Fuzzy logic based decision-making for urban platooning on urban roundabout scenarios

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Abstract. This paper proposes a fuzzy-based decision-making framework for urban platooning in roundabout scenarios. By utilizing fuzzy logic to handle uncertainties and imprecise inputs, the framework adapts the behavior of platoon vehicles based on real-time traffic conditions, vehicle dynamics, and safety considerations. In addition, a MPC-based platoon following controller is proposed to execute the actions defined by the decision-making approach. This approach is tested in Carla simulator with successful results, proving the proposal is feasible for platoon handling in urban roundabouts.

Keywords: Urban Platooning, Roundabouts, decision-making, control

1 Introduction

Connected and Cooperative Automated Mobility (CCAM) functionalities are improving transportation efficiency, comfort, and safety in the driving process. Some studies show that parking, traffic control, and Limited Traffic Zones in urban areas can improve the transition to fossil-free transport and reduce personal vehicle usage [2]. However, other concepts such as shared vehicles, electrification, and connected and automated platooning, among others, are becoming more common nowadays.

In recent years, roundabouts have largely replaced traditional intersections in urban environments because they facilitate smoother merging and navigation, reduce congestion, and improve traffic flow. However, even today, driving on roundabouts, especially in platooning and merging situations, requires special attention. [3] analyzes how connected and automated vehicles can cooperatively drive to reduce energy consumption and improve traffic flow during lane reduction, using a model-free deep reinforcement learning approach, improving comfort and acceptance of automated vehicle platooning. Some studies in China, such as the one by Chen et al. [4], show how the cognitive spatial-time environment modeling approach can solve the trajectory planning problem for automated vehicles in very dense traffic.

In the literature, most of the approaches to solving the platooning and merging problems with dense traffic are focused on highways. Han et al. propose a comprehensive multi-lane platooning algorithm with organized behavior via a hierarchical framework [5]. For the Decision-Making for Cooperative Vehicle Platooning, they adopt cooperative automated driving systems (C-ADS) framework for planning and control that incorporates both strategic and tactical levels to cope with complex multi-lane highway challenges. In [6], the characteristics of mixed traffic composed of human-driven vehicles (HDVs) and connected and autonomous vehicles (CAVs) in adverse weather conditions such as dense fog are evaluated with game theory (GT) to lane-changing policies in simulations.

Vehicle-to-vehicle (V2V) communication is one of the key aspects of cooperative vehicles. In [7], a control architecture for vehicle grouping and using V2V communication to ensure safe merging between vehicles from two platoons was presented. The goal was to avoid collisions with obstacles in optimum conditions when roads are crowded. Other works show cooperative services for Decision-Making with V2X techniques with CAVs and using visual horizon of perception [8]. An extensive review of Vehicle Platoon Merging and Splitting was recently published in [9], however, without any mention of roundabouts.

From a control perspective, Model Predictive Control (MPC) for heterogeneous platoons has been widely used in the literature. For example, [10] proposed a distributed MPC algorithm to solve the cruise control problem of a heterogeneous platoon with good results. [11] showed control for automated vehicles in platoons with a nonlinear MPC approach for coupled dynamics to solve the platoon constraints.

For the particular case of roundabouts, different approaches have been proposed, in which MPC-based control approaches also have presence [12]. However, other authors, such as [13], have proposed a lane-changing strategy for vehicles at the exit of a roundabout based on the Vehicle Profile (VP) in a traffic roundabout. This solution optimizes vehicle traffic and alleviates traffic congestion based on the collaborative strategy of vehicle-road-environment. Considering the nonlinear dynamics of vehicles in roundabouts and the need to impose safety constraints has also been analyzed in [14], in which lateral control schemes based on the concepts of Control Lyapunov Functions (CLFs) to enforce stability and High Order Control Barrier Functions (HOCBFs) have been proposed. In [15] the authors apply a game theoretic decision making in which they consider the several risk and comfort factors along a prediction horizon. They use the concept of the opposing vehicle for referring the vehicle inside the roundabout. However, one of the main concerns with the game theoretic is that the opposing actors are supposed to follow a certain set of rules. Therefore, losing generality. Recent works show also propose approaches to define the speed profiles for efficient merging with traffic in roundabouts [16].

