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Safe and Adaptive Roundabout Insertion for Autonomous Vehicle based Limit-cycle and Predicted Inter-Distance Profiles

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Abstract— **Roundabouts are a prevalent form of road infrastructure that effectively control traffic flow and significantly decrease the occurrence of accidents in contrast to traditional intersections. This paper, based on the Multi-Risk Assessment and Management Control Strategy (MRAM-CS) [1] aims to enhance this architecture by considering the obstacle behavior. The MRAM-CS allows autonomous vehicles (called Ego-Vehicles (EVs) in what follows) to determine whether to accelerate or decelerate at the arrival of the roundabout and to enter by applying an appropriate speed profile, determined online, which allows to respect appropriate distances with the vehicles circulating in the roundabout. This is done by using the Predictive Inter-Distance Profile metric (PIDP) and the dynamic progress of the minimum value of PIDP (mPIDP). The proposed control is based on Fuzzy-PID controller, allowing to update the PID gains according to Fuzzy Inference System (FIS) and the behavior feature (calm, aggressive or dangerous) of the other vehicles. Several simulations are performed to demonstrate the reliability and the safety of the proposed approach.**

I. INTRODUCTION

Roundabouts have emerged as the predominant form of intersection, with approximately 30,000 currently in use throughout France, effectively replacing traditional intersections. The main advantage of this type of road infrastructure is its ability to facilitate uninterrupted traffic flow while also significantly reducing the number of accidents by 50 to 70% [2]. This is accomplished by slowing down the speed of vehicles as they navigate in the intersection. Unlike intersections with traffic lights, the EV does not have a light indicator that allows to give permission to insert the roundabout or not. In the case of a roundabout, the EV must take the decision to make an insertion while taking into account its actual ability to engage and maintain a safe distance with other vehicles already in the roundabout whose have the priority. Some works deal with communication between vehicles in order to optimize the trajectories to fit in a roundabout using a Cooperative Adaptive Cruise Control (CACC) that allows to adapt a speed profile to maintain safety distances while saving the fuel or energy consumption [3], [4]. The communication vehicle-to-infrastructure is also proposed in order to have more details about the vehicles circulating in the roundabout and to have a more precise information about the position of obstacles which would be redundant with the EV's perception [5].

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To ensure the safety of navigating vehicles in roundabouts, a number of works have concentrated their efforts on developing a Model Predictive Control (MPC) systems that incorporate various contemporary techniques and methodologies. The authors in [6] propose the development of an MPC approach that includes an analytical calculation of travel time and speed control for EVs. This approach offers the advantage of determining the optimal travel time and promoting collision-free passage through a single-lane roundabout. In [7] an MPC is designed to ensure path tracking in a single lane roundabout. In [8] a Neural-MPC system is suggested for managing a multi-lane roundabout, generating static paths in real-time that align with the road topology. According to literature, roundabouts can be divided into distinct sections, which include the Decision Zone where the EV does not hold priority and must assess the feasibility of a safe insertion. The Transition Zone facilitates access to the Ring Zone, which is followed by the Exit Zone that permits the EV to exit the roundabout [9], [10]. Various methods are employed to establish a path through the identified areas. Among them, one can observe techniques that rely on Bézier curves [11] or clothoids [10], [12]. In the proposed paper, the overall path required to navigate through the roundabout and that respects the code and the structure of the road (i.e., the optimal path without considering the obstacles vehicles) is known by the EV [1].

In this paper, an improvement of the MRAM-CS [1] architecture is proposed with the treatment of an insertion on a two-lane roundabout. This global insertion process allows the generation of an adaptive speed profile that enables safe navigation through a roundabout while considering the obstacles behaviors (e.g., calm, aggressive or dangerous). This is achieved by using a Fuzzy-PID controller where the PID parameters and the safety distance are determined according to the obstacle behavior (the safety distance was a fixed value for all encountered obstacles in the previous work [1]). This paper is structured as follows. Section II presents the method to determine the behavior that must be adopted by the EV in order to maintain a safety distance with the Obstacle Vehicle (OV) navigating inside the roundabout. Section III presents the solution to determine speed profile that respects the safety distances with obstacles circulating in the roundabout. The simulation results will be presented in section IV and a conclusion and some prospects are given finally in section V.

