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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Model of autonomous driving in a roundabout scenario

LAUREA MAGISTRALE IN MECHANICAL ENGINEERING - INGEGNERIA MECCANICA

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1. Introduction

Autonomous vehicles are one of the future trends defined by the European Commission and a crucial field of research for future private and public mobility. This thesis work has the aim of creating a Digital Twin of a real roundabout scenario within which testing the capabilities of Autonomous Vehicles and the effect of their penetration in the simulation environment, specifically considering 20% and 80% AVs. The study, in fact, refers to the transition between the absence and presence of only Autonomous Vehicles. DRL (Deep Reinforcement Learning) policies will move Connected and automated vehicles taking decisions along all the simulations. They will be connected using edge computing technology, 5G mobile communication protocols and using a V2N2V communication [4, 5]. Such a complex simulation environment is part of an extended project called AI@EDGE [2] that has the objective of studying the effect of many types of automation inside a real network, among which road mobility. Firstly, the simulation environment is built by creating effective communication between the three platforms implemented:

- the Driving Simulator, i.e., DriSMi, which allows introducing the human factor directly to the simulation, making this study capable of innovative experimental results;
- the Artificial Intelligent Framework which contains the DRL policy and governs the AVs' actions in the simulation, using RL algorithms applied by Flow;
- the traffic simulation built in SUMO, primarily responsible for the environment design and all operating logic of the network and the vehicles.

Preliminary tests were carried out in order to optimise the system configuration by developing algorithms for trajectories interpolation and by changing the roundabout design to avoid negligence in compliance with the rules of right of way. It has been developed a *Replay* scenario considering the vehicle dynamics and behaviour; it will be used to test the usability of the created autonomous vehicles by human users considering their comfort and overall feeling of safety. This will result in a great step forward in the research activity of the AI@EDGE project and, therefore, in obtaining valid results in order to present a possible future solution for this industry.

2. Preliminary environment

The simulation environment is really complex and must be carefully obtained to mimic reality.

It will act as a Digital Twin of the real vehicle and of the real scenario, reducing drastically prototyping errors, costs and environmental impact. To achieve an effective scenario, a preliminary environment is obtained highlighting the simulation criticalities and most relevant details. The main component of the simulation are: the network geometry and traffic distribution; the communication between all devices used to obtain the functioning Driving Simulator; the AVs policy merit DRL function.

2.1. Preliminary network

The preliminary roundabout is an artificial mini-roundabout with three legs. The internal radius of the roundabout is 9 m and the external one is 15 m. Its main components are the junctions: reference points of the network linked together by edges on which vehicles will run. Edges are composed of specific lanes that in this scenario are just one per each direction of travel.

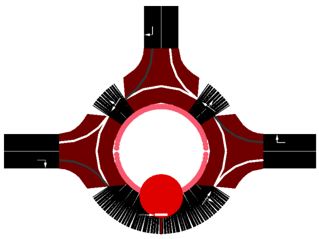


Figure 1: Details of the circulatory roadway of the preliminary network.

Figure 1 shows the roundabout built inside SUMO. In red and burgundy are highlighted the junctions of the network and inside of them it is possible to denote the lanes connecting the entering lanes, the circulatory roadway lanes and the exit ones. The three legs are about 110 m long so as to allow proper approach and exit from the roundabout. Considering all the edges of the network, it is possible to define: external edges with a maximum speed set to 50 km/h and internal edges for which the maximum speed is set to 34.2 km/h.

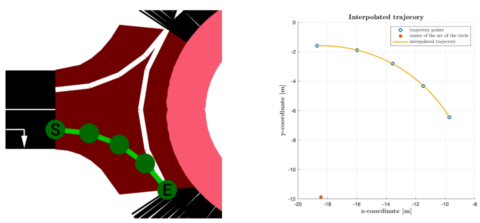
2.2. Communication implementation

The main devices communicating during the simulation are three: Flow, a library which enables the creation of an interface between the SUMO simulation and all Deep Reinforcement Learning libraries (i.e. RLlib) used to run the autonomous vehicles; SUMO, a microscopic traffic simulator allowing intermodal traffic systems and, finally, the Driving Simulator. A similar communication configuration is built in [1]. Flow represents the AIF. SUMO [3] is the microscopic traffic simulator. The Driving Simulator is used both to display the environment to the human user and to let the ego car interact with all other vehicles.

