employing an optimization-free procedure to calculate the reconfiguration gains. Additionally, the FRA-OCS has the ability to recompute the convergence gains when necessary, ensuring continuity during the transition from one configuration to another under its formalism. This section outlines the procedure used to formulate the system of equations that must be solved to reconfigure the formation from its initial shape to the final one, while considering the initial and desired dynamics of the CAVs within the formation.

Using the state S in eq. (3), the convergence model of the formation reconfiguration error is a system of second order linear differential equations, given in eq. (5).

$$\begin{aligned} \ddot{e}_{h_1} + (\lambda_{h_1} - a_{h_1})\dot{e}_{h_1} - a_{h_1}\lambda_{h_1}e_{h_1} &= 0 \\ \ddot{e}_{l_1} + (\lambda_{l_1} - a_{l_1})\dot{e}_{l_1} - a_{l_1}\lambda_{l_1}e_{l_1} &= 0 \\ &\vdots \\ \ddot{e}_{h_N} + (\lambda_{h_N} - a_{h_N})\dot{e}_{h_N} - a_{h_N}\lambda_{h_N}e_{h_N} &= 0 \\ \ddot{e}_{l_N} + (\lambda_{l_N} - a_{l_N})\dot{e}_{l_N} - a_{l_N}\lambda_{l_N}e_{l_N} &= 0 \end{aligned} \tag{5}$$

The general solution $x(t)$ (representing the general form of e_i and its derivatives) of the system in eq. (5) can be written as:

$$x(t) = \alpha_1 e^{\beta_1 t} + \alpha_2 e^{\beta_2 t} \tag{6}$$

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. (7) 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. (6). 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.

$$\mathcal{V}(t) = K_1 e^{at} + K_2 e^{-\lambda t} + c \tag{7}$$

with a and λ being the roots of the differential equation in eq. (5). 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. (5) 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. (8). Consequently, t_{max} permits to dynamically adapt the acceleration dynamic of the CAVs w.r.t. the length of the anticipation zone.

$$\dot{\mathcal{V}}(t_{max}) = aK_1 e^{at_{max}} - \lambda K_2 e^{-\lambda t_{max}} = 0 \tag{8}$$

(b) The velocity profile generator in eq. (7) 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. (9) is introduced.

$$K_1 e^{at_f} + K_2 e^{-\lambda t_f} - K_1 - K_2 + \mathcal{V}^{init} - \mathcal{V}^{end} = 0 \tag{9}$$

(c) Based on eq. (7), the expression of the position $P(t)$ of the CAV can be written as in eq. (10).

$$P(t) = \frac{K_1}{a} e^{at} - \frac{K_2}{\lambda} e^{-\lambda t} + (\mathcal{V}^{init} - K_1 - K_2)t + d \tag{10}$$

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. (11) is proposed.

$$M(t) = P_{ref} - P(t) \tag{11}$$

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. (12) is used.

$$\begin{aligned}(\mathcal{V}_{ref} t_f + P_{ref_0}) - [\frac{K_1}{a} e^{a t_f} - \frac{K_2}{a} e^{-\lambda t_f} + \\ (\mathcal{V}_{min} - K_1 - K_2) t_f + P_0 - \frac{K_1}{a} + \frac{K_2}{\lambda}] - M_f = 0\end{aligned} \tag{12}$$

To solve equations (8), (9) and (12), 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 evaluate the effectiveness of the proposed FRA-OCS in ensuring safety and smooth dynamics during on-ramp merging on highways, two specific scenarios were simulated. The simulation results for these scenarios can be viewed at: https://shorturl.at/EIV89.

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

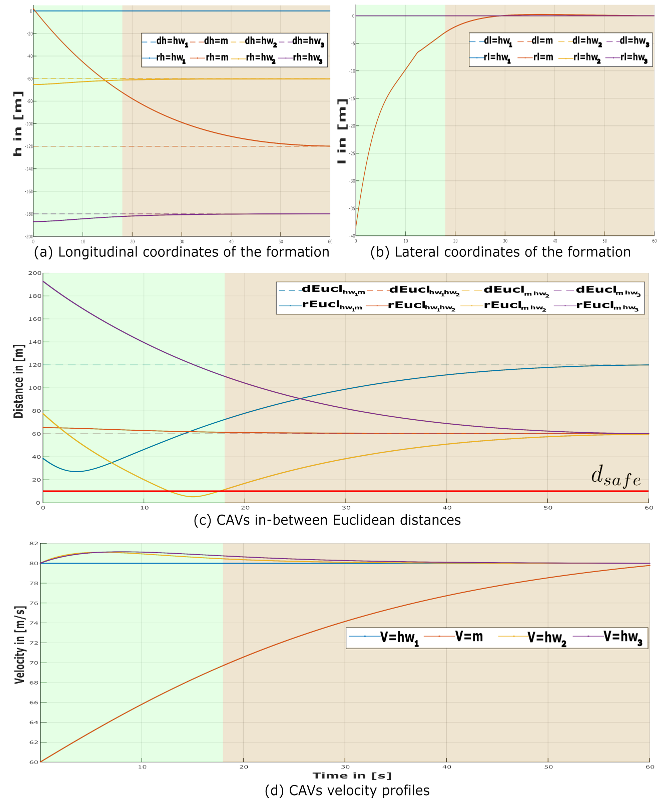
The following simulation aims to perform the reconfiguration of a formation composed of five CAVs (cf. Figure 2). The initial position of CAV$_m$ is configured to trigger the safety criterion during the merging maneuver under the nominal mode. With the help of the FRA-OCS, four potential passing sequences 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