II. INSERTION ON ROUNDABOUT

The proposed strategy for a roundabout insertion is based on a pre-planned path and a method to determine the behavior of the EV to ensure that he respects the safe distances with the obstacles circulating on the roundabout. The following subsection (cf. section II-A) introduces the method used to create the appropriate path to follow. This is not the aim of this paper but this is needed to apply constraints on the EV's speed and to have self-contained paper. The second subsection (cf. section II-B) explains the method to define the behavior of the EV that should be adopted while considering its actual actuation capacity (its maximum velocity and acceleration).

A. Path planning based on Limit-cycles

To create a path for entering a roundabout, an Elliptic Limit-Cycle (ELC) trajectory is generated, which is formed by an elliptic periodic orbit that corresponds to an ellipse of influence. Previous works [13] have demonstrated that this ellipse of influence can be created around an obstacle to navigate safely around it, while in another study [14], an ellipse of influence around the OV was used to overtake it. In this paper, this approach is utilized to generate a path for entering the roundabout [1]. The corresponding equations for creating the ellipse of influence are defined as follows:

$$\begin{cases} \dot{x_s} &= m y_s + \mu x_s(1 - x_s/a_{lc}^2 - y_s^2/b_{lc}^2 + c x_s y_s) \\ \dot{y_s} &= -m x_s + \mu y_s(1 - x_s/a_{lc}^2 - y_s^2/b_{lc}^2 + c x_s y_s) \end{cases} \quad (1)$$

with $m = \pm 1$ according to the direction of avoidance (clockwise or counter clockwise). (x_s, y_s) corresponds to the center of the roundabout, a_{lc} and b_{lc} characterize the major and minor elliptic semi-axes respectively. In case of a roundabout, $a_{lc} = b_{lc}$. The value of c determines the orientation of the ellipse, but it is not applicable in the case of a circle. On the other hand, μ is a positive constant that can be adjusted to regulate the speed of convergence of the ELC trajectory towards the ellipse of influence. This last term allows to fit the curve entry and minimize the curvature according to the roadsides (cf. Figure 1). Once the intended exit of the EV has been determined, it is necessary to choose between the internal or external lane to reach the destination, based on the applicable road rules.

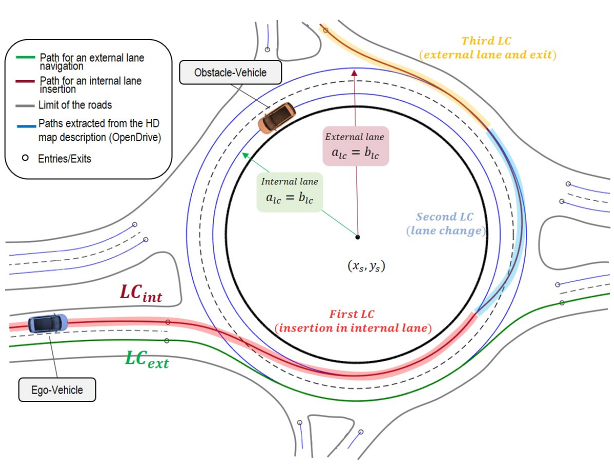

Fig. 1. Define a Limit-Cycle (LC) trajectory considering structure and the code of the road.

Bezier curves and clothoids were utilized in [9] and [10], respectively, to address the issue of achieving comfortable roundabout insertion. The selection of Limit-Cycle (LC) method for defining trajectories on a roundabout was motivated by the ability of these LC methods to generate smooth and highly adaptable trajectories for the various phases of the roundabout, namely entrance, ring zone, and exit. Although path planning was not the primary focus of the paper, and was unrelated to the proposed technique for determining the speed profile, it is essential to monitor the evolution of the curvature to ensure passenger comfort by regulating speed in response to trajectory curvature. This aspect will be explored in further detail as part of the proposed comprehensive approach's future development. However, the strategy used in order to cross a roundabout in the different identified areas (cf. Figure 1), is presented.

B. Definition of the required behavior

The behavior of the EV, when entering a roundabout, must take into account obstacles those already circulate inside. In this paper, the EV's path is already defined (cf. section II-A) and it is supposed that the obstacle keeps his lane during the scenario. A collision is based on circles as buffers (cf. Figure 2) [15]. All obstacles are represented by only one circle, whereas the EV is represented by two. This is justified by the fact that it is important to know, for the behavior that must be adopted by the EV, whether the possible collision took place at the front of the vehicle or at its rear.