Flow starts the communication, beginning the simulation in SUMO using TraCI: a SUMO library giving access to a simulation through TCP. Once the simulation has been created, a second terminal is used to connect it to SUMO via TCP to: retrieve data about all vehicles, use it to display them in the Driving Simulator and communicate to SUMO, via UDP, the ego car updated position. This overall communication must happen in less than 0.005 seconds. During the exchange of data between SUMO and DriSMi it is possible to verify what happens inside the simulation environment and to manipulate the data retrieved. An example of that are the trajectories followed by vehicles that are defined as subsequent points linked together by means of straight lines and, for this reason, not precise enough. To solve this problem, a first simple algorithm has been implemented and used in the second terminal to interpolate curves.

2.2.1 Trajectory interpolation algorithm

In these preliminary tests, curves are considered as arcs of circumference for which the user must define centre coordinates, radius, steering angle and reference yaw. This is a simple interpolation but coherent with the need of keeping as low as possible the computational time.



(a) Original trajectory in SUMO.

(b) Interpolated trajectory.

Figure 2: Comparison between the original trajectory and the interpolated one.

2.3. AVs DRL policy

The policy lets the AVs interact with the simulation environment taking decisions and evaluating their effects. The policy has been trained only to optimise the crossing time of the roundabout; it is a neural network with 16 hidden layers. The algorithm used for policy training is Proximal Policy Optimisation (PPO), enabling the process to use online data as well. γ discounts all future moves with respect to the immediate next one and is set to 0.99. Generalised Advantage Estimation (GAE) is used to evaluate the difference between what the policy predicted an action would return and the actual return it got. The Kullback-Leibler divergence target is 0.02. Stochastic gradient descent logic is used to optimise the policy.

3. Preliminary tests

The main objective of preliminary tests is to understand the simulation environment's ability to replicate reality. On this property depend all the system performances and the manner in which the user perceives the simulation. The second objective is to understand if the user is able to appreciate any difference between the two main scenarios considered: 20% of humanly-driven vehicles and 80% of AVs and vice-versa. Specifically, every user will perform six simulations: they will start from all three legs of the roundabout two times alternating the two scenarios proposed. Since the policy has been trained to minimize the crossing time, it is relevant to investigate if users feel a difference regards traffic smoothness.

3.1. The questionnaire

The questionnaire has been built considering the objectives discussed in this section and also to acquire data as much as possible comparable. Both quantitative and qualitative information has been retrieved to have a complete description of the simulations from the point of view of the user. The questionnaire is divided into three sections:

1. the first is devoted to acquiring general participants' information;
2. the second is used to understand if the policy behaviour has been considered correct by the user;
3. the third is used to generally compare the two scenarios from a smoothness and safety point of view.

The questions need to be as clearer as possible since participants need to process a large amount of information. The third section is also used to understand if the participants' answers are coherent in the two main sections.

4. Preliminary simulation results

The test has been submitted by 12 participants. All of them successfully completed all six simulations. The two scenarios were proposed alternately between successive participants. With regards to compliance with the rules or right of way, no difference has been highlighted between the behaviour of AVs and humanly-driven vehicles. In both cases, some of them failed in respecting the priority rules. The main reasons for which this happened are:

- the AVs policy has been trained considering only the crossing time;
- due to SUMO architecture vehicles are able to see all others only if they follow a path near SUMO original trajectories.

Considering the third section's answers, it is possible to highlight a slight preference in terms of users' perception of the scenario in which 80% of the vehicles are AVs. Considering both smoothness and safety, a slight preference can be seen for this scenario, but data do not show an absolute preference. With regards to smoothness, the difference detected was not clearly identified. Possible reasons are:

- the participants' number is too small;
- every user had to face many simulations with almost no time to process the information;
- simulations lasted from 25 seconds to 40 seconds and participants had no time to appreciate differences.

Finally, two of the participants showed a complete inconsistency between the answers they gave in different sections of the questionnaire.

4.1. Comments and modifications

The following weaknesses of the network have been highlighted:

1. vehicles are not always able to detect the ego car inside the circulatory roadway;
2. traffic does not represent a realistic scenario;
3. vehicles do not follow trajectories adherent to reality;
4. participants did not understand most of the time the intentions of other vehicles.