Hence, in the literature, it can be seen that the traffic problem related to driving a platoon through a roundabout in urban environment has been analyzed within separate perspectives, considering control, trajectory planning or platooning approaches. However, there is still a gap related to the decision-making related to the management of roundabouts in urban environments. This work aims to provide insight into this field, by proposing a Decision Making framework that considers the scenario in which a platoon is split when driving through the roundabout to merge with the incoming traffic, and then merges again with the platoon members.

The rest of the paper is organized as follows. In section 2 a more in-depth description of the urban traffic problem is given so the reader can fully understand the motivation of this work. In section 3 the design details of both the Decision Making framework for roundabouts and the used platooning controller are provided. In section 4 the scenario where the Decision Making and control algorithms have been tested is explained in detail and the results of the simulations are presented in section 5. Finally, insight into the proposed methodology as well as some conclusions are discussed in section 6.

2 Urban traffic problem

Urban scenarios are extremely complex environments that require drivers to make numerous decisions due to the vast number of external agents surrounding the controlled vehicle and their potential interactions. This complexity is particularly evident in urban roundabouts, where traffic is constantly flowing and vehicles are constantly merging and intersecting.

The motivation behind this work is to develop a decision-making framework that enables a platoon of automated vehicles to safely navigate a roundabout in urban environments that are characterized by high levels of traffic. To this end, the proposed problem is depicted schematically in Figure 1. As the platoon approaches the roundabout, each member must make a decision about whether to merge with existing traffic and continue on its predefined trajectory or to stop in order to avoid a collision.

In addition, if traffic is dense, it may be impossible for the entire platoon to enter the roundabout as a single unit. In this scenario, the platoon must be split up, with each member navigating the roundabout on its own before merging back together on the other side. This requires introducing new strategies in the followers.

It should be noted that in this problem, the platoon leader is driven by a human, while the following vehicles are automated. This particular case is focused on Car-Sharing fleet repositioning scenarios, which are becoming increasingly important as more and more people turn to car-sharing services as a means of transportation. By developing a robust decision-making framework for automated platoons in urban environments, we can help to ensure that these services are safe, efficient, and accessible to everyone.

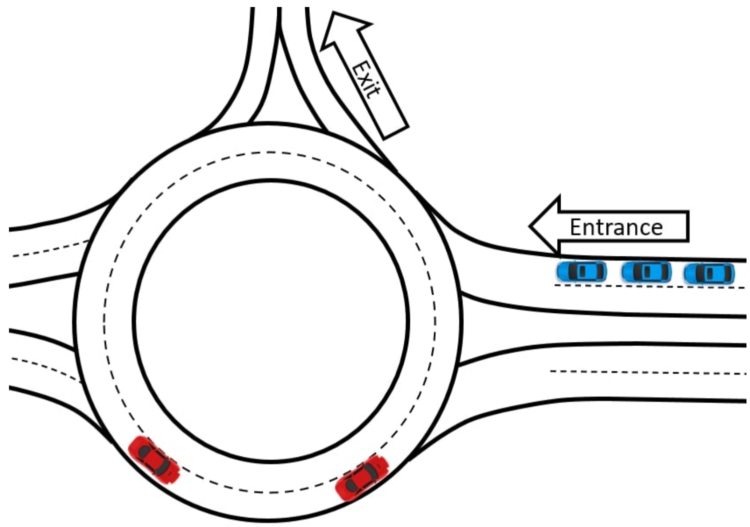

Fig. 1. Proposed urban traffic problem (platoon in blue and independent vehicles in red)

3 Decision Making Framework and Control

In the urban traffic problem proposed in Section 2 , each vehicle in the platoon has to evaluate the required space needed to enter the roundabout and continue its trajectory, ensuring safety while maintaining the traffic flow.