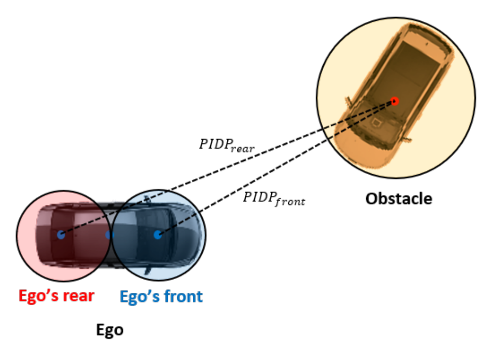

Fig. 2. Circles used as buffers to prevent collisions. The EV includes two buffers, one for the front and another for the rear.

Before explaining the proposed approach for determining whether the EV should accelerate or decelerate, let us define a metric that has been addressed in previous works [1], [16], [17]. This metric, named Predicted Inter-Distance Profile (PIDP), is used in the cited papers to assess and perform overtaking maneuvers on highways, represents the evolution of distance between two vehicles (EV and the considered obstacle). By knowing the path and dynamics

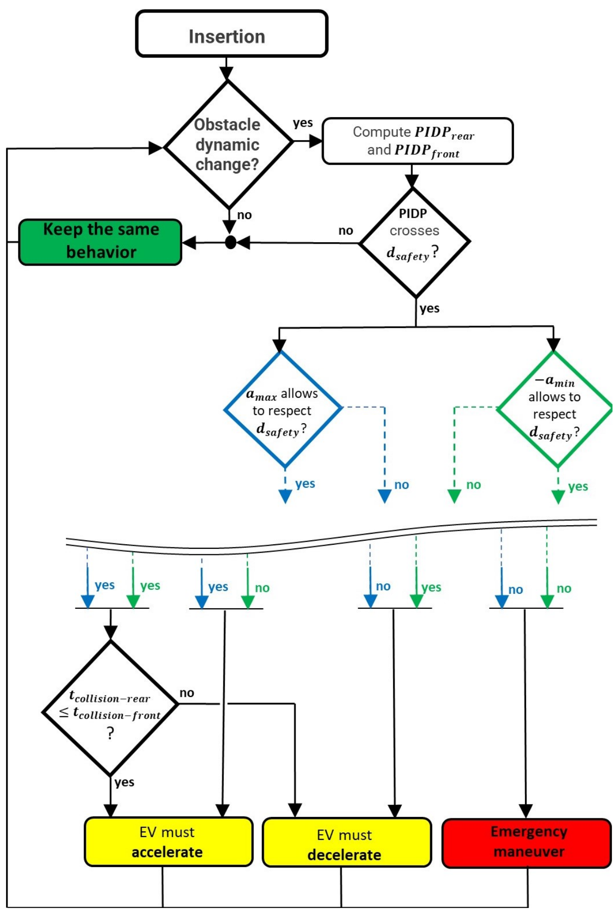

Fig. 3. Organizational chart which represents the method to define if the EV must accelerate or decelerate considering its actual capacity.

of both vehicles, and if these ones remain unchanged, it is possible to predict the evolution of the inter-distance between them (obviously, if a change is detected /identified in the dynamic of the vehicles this metric could be recomputed). As shown in Figure 4, both $PIDP_{rear}$ and $PIDP_{front}$ are represented. d_{safety} is the distance at which the Safety is Non Respected (SNR) and also takes into account buffer zones (cf. Figure 2) of each vehicle. According to Figure 4, $PIDP_{rear}$ cross d_{safety} before $PIDP_{front}$. This crossing point, t_{SNR}, is a time at which the safety is non respected if both vehicles keep the same path and dynamics. This figure provides information on the behavior that should be adopted. If $t_{SNR-rear} \leq t_{SNR-front}$, this means that the safety distance will not be respected on the front of the EV first and it must accelerate. If $t_{SNR-rear} > t_{SNR-front}$ means that the safety distance will not be respected on the rear of the EV first and it must decelerate. A judicious choice of the value of the safety distance d_{safety} will allow the EV to be more or less conservative according to the desired driving style and mainly the behavior of the other vehicles.