The first problem depends on the fact that the circulatory roadway is too wide for the preliminary roundabout, but it is possible to enlarge the central island. Considering the second problem, the number of vehicles has been chosen by taking into account the data exchange limit in terms of computational time and this led to a network in which queues are artificially built. For the final simulation environment, must be considered a complete calibration of the model. In this way, it will be possible to obtain the specific number of vehicles, their departure and arrival times and also the effect of their interaction with other traffic components. The last two problems are related to one another. To fix them have been adopted two solutions: to upgrade the trajectories interpolation inside the roundabout by implementing two algorithms and to use car turn signals – retrieved using TraCI from SUMO and used in the Driving Simulator – to give a visual indication of the vehicle direction.

4.1.1 First interpolation algorithm

The first interpolation algorithm is more precise but requires a higher computational time to be processed. The Python interpolator will create an interpolated function passing through some waypoints defined by the designer. The following trajectories have been obtained:

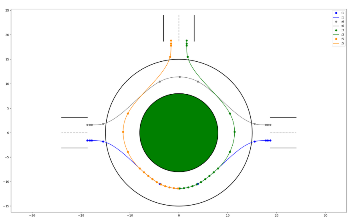


Figure 3: Final interpolated trajectories.

4.1.2 Second interpolation algorithm

The second interpolation algorithm is less precise but really faster and useful in the case of many vehicles in the simulation. The starting point of this algorithm is the same as the first one. Once all paths have been obtained, the x and y coordinates are concatenated to fill a lookup table on which the algorithm is built. This table is composed of three columns: the distance travelled by the vehicle, its x and its y coordinates.

Distance [m]	x	y
0,0974	91,5436	-95,0135
0,0994	-91,5422	-95,0120
...	...	...

Table 1: Example of the lookup table used to obtain interpolated points.

5. Replay

Replay refers to a specific simulation in which participants are placed in a vehicle driven by the AV policy. Inside the Driving Simulator, the ego car will repeat all actions of a generic AV. Through the Replay, it is possible to deeply evaluate some basic and crucial policy performances which are essential to achieve AVs that are truly usable in a realistic environment. This experiment has been realised using VI-car, replicating an AV position and speed profiles using a driver to obtain a closed control loop. Among all blocks used to develop the simulation in VI-car, the gear one has been modified by updating the upshift and downshift gear ratios. Firstly, have been analysed the lateral and longitudinal accelerations.

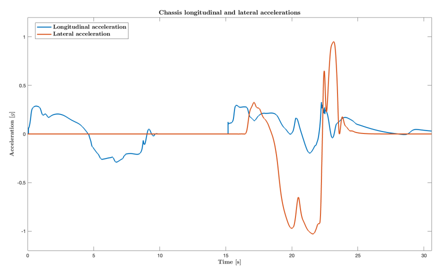


Figure 4: Chassis accelerations during the replay simulation.

They highlighted a wrong design of the policy, which reaches too high lateral accelerations becoming unbearable for the passenger. This must be considered by training a new policy accounting also for comfort and safety parameters. Considering lower velocities inside the circulatory roadway, the acceleration decreases to a maximum of 0.435 g, as shown by figure 5.

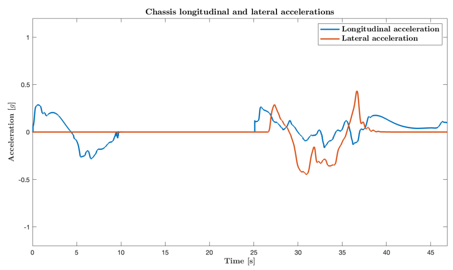


Figure 5: Longitudinal and lateral accelerations for the modified scenario.

The driver also becomes more capable of following the imposed trajectory, with a final result presented in figure 6.

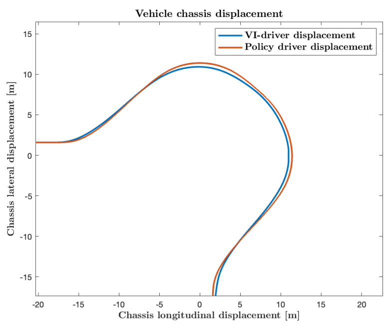


Figure 6: AV displacement comparison between SUMO and VI-car trajectories.