In order to develop an approach for platooning in the aforementioned scenario, in this work the decision architecture developed in [1] will be taken as starting point. In this work, a Finite State Machine (FSM) is proposed to implement the global behavioural planner of each follower in an urban platoon. As it can be seen in Figure 2, the FSM is composed by 5 states: 1) a waiting state, in which the follower vehicle is parked and stopped; 2) a de-parking state, in which the vehicle de-parks in order to join the platoon; 3) a joining state, in which the vehicle is integrated into the platoon; 4) platoon following, in which the vehicle follows the platoon leader trajectory; and 5) a parking state, in which the vehicle disconnects from the platoon to park. Each of the follower vehicles in a platoon can be in one of the aforementioned states at a time, and each state presents its own trajectory generation and control strategies [1].

Hence, in order to consider the roundabout problem into the aforementioned decision architecture, the platoon following and joining states have to be adapted. The next subsections detail the approaches proposed for this purpose.

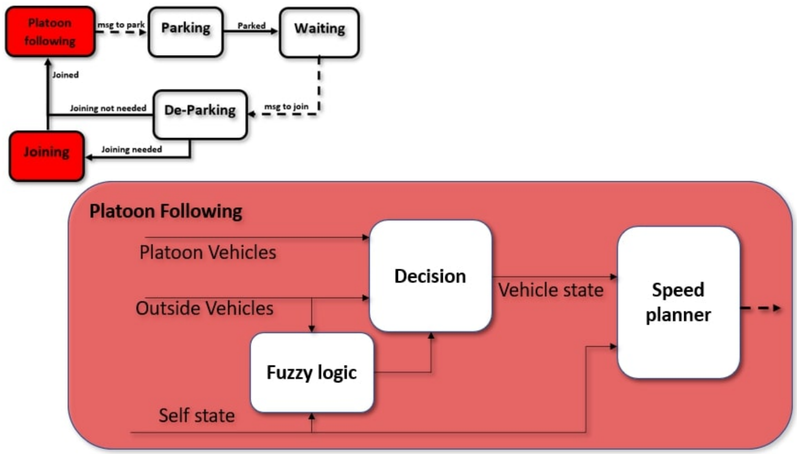

Fig. 2. High level FSM with detailed decision process inside platoon following speed planner. Platoon Vehicles represents the state of the vehicles inside the platoon while outside vehicles represent the state information of the vehicles that are not following the platoon.

3.1 Fuzzy logic Decision Making

Once a follower vehicle in a platoon arrives at a roundabout in which other vehicles may be present, the first step is to define whether the vehicle enters the roundabout and follows the platoon leader or if it stops and waits until safety is ensured. In this work an intuitive Fuzzy Logic approach has been implemented into the decision making algorithm to perform this task (2).

The selection of the variables considered by the Decision Making algorithm has been carried out by considering human reasoning when it comes to make this same decision. Hence, distance to the opposed vehicle, self speed and opposed vehicle speed are used as inputs variables. The following fuzzy sets have been defined for the aforementioned variables:

- Distance to the opposed vehicle, calculated as the euclidean distance to the opposed vehicle: Very close (VC), Close (C), Far away (FA), Very far away (VFA)
- Speed of the controlled vehicle/ Speed of the opposed vehicle: Slow(S), Medimum (M), Fast (F)

Finally, the output of the fuzzy logic algorithm is defined by an action variable. It can get two possible values that have been separated in trapezoidal fuzzy sets: Follow opposing vehicle (FOV) and Stay in platoon (SIP).

Once the result is retrieved it must be interpreted, or deffuzyfied, transforming the float value into a boolean.

The set of rules have been selected so they are consistent with the decisions a human driver would take in this exact scenario. In Table 1 these are represented using the pre-established acronyms of each fuzzy set.