The organizational chart (cf. Figure 3) shows the proposed approach to define the EV's behavior. If a dynamic change from the OV is observed, $PIDP_{rear}$ and $PIDP_{front}$ are computed and the crossing between one of those and d_{safety}

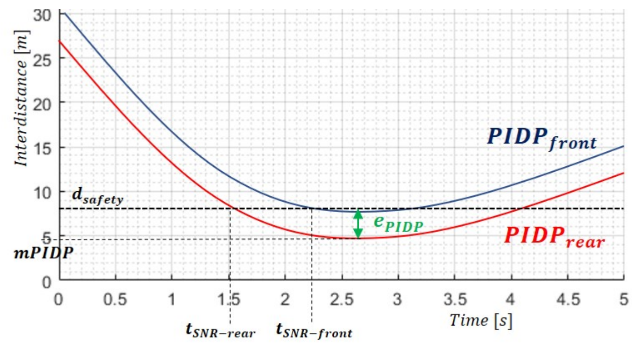

Fig. 4. Predictive Inter-Distance Profile (PIDP) for both parts of the EV.

is searched. Before to apply an acceleration or a deceleration, we need to ensure that the EV has the capacity to accelerate or decelerate. This can be determined by applying the maximum acceleration and deceleration that the EV can provide during the insertion. To define the position and the speed of each vehicle at each time step to the end of the maneuver, the length of both expected paths (for the EV and the other obstacle-vehicle) must be known. The path P_k is composed of several points p:

$$P_k \quad = \quad (p_k^1, p_k^2, p_k^3, ...p_k^n) \tag{2}$$

with p_k^n, the last point of the path maneuver and k can be for the EV or OV path. The length $l_k^{(i)}$ between two consecutive points is computed:

$$l_k^{(i)} \quad = \quad |p_k^{(i)} - p_k^{(i-1)}| \tag{3}$$

And the total length L_k of the path maneuver is the sum of all length $l_k^{(i)}$:

$$L_k = \sum_{i=1}^{n} l_k^{(i)} \tag{4}$$

To determine the future position of the EV on the path P_k, at each time step, the curvilinear abscissa S_{t+1} on the pre-planned path is computed as follow:

$$S_{t+1} \quad = \quad S_t + v_t \cdot t + \frac{1}{2} \cdot a_t \cdot t^2 \tag{5}$$

with v the speed of the considered vehicle and a its acceleration. The same equation is used for the OV and PIDP is computed. Two constraints are necessary to consider the EV's ability to accelerate and the comfort of the passengers:

- The acceleration limit a_{max} must be known and the actual acceleration must be considered to find out if the EV can apply this acceleration.
- The speed achieved consequently to the application of this acceleration limit must respect the lateral acceleration $a_{lat} = \frac{v^2}{r}$ where the curvature of the defined path is $r = \frac{1}{curvature}$ and v, the speed of the vehicle.

Another situation can appear when an acceleration or deceleration does not allow to respect the safety distance

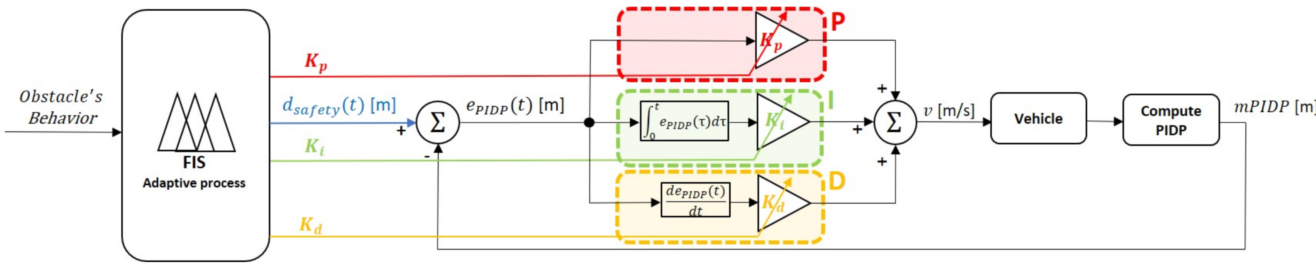

Fig. 5. Proposed longitudinal velocity control of the EV based on Fuzzy-PID structure.

with the OV during the insertion (cf. Figure 3). This situation called emergency maneuver needs to use an evasive maneuver algorithm [18], to avoid the collision. This situation is not treated in this paper.