(a) Longitudinal coordinates of the formation
(b) Lateral coordinates of the formation
(c) CAVs in-between Euclidean distances
(d) CAVs velocity profiles

Fig. 3. Scenario 1: simulation results

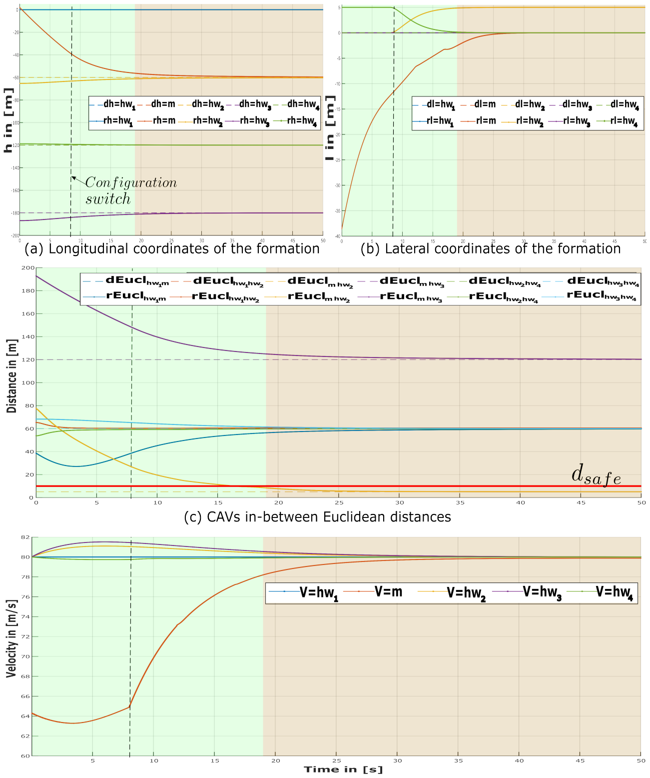
results when the merging CAVs is located in the segment A (cf. Figure 2, Segment A in green), while the red shaded part represents the results for the segment B (cf. Figure 2, Segment B in red).

Figure 3 displays the longitudinal and lateral formation coordinates in (a) and (b), respectively. To ensure appropriate longitudinal separation between the CAVs in the desired formation shape, an inter-vehicle distance of approximately $2[s] \times \mathcal{V}[m/s]$ is maintained. The formation's inter-vehicular Euclidean distances are shown in (c). Notably, the positioning of CAV_{hw_2} before CAV_m as determined by the sq leads to their inter-vehicular Euclidean distance exceeding the safety threshold d_{safe} while CAV_m is still within segment A, without any risk of collision. The CAVs' velocity profiles are displayed in (d), adhering to 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 second scenario aims to assess the FRA-OCS's responsiveness to on-road environment dynamics. Initially, a formation reconfiguration with five CAVs is considered, similar to the previous scenario. However, at $t = 8s$, a fifth CAV decides to join the formation, rendering the initial sq (cf. Section V-A) unsafe. The coordination mode recalculates a suitable sq to ensure safety, considering four passing sequences. Table II presents the numerical results of the two best sq.

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.



(a) Longitudinal coordinates of the formation (b) Lateral coordinates of the formation

(c) CAVs in-between Euclidean distances

(d) CAVs velocity profiles

Fig. 4. Scenario 2: simulation results

TABLE II

SCENARIO 2: NUMERICAL RESULTS OF THE COOPERATION MODE

sq	$V_{hw_1}, V_{hw_2}, V_m, V_{hw_4}, V_{hw_3}$					$V_{hw_1}, V_{hw2_{1\to2}}, V_m, V_{hw_4}, V_{hw_3}$				
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 inclusion of the fifth CAV at $t = 8s$ prompted a swift reconfiguration of the FRA-OCS, resulting in a configuration switch at the same time (cf. Figure 4, (a) and (b)). The FRA-OCS formally ensures the continuity of the reconfiguration process. Figure 4(c) displays the Euclidean distances between the CAVs. The selected sq places CAV_{hw_2} and CAV_m at the same longitudinal coordinates but in different lanes, ensuring that all in-between distances in segments A and B are greater than d_{safe}. The velocity profiles of the CAVs are depicted in Figure 4(d). During the configuration switch at $t = 8s$, the velocity generator part of the FRA-OCS ensures the continuity of the velocity profiles.

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 implementing the proposed strategy on real vehicles.

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