Distance	**VC**		
Oposed / **Controlled**	**S**	**M**	**F**
S	FOV	FOV	FOV
M	FOV	FOV	FOV
F	FOV	FOV	FOV

Distance	**C**		
Oposed / **Controlled**	**S**	**M**	**F**
S	FOV	FOV	SIP
M	FOV	FOV	SIP
F	SIP	SIP	SIP

Distance	**FA**		
Oposed / **Controlled**	**S**	**M**	**F**
S	SIP	SIP	SIP
M	SIP	SIP	SIP
F	SIP	SIP	SIP

Distance	**VFA**		
Oposed / **Controlled**	**S**	**M**	**F**
S	SIP	SIP	SIP
M	SIP	SIP	SIP
F	SIP	SIP	SIP

Table 1. Rules of the fuzzy logic

3.2 MPC-based platoon following controller

In order to control the behaviour of the platoon in the roundabout, a Cooperative Adaptive Cruise Control (CACC) has been designed in combination with an MPC-based lateral control that ensures that the follower is within its lane and follows the platoon trajectory.

The CACC system is implemented using a MPC based controller for the longitudinal control of the followers in the platoon. The use of predictive control allows a better interaction between the platoon and the vehicles in the roundabout. For this purpose, the longitudinal control is carried out considering the distance with the preceding vehicle. In the case of the roundabout, the preceding vehicle can be either the precedent platoon follower (or the leader), or the opposing vehicle that is inside the platoon. This will depend in the decision taken by the Fuzzy Logic Decision System detailed in the previous subsection.

The goal of the CACC approach is to maintain a constant distance to the preceding vehicle in order to ensure that no collisions exist and ensure the so called string stability when multiple vehicles exist. For this purpose, the MPC considers not only the dynamics of the ego vehicle, but also the speed of the preceding vehicle and the distance between them and the speed of the leader vehicle. The CACC output is the instantaneous optimal reference speed of the follower vehicle, which will be then be applied using a low level speed controller.

To be able to optimize the value of the follower's speed, the MPC requires a model of the ego, precedent and leader vehicles. As the study case analyzed in this work is an urban scenario with low speeds, a simplified longitudinal kinematic model approach has been selected to predict the relative distance behaviour of the considered vehicles, considering them as punctual masses with certain speeds. Hence, the model depicted in Eq. 1 is used for MPC implementation,

$$\begin{aligned} \dot{x}_{rleader} &= v_{leader} - v \\ \dot{x}_{rfront} &= v_{front} - v \end{aligned} \tag{1}$$

where v is the speed of the ego vehicle and v_{front} and v_{leader} are the speeds of the precedent vehicle and the leader, respectively. x_{rfront} and $x_{rleader}$, however, are the relative distances between the ego vehicle and both the precedent vehicle and the leader, respectively. These will be the controlled variables.

Hence, the CACC control law,

$$\begin{gathered} v^{+} min J(x_{rleader}, x_{rfront}, v) \\ s.t \\ v \in (0, v_{max}) \\ x_{rleader} > x_{rleadermin} \\ x_{rfront} > x_{rfrontmin} \end{gathered} \tag{2}$$

where v_{max} is the maximum admissible speed of the follower, $x_{rleadermin}$ and $x_{rfrontmin}$ are the minimum admissible distances to the precedent and leader vehicles, respectively. The output of the minimization problem is the speed of the vehicle v, which will be calculated to optimize the cost function,

$$J = (\hat{\mathbf{x_r}} - \mathbf{x_{ref}})^T \ \mathbf{Q} \ (\hat{\mathbf{x_r}} - \mathbf{x_{ref}}) + \mathbf{v^{+}}^T \mathbf{R} \, \mathbf{v^{+}} \tag{3}$$

where $\hat{\mathbf{x_r}}$ and $\mathbf{v}^{+}$ are the predicted distances and optimal speed calculated for the desired prediction horizon h, while $\mathbf{Q}$ and $\mathbf{R}$ are the weighting matrices used to tune the controller.

For the proposed scenario, it has been decided to use a higher **R** factor, specifically 30, so the controller doesn't present too much error. Nevertheless, the value of the **R** factor is not much larger than **Q**, which has been set at 20, as the control action would be too aggressive and thus it would generate higher accelerations for follower vehicles.

In addition, the upper limit of the vehicle speed has been set at the merging speed, i.e., $36 km/h$, while, with respect of the minimum relative distances, lower constraints have been set at $7m$ and $7n\,m$, where n is the relative position of the follower vehicle in the platoon. These are the minimum distances wanted between the follower and both the vehicle in front and the leader of the platoon, respectively.