III. Adaptive speed profile determination based on Fuzzy-PID Controller

The main aim of this paper is to apply an appropriate speed profile that allows the EV to respect the safety distance d_{safety} with the surrounding obstacle considering its behavior. This algorithm is based on the PIDP metric explained in section II and on the previous works [1]. The enhanced proposed control uses Fuzzy-PID controller, allowing to update the PID gains according to a Fuzzy Inference System (FIS) (cf. section III-A) and the behavior (calm, aggressive or dangerous) of the other vehicles (cf. section III-B) in order to adapt the safety distance according to the identified behavior of the obstacle.

A. Dynamic obstacles behaviors

A review on the different driving style is done in [19]. The authors consider three possible behaviors: *Steady* or *Calm*, *Aggressive* and *Dangerous*. A *Steady* or a *Calm* obstacle, in the proposed strategy, navigates at a constant speed or normal/slow speed (in accordance with traffic rules). An *Aggressive* obstacle navigates at high speed or accelerates/decelerates abruptly. Unlike a *Calm* obstacle, an *Aggressive* obstacle intentionally increases the risk of collision due to competitiveness or hostility. The third behavior retained for this paper, and the most dangerous for the EV, is a *Dangerous* obstacle defined by a chaotic behavior characterized by irregular speed profiles with excessive acceleration and/or deceleration. Remember that for the cases treated in this paper, the obstacle keeps its lane. So, a chaotic behavior is reported on the speed profile of the obstacle which is irregular and can include excessive acceleration and/or deceleration. The identification of the behavior of the obstacle is not the purpose of this paper, we consider that the obstacle has the pre-determined behavior. In other words, its speed profile corresponds to the behavior described above and it keeps its behavior during the scenario. It is common to represent the behavior of a vehicle by Fuzzy logic Inference System (FIS) because it allows to represent logic as a degree of truth instead of binary, like true or false.

In this paper, the dangerousness of the obstacle's behavior is between $[0, 1]$ like what is shown in Figure 6 and it is characterized by membership functions defined by Gaussian Membership Functions (GMF) representing the 3 identified behaviors (Calm, Aggressive and Dangerous). These GMF allow setting the appropriate safety distance d_{safety} based on the behavior of the detected dynamic obstacles. For a calm obstacle, the safety distance is set lower than for an aggressive obstacle to anticipate acceleration or deceleration from the obstacle (cf. Table I). The safety distance for a dangerous obstacle is considered to be the maximum (cf. Figure 6). This anticipation helps to reduce the impact of the obstacle's speed variation, on the EV's speed profile (cf. section IV).

Behavior	Calm	Aggressive	Dangerous
Distance	Low	Medium	High

TABLE I

Safety distance depending on the obstacle's behavior.

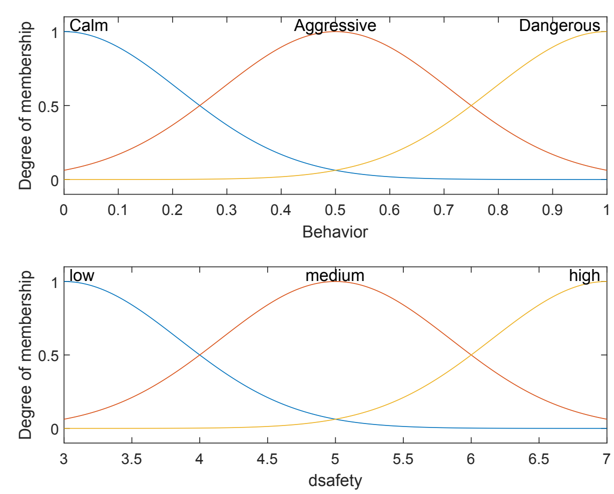

Fig. 6. The membership functions are defined by Gaussian Membership Functions (GMF) to determine the suitable safety distance that must be respected. These GMF are standardized (between 0 and 1) but the safety distance, considering the obstacle behavior, is between 3 and 7 meters. The membership functions for the parameters K_p, K_i and K_d are not presented here but there are set to reach the safety distance more or less quickly depending on the obstacle behavior.