This final modified scenario has been tested inside the Driving Simulator to account for the first impressions and feelings of a passenger inside the AV built. Overall, the impression has been positive and the passenger managed to complete several tests. Some discomfort has been denoted, mainly while the vehicle was exiting the roundabout.

6. Final environment

This final section summarises what has been obtained in all previous sections. It aims to describe the final and complete simulation environment in which all experimental tests can be carried out. The results of these tests will be crucial not only to verify all design choices but also to validate the policy and its ability to drive inside the roundabout.

6.1. The roundabout

It has been chosen a four-leg mini-roundabout located in Milan and composed of one internal lane, like the one used in the preliminary tests. It shows medium-high traffic so being a challenging environment for the AVs policy. Moreover, it has some important details which make the simulation more realistic and general, such as its standard configuration widely distributed in Europe with significant flows. The roundabout's network is built inside SUMO environment using the same tools described for the preliminary scenario.

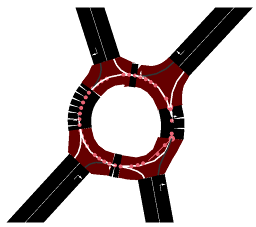


Figure 7: Circulatory roadway of the final network.

6.2. Traffic calibration

Once the roundabout has been chosen, it is possible to calibrate the traffic getting as a final output the specific flows of vehicles entering and exiting the roundabout and the values of the SUMO parameters which drive the traffic distribution along all the simulations. To obtain this calibration has been necessary the collaboration with the Mobility and Transportation Laboratory of the Department of Design of PoliMi.

6.3. Final Tests and questionnaire

Final tests have a similar structure to the preliminary ones. Since there are more legs and greater traffic, participants will remain in the simulation environment for a longer time than in the preliminary network. They will start from fixed points equal for all of them from every leg, going down the straight, entering the roundabout and exiting at the third available exit. It was chosen to present a questionnaire as the one described in section 3.1. In this way, it is possible to ensure the comparison between the results of the two tests carried out. To better comment the results of these tests, it is crucial to highlight that simulations showed a reduction in the average crossing time of 25,43% inside the circulatory roadway, and of 12,88% considering the whole simulation for the scenario in which 80% of vehicles are AVs.

6.4. Final results

Participants were chosen from outside PoliMi so that they were not informed about the Driving Simulator or its operation. An attempt is made to obtain results as general as possible; on the other hand, the general inexperience of the users must be considered because, in some cases, can compromise the results. The roundabout obtained for this final simulation environment turns out to be perceived as largely more realistic and, for this reason, the results obtained are certainly of greater value in this field of research.

Global preference	Quantity
Significantly pref. 1 to 2	0
Partially pref. 1 to 2	3
Partially pref. 2 to 1	3
Significantly pref. 2 to 1	4
No preference	0

Table 2: Global preference between the two scenarios. Scenario 1 has 20% of AVs, scenario 2 has 80% of AVs. "Pref." stands for *preferred*.

It has been demonstrated a better behaviour of vehicles in the 80% AVs scenario in respecting the rules of right of way. Modifications applied have been effective in limiting the consequences of a bad environment design. Traffic inputting the roundabout has been perceived in the same way for the two simulation scenarios without any visible difference and the traffic smoothness has been overall perceived equally. Participants felt generally safer in the second scenario which was why it was preferred by the majority. This is one of the most important results of this questionnaire and final tests: users felt better with more AVs in the network proving the validity of the study.

7. Conclusions

The first important result has been the creation of a stable and functioning communication system between Flow, SUMO and the Driving Simulator. This enabled the development of a preliminary simulation environment and an effective Digital Twin. Thanks to the final simulation environment, the following results have been achieved:

1. the policy has proven to be able to handle different environment geometries;
2. the AVs were able to handle a variety of driver behaviours, being tested with various and different participants, both by simulator experience and more general driving experience;
3. for the most part, participants felt safer and preferred the scenario with a higher percentage of autonomous vehicles. For future tests, it will be necessary to give participants more time to understand the operation of the simulator and thus feel safe during the test;
4. the *Replay* simulation has been crucial to completely understand the policy performances, also considering safety and comfort;
5. the traffic calibration led to a better-performing scenario.

References

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