4 Simulation based implementation

In order to test the validity of the control architecture in the proposed traffic problem a specific scenario has been designed using Carla Simulator. This simulator uses Unreal Engine 4 to create 3D scenarios combined with simulated sensors in order to create a realistic environment. It got its first release in 2017, and since then, it has attracted the attention of the investigation community. Through projects like [17], where a Deep Learning based car following model is tested, it can be seen that the implemented vehicle dynamics are well considered. Meanwhile projects like [18], where Carla simulator is used in to study the driver behavior during a take-over maneuver proves the relevance of its graphic design in the state-of-the-art perception studies.

The testing has been performed in a standard four way roundabout with two lanes as depicted in Figure 3. A three vehicle platoon is considered as a study case, which will try to drive through this roundabout. However, two vehicles follow a predefined route within the roundabout at a constant velocity of $8m/s$. These are considered to be external agents that are going to interrupt the platoon following maneuver, i.e., the opposing vehicles. Therefore, their speed and positions have been synchronized with the platoon in order to ensure that they interrupt the platoon. This way, one vehicle will make the platoon split between the leader and the first follower and the other will do the same between the two followers.

Fig. 3. Testing roundabout

The information needed for the car following between the followers and the vehicles inside the roundabout is supposed to be available for the use case for simplicity purposes, although the cohesive assumption regarding the work in [1] would be to use a vehicle to infrastructure (V2I) communication solution.

The goal of the simulation is to test the functionality of the new subsystems implemented in the state machine by forcing a platoon split in several points. The followers should be able to catch up with the platoon leader and maintain a safe distance.

For this particular scenario the proposed fuzzy decision making approach is implemented with triangular membership functions, as they are computationally less expensive than other alternatives, like Gaussian or Sigmoid functions. In this regard, the fuzzy values have been tuned empirically, having started from a somewhat rational guess for the membership functions (table 4. The maximum speed of the leader of the platoon has been set to $10m/s$, therefore, from $0m/s$ to $5m/s$ (half of the platoon speed) is considered L speed. The actual platoon speed is set within the boundaries of the N speed, which are $4m/s$ to $12m/s$. Values higher than that and up to 50m/s are considered H speed values and the follower vehicles should only reach this state when trying to reunite with the platoon leader.

Distances in this application are harder to define. Since the euclidean distance is used, its relation with the velocities is complex to reproduce mathematically. The VC distance membership is almost the equivalent of the distance travelled by a vehicle at Low speed in 1s. This same reasoning is applied for the C and FA distances with M and H speeds. Values bigger than $35m$ are considered VFA.

Distance	**Begin**	**Top**	**End**
VC	0	4	8
C	7	9	13
FA	13	22	35
VFA	33	100	200

Speed	**Begin**	**Top**	**End**
L	0	2	5
M	4	8	12
H	11	30	50

5 Results and Discussions

The results of the maneuver are split in 4 steps (Figure 4), so the action of the fuzzy logic Decision Making algorithm can be well interpreted and understood. The follower vehicles start the simulation parked and are picked up one by one once the last vehicle of the platoon drives near them.

When arriving to the roundabout (Step 1) the first follower is at 10 meters of the leader, while the second follower has not reached a steady state distance with the leader, thus, the small distance variation in Figure 4. In the same figure it can be seen that the relative distance of the first opposing vehicle, whose relative distance to the follower is depicted in Figure 4, reduces as it approaches through the roundabout. The decision system implemented for follower 1 then establishes that it should wait for the opposing vehicle to drive through the roundabout, and then start following it instead of the platoon leader. The flag related to this change in the decision making system is depicted by the green signal having the value 0 (following the leader) to 1 (following the opposing vehicle), at second 8.95.