B. Adaptive Fuzzy PID controller

Once the information on the appropriate safety distance is known, corresponding to the obstacle behavior, the EV must apply the best speed profile to maintain PIDP above the desired safety distance d_{safety}. If the dynamics and the trajectories of both vehicles are kept, the idea is to control the expected minimum predicted inter-distance profile $mPIDP$. The error e_{PIDP} represented by the difference between d_{safety} and $mPIDP$ (cf. Figure 4) can be expressed as follow:

$$e_{PIDP} = |d_{safety} - mPIDP| \tag{6}$$

The sign of e_{PIDP} depends on the behavior that must be adopted (acceleration or deceleration) from the EV. The considered error is positive if the EV has to accelerate and negative if he has to decelerate. At each time step, the error e_{PIDP} is computed and a PID controller applies a correction based on proportional, integral and derivative of this error according to the following well known PID formulation:

$$u(t) \quad = \quad K_p e_{PIDP}(t) + K_i \int_0^t e_{PIDP}(t)dt + K_d \frac{de_{PIDP}}{dt} \tag{7}$$

with K_p, K_i and K_d respectively the proportional, integral, and derivative coefficients and the command u is the speed that the EV must add to the precedent one to converge $mPIDP$ toward the d_{safety} limit. Figure 5 shows the structure used to adapt the PID coefficients, depending on the obstacle behavior. The same FIS bloc is used to update the safety distance d_{safety} and the 3 coefficients of the PID. This improves response time according to the behavior of the obstacle (cf. Figure 7).

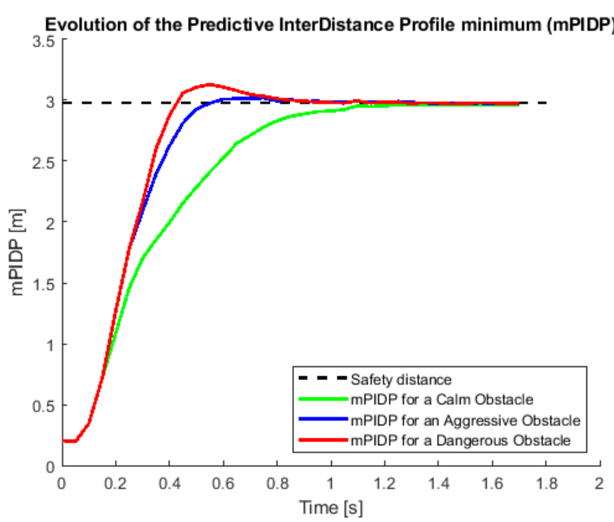

Fig. 7. PID setting by the FIS bloc. This allows to reach faster or slower the safety distance depending on the obstacle behavior.

The convergence time has a direct impact on the speed profile of the EV. For a calm obstacle, the coefficient has been set to have a smooth evolution of the speed unlike for a dangerous obstacle where the safety distance must be reached quickly. In all of those cases, the speed and acceleration limits must be respected (cf. section II-B).

IV. Simulation results

The simulation results have been performed on Matlab/Simulink. To highlight the proposed strategy, a two-lane roundabout with one lane insertion has been created. The scenario includes an obstacle on the external lane at a constant speed. The EV arriving at the intersection must take the decision to accelerate or decelerate considering the OV and the curvature of the path. Let us consider some constraints that the EV must take into account:

- The maximum acceleration a_{max} is $3m/s^2$.
- The maximum deceleration $-a_{min}$ is $-3.5m/s^2$.

These limitations are considered during the first part of the decision making when the feasibility of the insertion is evaluated (cf. Figure 3).

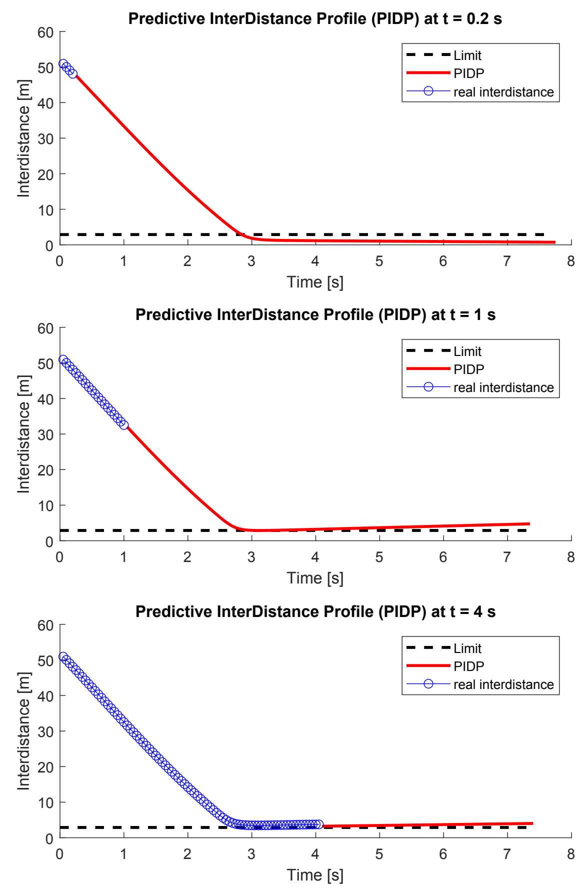

Fig. 8. Evolution of PIDP during the scenario. The fuzzy PID allows to maintain the safety distance. The dotted line limit represents d_{safety}.

At the beginning of the scenario, the speeds for the EV and the obstacles are respectively $10m/s$ and $10,2m/s$. The initial acceleration for both is equal to zero. The actual dynamic of both vehicles imply a noncompliance with the safety distance during the insertion with $mPIDP < d_{safety}$. At time $t = 0s$, the OV behavior is identified.

We can see in the Figure 8, at the beginning of the scenario, ($t = 0.2s$), that the PIDP does not respect the safety distance. If both vehicles keep the same dynamics, a collision will occur. At each time step PIDP and the error e_{PIDP} are computed and the applied speed allows convergence towards the safety distance d_{safety} (cf. Figure 8 for $t = 1s$). At the moment when the EV is closest to the OV (around $t = 2.8s$), the safety distance is respected. However, this scenario represents an insertion for a calm obstacle. Let us now show what happens with a dangerous obstacle (with acceleration) when the EV insert the ring zone of the roundabout.

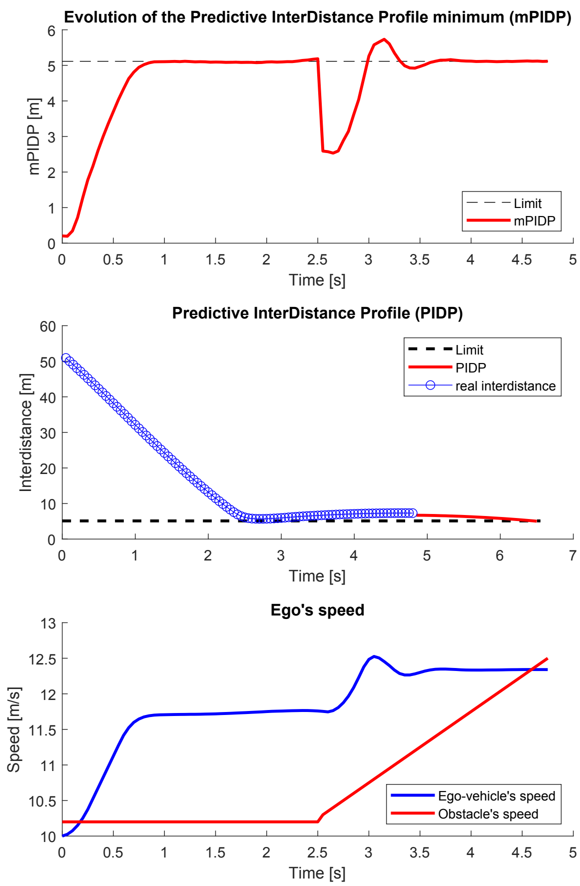

Fig. 9. Scenario with a dangerous obstacle where this last one accelerates when the EV enter the ring zone of the roundabout. The dotted line limit represents d_{safety}.

At the beginning of the scenario, the safety distance is reached by applying a smooth acceleration. At $t = 2.5s$ the OV accelerates with $a = 1m/s^2$. This acceleration has an impact on the PIDP. If the EV does not react to this new dynamic of the obstacle, a collision will appear like what is shown in Figure 9 where the minimum of PIDP (mPIDP) decreases from 5 to 2,5. A new speed profile is computed to reach the safety limit taking into account the new dynamic of the OV. We can notice that at the end of the scenario (around $t = 3s$), the EV decelerates while it is above the safety distance. This simulation aims to show the efficiency of this approach that works like an Adaptative Cruise Control but with a formulation that adapt itself according to rectilinear movements. The same algorithm has been tested intensively for several other configurations and behaviors of the OVs, and the proposed overall approach for safe roundabout crossing exhibit high efficiency results. For instance, it was tested for an insertion to the internal lane on the roundabout, with an OV on this lane. The right speed profile is applied. To know more about the tested scenarios, see the video at this link: https://urlz.fr/lBr5

In these batch simulations, 300 different scenarios were tested. The initial speed of both vehicles is randomly chosen between $3m/s$ and $11m/s$. The behavior of the obstacle-vehicle for each simulation is also chosen random between $-1m/s^2$ and $1m/s^2$ at any time during the scenario. During these 300 insertions on a roundabout, there were 92 scenarios where the algorithm was activated (for others cases initials speeds allowed already a safe insertion), 9 scenarios where the dynamic change from the OV forced the EV to stop (i.e., speed of the EV is equal to zero). On 92 scenarios, the EV decided to accelerate 16 times and decelerate 76 times. On 300 scenarios, there was zero collision.