After splitting from the leader and having decided to wait for the opposing vehicle (Step 2), the first follower waits until the distance to the opposing vehicle is big enough to enter the roundabout. In this case a fixed distance of 10 meters has been established. Since both followers are not moving during this step the relative distance between them does not grow either, as can be seen in the Follower 2 platoon distance depicted in Figure 4 Step 2. On the other hand, it is

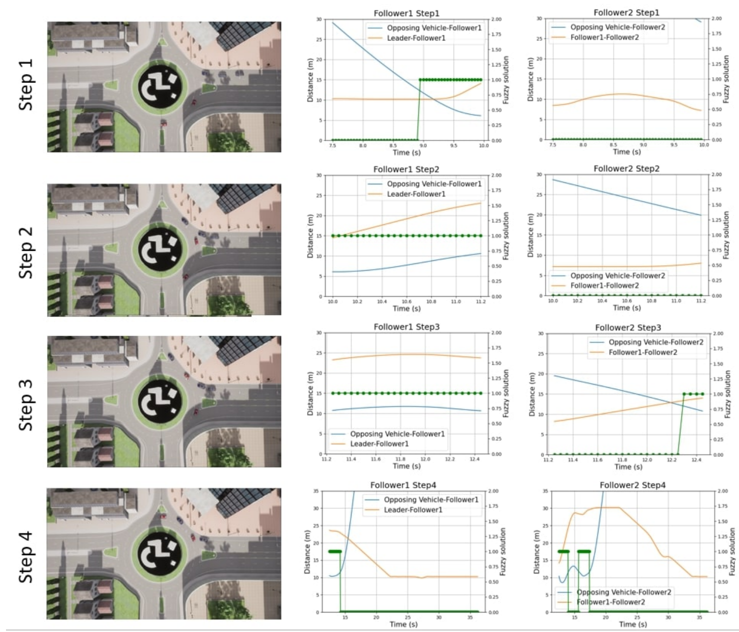

Fig. 4. Results of the simulation divided in 4 steps. In green the output of the decision system is depicted.

seen that the relative distance of the leader with respect to follower 1 increases, as the leader drives though the roundabout.

Once the reference safety distance with the opposing vehicle is achieved, the developed longitudinal controller tries to keep the first follower at this distance during Step 3. Hence, during this step, Follower 1 enters the roundabout and follows the opposing vehicle that is in front of it. The second follower, on the other hand, evaluates the relative distance of the next opposing vehicle, and even if it starts to move through the roundabout, the Decision Making system establishes that in order to ensure safety, it should stop and wait to the second opposing vehicle to drive through the roundabout. This is seen at second 12.3 in Figure 4 Step 3.

Figure 4 Step 4 shows the development of the inner distances of the platoon until they reach an stabilization point, hence, the moment they reach the platoon distance. For the first follower it is possible to see it starts to exit the roundabout on second 14, as the opposing vehicle continues driving in the roundabout, but the leader trajectory exits it. At this point, the decision making system changes the distance reference to the platoon leader, and Follower 1 proceeds to increaset its speed to join the platoon leader and maintain a constant distance of 10 meters. The second follower follows a similar procedure, 3 seconds later, as the opposing vehicle continues through the roundabout and the decision making indicates to follow the relative distance to Follower 1. At second 34 the platoon is again merged.

Note that the maximum speed of the vehicles is limited to the maximum speed of vehicles on urban traffic scenarios using the restrictions of the MPC controller explained in section 3.2.

6 Conclusion

In this work the problem of a platoon splitting due to a roundabout is tackled using Carla simulator as a simulation environment. For this a fuzzy logic based Decision Making model is proposed in which three inputs are provided: The velocity of the controlled vehicle, the velocity of an opposed vehicle and the distance to that opposed vehicle. This process is repeated for every vehicle in the roundabout and an action value choose whether to use the platoon predecessor or the vehicle in the roundabout as following reference. This algorithm has been tested with a three vehicle platoon and two vehicles inside the roundabout.

The proposed Decision Making method proves to be fit for the situation where the obstacles drive at a constant speed of $8m/s$ since there is no collision inside the roundabout. However it is still dependent of the controller vehicles knowing the relative distance to the obstacles and their velocity. Therefore, they need either an embedded perception system or a communication with a unit that can provide that information.

Future work will be focused on integrating more interaction with the urban environment to the framework proposed in the work [1]; such as, traffic light and pedestrian interaction as well as a local planning for obstacle avoidance inside the platoon.

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