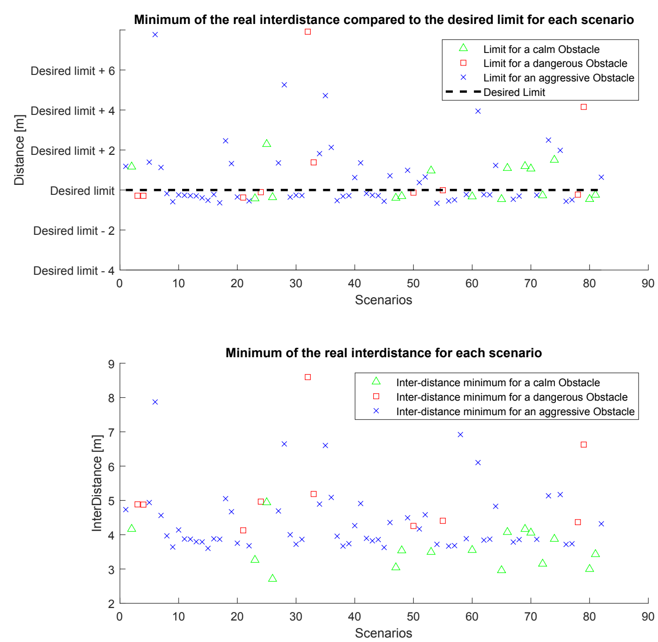

Fig. 10. Results of the batch simulations. The proposed algorithm was activated 92 times during the batch and the safety has always been ensured. The desired limit for a calm obstacle is between $3m$ and $4m$, $4m$ and $6m$ for an aggressive obstacle and $6m$ and $7m$ for a dangerous obstacle.

The safety limit, represented with the minimum of the real inter-distance for each scenario (cf. Figure 10), is not always respected. On 83 scenarios where the algorithm was activated and the EV was not stopped, the minimum of the real Inter-Distance is above the safety limit 34 times and under 49 times (cf. Figure 10, first graphic starting on the top). This first graphic represents the desired safety limit on Y-axis. This desired safety limit is between $3m$ and $7m$ and depends on the obstacle behavior (cf. Figure 6). This parameter can be set manually according to the size of the vehicle (cf. Figure 2) because the distances of buffers are taken into account in d_{safety}. The minimum value under the safety limit (black dotted line) is $0,33m$ can represent an error margin, but not significant when this error is reported on the real minimum of the inter-distance between the two vehicles (cf. Figure 10, second graphic).

V. Conclusion and Prospects

This paper proposed an insertion process for entering a roundabout with a path planning based Limit-cycles and an adaptive speed profile, computed online, to respect the safety distances with obstacles-vehicles navigating inside while considering their behaviors. It allows to enhance the MRAM-CS architecture presented in the previous work [1]. This method is based on the Predicted Inter-Distance Profile (PIDP) by computing the progress of the minimum of PIDP (mPIDP). The aim of the proposed approach is to ensure the reliability of roundabout insertions, while taking into account the EV's capacity to maintain the safety distance and by including constraints on the longitudinal acceleration. The proposed control is based on Fuzzy-PID controller, allowing the updating of the PID gains according to Fuzzy Inference System (FIS) and the safety distance that must be respected considering the behavior feature (calm, aggressive or dangerous) of the other vehicles. A batch simulations of 300 roundabout insertions has been performed to demonstrate the reliability and safety of the proposed approach. As short-term perspective it is planned to implement the proposed approach on the autonomous vehicles available in the laboratory. The proposed approach will be also enhanced by considering the evolution of the curvature path as an entry of the Fuzzy-PID controller. A learning-based approach can be also considered such as an Adaptive Neuro Fuzzy Inference System (ANFIS) learning from the batch simulation.

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